破碎變數에 依한 밀의 硬度測定에 關한 硏究

Study on Wheat Hardness Measurement in terms of Comminution Parameters

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摘 要

穀類의 硬度는 穀類의 分類, 性狀의 파악, 等級을 表示하는데 있어서 重要한 物理的 量으로서, 特히 近來에 와서 그 測定方法에 關한 硏究가 活潑히 進陟되고 있다. 本硏究에서는 이때까지 여러 硏究者에 의하여 提示된 밀의 硬度測定方法에 關하여, 批評하고 測定尺度에 關한 理論을 體系化하였다. 보다 나은 硬度測定 方法을 開發하기 위하여 破碎理論(Comminution theory)를 Brabender burr-mill 에서의 破碎過程에 適用하였다. 定常的인 破碎過程에 關한 에너지와 粒子減小에 關한 關係式을 誘導, 이로부터 硬度指數를 定義하였다. 偶力測定의 銳敏度를 높이기 위하여 Brabender 機械를 機械的 測定裝置에서 電氣的 測定裝置로 改造하였다.

Brabender 系統에서 얻어진 破碎變數는 Flour Yield, Gaudin-Schuhmann 方程式의 分布 및 粒子係數, 代表粒經, 最大破碎抵抗, 平均破碎抵抗, 破碎에너지, 破碎指數, 硬度指數등이었다. 82種의 다른 品種의 밀을 實驗하여 얻은 위의 破碎變數들을 單純線型相關分析에 의하여 比較하였다. 重要한 結果를 要約하면 다음과 같다.

1. 粒度의 特性을 測定하여 얻은 硬度의 指數値는 破碎에 要하는 Energy 와 相關關係는 있지만 極히 긴밀한 關係에 있다고는 할 수 없었다.

2. 粒度의 特性에서 얻은 여러 變數中에서 Flour Yield 가 硬度의 尺度를 가장 잘 表示하여 주었으나 軟硬의 두 分類에만 適合할뿐 엄밀한 分類의 尺度로서는 不適合하다고 認定되었다.

3. Brabender burr-mil 에 對하여 에너지와 粒度減小에 關한 關係式을 誘導하였다.

$$E=\overline{A}\times X_{\gamma}^{-\beta}$$

여기서 E=單位重量當의 破碎에너지
X_{γ}=累積部分 重量의 10%에 相應하는 破碎된 밀의 粒經
β=Gaudin-Schuhmann 方程式의 分布係數이다.

이 方程式에서 硬度指數($TI=\overline{A}$)를 다음과 같이 定義하였다.

$$TI=\overline{A}=EX^{\beta}_{\gamma}$$

이 方程式은 粒度特性과 破碎에너지 두가지 要因을 包含하고 있으며 硬度指數는 粒度特性과 破碎에너지 두가지에 대단히 強한 相關關係를 나타내었다 그러므로 이 두가지 要因을 測定하는 尺度로서 利用할 수 있을 것이다.

4. 破碎指數(GI)를 定義하는 式은

$$GI=EX_{\gamma}$$

로서 Rittinger 方程式 $E\propto\left(\frac{1}{X_2}-\frac{1}{X_1}\right)$에서 $X_1 \gg X_2 = X_{\gamma}$일 때 변형된 것이다. 이 破碎指數는 다른 破碎 變數들과의 相關關係에 있어서 破破指數와 거의 비슷하게 나타 났으나 相對的으로 粒度特性에는 強하고 破碎에너지에는 弱하였다.

Introduction

Kernel hardness has been measured as a mean of assessing the mechanical properties of cereal grains. A better system for measuring kernel hardness has been the object of a great deal of interest and investigation in connection with grading, classifying, and identifying the type of grains for a particulor use.

Systems for measuring kernel hardness that have been developed in the past sixty years have been based on a wide range of different techniques,

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principles, and assumptions. One of the important up-to-date techniques is to use the parameters from the comminution process by using standardized grinding machines. The past works in this area could be classified in three categories according to the nature of parameter for which the measurements are being made; (1) Particle size characteristics of the ground product, such as particle size index [22, 28] flour yield [2, 14] and flour surface area. (2) Energy transformation involved in comminution, such as the parameters that have been defined from the Brabendertime-torque curve [2, 21, 22]. (3) Energy-size reduction relationships, such as flour surface area per unit work[2].

Actually, the topics in the classifications are problems in the study of comminution phenomena. For the study of comminution, there is more interest in the understanding of a governing law among the comminution variables so that the phenomena may be predicted for any grinder, operation condition, and material to be ground. Instead, hardness measurement in terms of comminution parameters are more concerned with the method that gives a powerful differentiating measure of difference of wheat hardness for a grinder and its operation condition.

In this study, some of the recent developments being made in the area of comminution theory will be applied to the measurement of wheat hardness. Based on the comminution concept, the quantities or parameters for rating wheat hardness will be more regorously defined than it has been in the past. Quantities so defined will be compared by testing 82 different varieties and /or locations of growth of wheats.

A review of literatures

1. Hardness measurement of wheat in terms of commiution parameters.

The eariest attempt to measure wheat hardness in terms of fracture strength, energy requirement for crushing or comminution, or a parameter which can be obtained from the subsequent product of grinding was performed by members of the Kansas Agricultural Experimental Station. Roberts[24] reported on a testing machine that crushed kernels by adding weight to an loading arm. The weight required to crush the kernel was taken as an index of kernel hardness. However, this test was not adopted because the test was tedious to perform.

Measuring wheat hardness by a standardized grinding procedure was reported by several investigators [2, 14, 22]; one of the most popular machines for their work was the Brabender hardness tester. The Brabender tester consists of a small burr mill fitted to the dynamometer coupling of a farinograph. It has been used widely for determining the hardness of barley. This device produces the torque-time curve, called as the Durograph curve. The torque-time curve along with the particle size distribution of ground material defines a number of new indexes of kernel hardness, as shown in Table 1.

The data obtained by Anderson,etc.[2] demonstrated that flour yield or flour fraction surface area from the Brabender burr mill or the pin mill can be used to rate wheats according to kernel hardness, even though flour yield from pin mills was about 3 times that obtained with the Brabender tester under the conditions chosen. It was also shown that the most sensitive measure of hardness was the flour fraction surface area per unit work required for grinding. Variations of the hardness range were reported well over 20 fold with these tests. However, the authors failed to show the precision of the technique; the variation of such wide range may have little meaning unless the standard error is small. It may be observed that the surface area calculation may involve a large deviation especially in connection with fine particle measurement.

Greenaway [14] substantiated many of the Brabender investigations performed by Anderson, etc. on commercial wheat. A correlation coefficient of 0.93 was obtained for the regression line relating wheat hardness index and protein content per square meter of flour surface area and

0.85 between wheat hardness index and pearling index. He argued that any index for wheat hardness should be meaningful or of value if correlations with the other indexes of quality such as protein content, flour yield, etc. exist. The higher correlation coefficients between wheat hardness index and protein content were attributed to the fact that protein acts as a cohesive agent binding the endosperm particles together and thus causing more resistance to milling.

One of the most extensive works on the grain comminution was done by Mepplink and his coworker in the INSTITUUT VOOR GRAAN MEE EN BROOD TNO, the Netherland.[22] According to these investigations, the Ae-value appeared to be significantly affected by moisture content for a given material. The moisture effect was so dominant that softer wheat at 18% moisture appeared to be much harder than a harder class of wheat at 10% moisture content. A comparison of the Durograph curve between hard and soft wheats for different moistures revealed that the pronounced moisture effect could be attributed mostly to the L-value which increased considerably as the moisture content of grain increased, the response of which being more pronounced for softer wheats. However, the Ae-value showed the best differentiation between hard and soft wheats for low moisture grains. The effort to make use of the other Durograph values, such as H-and L-values or any combination of them, was unsuccessful because none was preferred to the Ae-value.

Durograph curves and the granulation of the ground material are the two independent measurements that come from the single comminution of a given wheat. Mepplink combined these two measurements into a single parameter in order to formulate the idea that more energy may be required to attain a finer granulation for a given material and machine setting or that more energy may be required to comminute a harder wheat to attain a comparable degree of granulation with the same machine setting. To this end, the d-value, which is the percent weight passing over 0.125 mm wire sieve for the wheat ground in the Brabender hardness tester, was chosen from granulation analysis. The quantity, Ae-value divided by the d-value, was examined and then discarded because it provided no advantages over the d-or Ae-values. It may be worthy to note that neither the d-value nor the Ae/d value has specific physical meaning, but are arbitrarily selected quantities.

The particle size index has been the one of the parameters for indicating wheat hardness, which, without reference to energy or torque required for grinding, makes use of the characteristics of particle size distribution of the material ground in a standard machine. It may be natural to assume that harder wheat may produce a coarser or grittier flour than softer wheat for the same machine setting. Mepplink used the MIAG burr mill through which 25 grams of wheat was ground. The product was sifted over a 0.125 mm wire sieve with the Ro-Tap machine for the period of 10 minutes. The percentage of the material passed through the sieve was taken as the particle size index. Their work showed that the range of the particle size indexes for the different varieties tested was from 9.9 to 48.2% with a standard error of 0.36%, calculated from 230 replicates. This provided a good differentiating ability between the hard and soft classes of wheat. An earlier work by williams [28], with a LABCONCO grinder and sifting over 200 Tyler sieve (0.074 mm opening), provided the similar results when testing various types of Australian wheats at about 10% moisture content.

The particle size index showed a considerable variation due to the change of grain moisture content, and it also varied with kernel sizes. Increasing the grain moisture content caused the particle size index to increase, giving approximately a linear relation for the 10 to 14% moisture range and greater increase for the higher moisture contents. The effect of kernel size on the particle size index was not as significant for harder classes of wheat in regard to the decrease of the index with the increased kernel size. Kernel size effect, however, was different according to the grinder used.

Table 1. Parameters used to rate wheat hardness in terms of comminution parameter

Parameter	Definition	Investigator	Unit
H-value	Maximum height of the	Mepplink	BU**
Wheat hardness peak	Brabender troque-time curve	Greenaway	BU
Twisting moment of rupture	Average torque in a special grinder with a torsional dynamometer	Kuprits	kg-m
L-value	Length of curve or time of	Mepplink	BU
Wheat mellowness	grinding	Greenaway	BU
Wheat hardness index	Wheat hardness peak divided by % flour yield	Greenway	BU
Ae-value Work	Area beneath the Brabender torque-time curve		cm^2 kg-m
Specific power expenditure	The area coverted to power	Kuprits	J/kg
Flour yield Flour %	Percentage of material passing through the U.S. No. 100 sieve of the material ground in the Brabender burr mill	Greenaway, Mepplink, Anderson, et al.	%
Flour surface area	Method given by Gracza	Greenaway Anderson, et al.	m^2/g
Flour surface area per unit work	Flour fraction surface area divided by work expenditure of 100g wheat grinding in the Brabender burr mill	Anderson. et al.	m^2/g m-kg
Particle size index	% material passing through 0.125-mm wire sieve of 25 g wheat ground in MIAG burr mill	Mepplink	%
Particle size index	Sifting over No. 200 sieve for the product ground by LABCONCO	Williams	%

* Refer to References,

** BU designates the Brabender unit.

2. Comminution theory.

Comminution refers to the process of fragmentation of solids. Since kernel hardness of wheat is required generally for identifying the type of grain in connection with the processing of grain to flour or size reduction, it may be worthy to review briefly different aspects of comminution theory.

Arbiter and Harris [3] proposed to use a three-dimensional weight-size-time coordinate system as a frame of reference for unifying and interpreting the comminution theory. Theoretical investigations of comminution have been concerned with various aspects of the weight-size-time surface; usually simplification are made by considering the projection of this surface on the three planes. This leads to a classification of past work into three parts: (1) particle size distribution (size-weight plane), (2) kinetic studies(size-time and weight-time planes), and (3) comprehensive (three-dimensional).

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 the mean size, a particular particle size, or surface area is generally inadequate to completely characterize a distribution function. Most of the particulate materials require at least two parameters to adequately describe its distribution function. A number of methods have been adopted for arriving at a mathematical description of particle size distribution. Many equation can be derived from:

$$\frac{dy}{dx}=AX^{-1}e^{-bx^n} \qquad (1)$$

where Y is cumulative fraction of material smaller than size X. The remaining terms are constants.

The Gates-Gaudin-Schumann equation[8,26] is given when n=0:

$$Y=100(X/K)^{\alpha}$$

and the Rosin-Rammler equation [25] when $\alpha=n$:

$$Y=1-e^{-bx^n} \qquad (3)$$

Equation (2) gave a straight line on the log-log grid paper with two parameters, b and n, to be specified. The equation is often criticized for its poor representation of the larger sizes of particle size distribution. A semi-empirical argument concerning the sum of exponentials leads to Equation (3)

From an equation for the distribution of flaw spacings in a single particle, the distribution of particle sizes corresponding to single comminution event is as follows:

$$Y=1-e^{-bx} \qquad (4)$$

where b= a constant

A recent outstanding derivation of Equation (4) is due to Gilvarry [10,11,12] who considered edge, facial and volume Griffith flaws [15] activated by the imposed stress. Edge flaws represent the dominant mode of fracture.

A recently derived size distribution defined from a statistical derivation is due to Gaudin and Meloy [9].

$$Y=1-(1-X/X_{max})^{\alpha 1} \qquad (5)$$

The equation is claimed to more adequately represent coarse sizes of comminution products resulting from britile fracture. The logarithmic representation of Equation (5) is extended in the coarse size region and contracted in the fine size region which is the reverse of all other distribution equations.

The log-normal distribution often used for the product of comminution by plotting cumulative percent finer on a probability scale versus particle size on a logarithmic scale. The particle size should appear as a straight line on log-probability grid paper in order for the distribution to be defined as log-normal. From the unique characteristics of log-normal distribution, considerable information can be derived such as geometric mean size, specific surface area, volume, etc.

Gracza[13] compared the Rosin-Rammler representation to the log-normal equation using ten flour samples and found the Rosin-Rammler representation more accurate. Hanson[17] found that the log-normal representation is not a reasonable representation for 14 to 200 mesh products of wheat comminution obtained from the hammer mill.

For nearly a century the development of relationships between the energy necessary to fracture ores and the resulting product size distribution has been investigated. The attempt is generally made to correlate one or more parameters describing the size distribution with input energy or period of time for comminution. The common characteristic of the various postulates advanced had been the lack of conclusive experimental support.

Theories advanced relating energy to size reduction of brittle solids stemmed from a single proposition attributed by Walker, Lewis, McAdams, and Gilland[27]:

$$\frac{dE}{dX}=\frac{C}{X^n} \qquad (6)$$

where dE represents an increment of energy flow into the comminution system, X particle size, dX the increment of size change, and C and n are constants. Harris[16] stated that the equation is a general mathematical statement, but that it has not been demonstrated to be a physically meaningful explanation.

The subject of the relationship between energy and size reduction has been dominated for a century by the Kick-Rittinger controversy.

Integrating Equation (6) when n=1 gives

$$E \propto \log(X_1/X_2) \qquad (7)$$

where the subscripts 1 and 2 refer to average size before and after fracture, which is Kick's equation. Kick's proposition has been stated variously as: "the energy required for producing anologous changes of configuration of geometically similar bodies of equal technological state varies as the volumes or weights of the bodies". When n=2, integration results Rittinger's equation:

$$E \propto \left(\frac{1}{X_2} - \frac{1}{X_1}\right) \qquad (8)$$

Since specific surface is inversely related to particle size, Equation (8) becomes:

$$E \propto (S_2 - S_1) \qquad (9)$$

That is, Rittinger's law states: "the useful work accomplished in crushing and grinding is directional to the new surface area produced, and to the reciprocals of the product particle diameters. This statament is merely a more or less arbitrary definition of useful work. However, he was evidently guided by the idea that all of the energy of grinding went into new surface, and this implication is the basis of the Rittinger theory.

Bond's third theory of comminution[4] is obtained by substituting n=1.5 in Equation (6), integrating and rearranging.

$$E \propto (X_2^{-1/2} - X_1^{-1/2}) \qquad (10)$$

Obviously, energy requirements for Bond's law lie between those predicted by the earlier two laws.

Before Bond's law appeared, it was known that Rittinger's law applies primarily in comminuting relatively small particles, while Kick's law generally holds for large particles. The evidence indicated that the value of n depends not only on the material ground but also on the kind of grinding system. Bond's equation made allowance for this variation in the working index (the proportionality constant), whose evaluation for any given material involves using an arithmetic mean value based on data accumulated from many different systems.

Bond developed his equation using the "crack theory"; he demonstrated the physical meaning of the n value, and offered an explanation as to why this n value might consistently equal 1.5 for all kinds of materials. However, depending upon the nature of crack formation some materials show exponents close to 2; others close to 3. This power must be viewed not as a universal constant, but a function of the material considered.

In suggesting a means of interpreting the exponent n in Equation (6), Holmes[20] revised Bond's third theory starting from Kick's law. His method leads to:

$$\frac{dE}{dX} = \frac{C}{X^{1+r}} \qquad (11)$$

where r is called a deviation from Kick's law. The values for r in Kick's, Rittinger's and Bond's equations are then 0, 1, and 1/2 respectively. These values are found by curve fitting to the general equation:

$$E \propto \left(\frac{1}{X_2^{r}} - \frac{1}{X_1^{r}}\right) \quad (r \neq 0) \qquad (12)$$

and for $X_2 \ll X_1$,

$$E \propto 1/X^{r} \qquad (13)$$

He demonstrated that r varies from 0.25 to 0.73 for several materials, and that such a concept leads to a more consistent proportionality constant that calculated by Bond.

Charles equation[9] obtained without rigour by combining Eq. (6) with the Gates-Gaudin-Schuhmann equation(Eq. (2)), has attracted considerable attention since it was first proposed. The equation, which at present is empirical, relates energy input, E, with product size modulus, K, and may be written

$$E = AK^{-\alpha} \qquad (14)$$

A and a are constants; the constant, a, depends primarily upon the nature of the feed and also on the manner of comminution. It has values between about 0.3 and 1.4, and for a given material is generally higher for impact crushing and lower for grinding in tumbling mills.

Agar and Charles[1] determined the constant, A, under similar experimental conditions, and compared its reciprocals(1/A value) to rate the grindability of various. materials. Hansen and Stewart[18] followedt he same procdure as Agar and Charles and applied it to agri-cultural grain comminution. A comparison of cereal grain grindability was made by:

$$\frac{1}{A}=\frac{F_1}{E} \qquad (15)$$

where F_1 is the weight fraction smaller than the particle size of 1 mm. They indicated that useful information about comminution characteristics of any ground feed can be represented by grindability and distribution modulus parameters.

It may be noted that the energy size-reduction relationships summarized above are given under the assumption that particle fineness can be expressed as a single parameter. As mentioned earlier, this assumption requires careful consideration in view of the complexity of particle size distribution. A number of investigators used the size modulus k in the Gates-Gaudin-Schuhmann equation, or an equivalent parameters. Bond used the 80 percent passing size Y_{80}, and Hanson and Stewart[18] and Charles[4] simply choose the fixed particle size (1mm) in defining grindability.Since $S\propto 1/X$ for a narrow size range specific surface is frequently substituted for the reciprocal of mean particle of mean particle size. This can not be validly assumed for a particle size distribution.

Headley and pfost[19] related the grinding energy to the change in the surface area of the ground feed based on the assumption that the particle-size distribution of grains both whole and ground are log-normal. The surface area was expressed primarily as a function of the log-normal geometric standard deviation, $\overline{s}_{gw}$, and the geometric mean particle size, $\overline{d}_{gw}$. The energy and particle size distribution for the feed-stuff were obtained a linear regression analysis to be evaluated for the pilot-sized hummer mill and range of hammer mill screen size.

The time variation of screen-size fraction is another subject of kinetic study in comminution.

Roberts[23] used simple first-order kinetics to determine the rate of disappearance of screan oversize. He found that some of his data could be fitted to the first-order equation, but other data could not.

Bowdish[6] extended Roberts' work by analogy with chemical kinetics and obtained differential equations for zero, firist and second-order kinetics:

$$-\frac{dY}{dT}=kY^{a}B^{b} \qquad (16)$$

where Y is concentration of oversize, B the ball area, T the number of revolution of the ball mill, and k is constant. A first order eqation is obtained when a=1 and b=0; it corresponds to grinding when the effect of ball was included in the constant. If the effect of ball area was considered, grinding becomes a second-order phenomenon (a=1, b=1). The rate of breaking of oversized particles should remain constant if the fines are removed as they formed. This indicates a zero order phenomenon in which case a and b are zero.

Derivation of Enerdy-Size Reduction Equation for the Steady-State Comminution Process.

The Brabender burr mill is a single pass or open circuit type of grinding. The grinding process may be defined best as the steady-state operation with respect to time, since the same conditions in reference to energy input and product particle characteristained fairly well throughout the process. The process is different than in the ball or tumbling mill, which are described as transient-tsate operation process.

Energy-size reduction relationships developed in the dast are concerned with the transient-state process. Therefore. it is desireable in this study to develope the relation for the steady-state grinding operation.

Assuming that the product particle-size distribution may be described by the Gaudin-Schuhmann equation,

$$Y=A_1X^{\beta} \qquad (17)$$

the weight of ground material, dG, which is smaller than some arbitrary particle size X and ground for a pariod of time dt is given by

$$dG=Y\,dW=A_1X^{\beta}dW$$

where dW is the ground material that passed through the grinding zone for the period of dt.

From the requirements for the steady-state, the total energy expended, E_t, and the total weight of the undersize, G, during the entire grinding time t are given respectively by

$$E_t= t\ dE \qquad (19)$$

and $$G=t\ dG \qquad (20)$$

where dE is an infinitesimal energy expended during the time dt. By eliminating t from Eq. (19) and (20)

$$\frac{dE}{E_t}=\frac{dG}{G}$$

or $$dG=\frac{G}{E_t}dE \qquad (21)$$

Now combining Eq. (18) and (21)

$$\frac{G}{E_t}dE=AX^{\beta}\ dW$$

or $$E_t=\frac{G}{A}\ \frac{dE}{dW}X^{-\beta} \qquad (22)$$

$\frac{dE}{dW}$=a constant for a given material and the steady-state.

For a given $G=G_r$, then $X=X_r$ and $G_r=\lambda\ W$ where λ is a constant. Therefore, Eq. (22) becomes

$$E_t=\frac{G_r}{A}\ \frac{dE}{dW}X_r^{-\beta}$$

$$=\frac{\lambda W}{A}\ \frac{dE}{dW}X_r^{-\beta}$$

Finally,

$$E=\frac{E_t}{W}=\frac{\lambda}{A}\ \frac{dE}{dW}X_r^{-\beta}$$

or $$E=\bar{A}X_r^{-\beta} \qquad (23)$$

where E is energy expened for grinding unit weight, $\bar{A}$ and β are constants.

Eq. (23) is the energy-size reduction relationship for the steady-state grinding. If X=K=the size modulus in Eq. (22), then $\lambda=1$ and G=W

$$E=AK^{-\beta} \qquad (14)$$

which is identical to Charles' equation as given in Eq. (14). From Equation(23).

$$\bar{A}=EX_r^{\beta} \qquad (24)$$

$\bar{A}$ was defined in this study as the toughness index and used for characherizing the toughness of various kernels in the burr mill grinding. Compared with the grindability which was defined by Charles[1] and later Hansen and Stewart[18], the toughness index includes an additional factor, the distribution modulus β. Therefore, the toughness index accomodates the situation where the distribution modulus from different materials is quite variable. As Eq. (24) indicates, the toughness index $\bar{A}$ increases as grinding energy E, the representative size X_r and the distributoin modulus β increase. Under the identical conditions of the Brabender burr mill operation, more torque input to the grinder shaft required to grind harder wheats than softer ones. Therefore the toughness index in accordance with the increases in accordance with the increased E for harder wheat. As illustrated in Fig 5, the particle size distribution parameters A_1 and β generally increase as wheat is getting harder. Therefore, the toughness index accommodates two factors, the energy input and the particle size characteristics in such a way that the toughness index is magnified to the multiple of two factors which are equally the same direction to the toughness index.

Experimental Equipment

The machine used in this study to analyze the comminution parameters was the Brabender hardness tester. The Brabender hardness tester consists of a grinding unit and the Farinograph dynamometer. The working tool of the grinding unit is the burr mill, which consists of a vertically revolving cone and stationary mantle. The surfaces of the cone and mantle are equipped with corrugations; the clearance between these corrugated surfaces gradually narrows toward the bottom. The overall view is shown in Fig.1.

The grain kernals which have fallen into the grinding zone are subjected to simultaneous deformation by compression and shear. The size reduction process continues until the ruptured particles are fine enough to pass through the preset clearance between the mantle and cone. The degree of grinding is adjustable by turning the threaded mounting of the maunting of the mantle. Different rates of grinding are obtainable by changing the driving motor-speed.

The Brabender system is equipped with the Farinograph dynamometer. Torque required to drive the grinding shaft is measured by the dynamometer and transmitted to a lever arm that acctuates the recording pen. the recording paper is driven by a small motor.

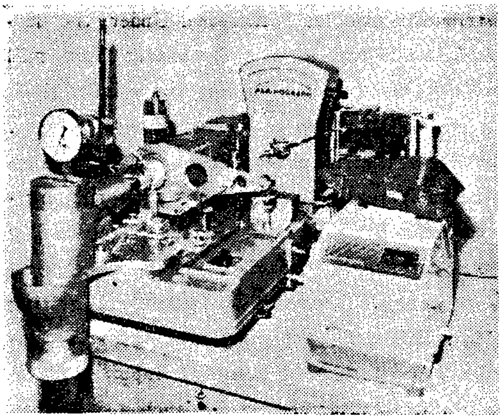

Fig. 1. The Brabender hardness tester.

A modification was made in the Brabender system. The parpose of this modification was to replace the Farinograph by the strain gage amplifier and recorder systems that give a greater sensitivity in making the torque measurement. The lever arm was locked completely so that motion could not be transmitted

to the be 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 torque of the

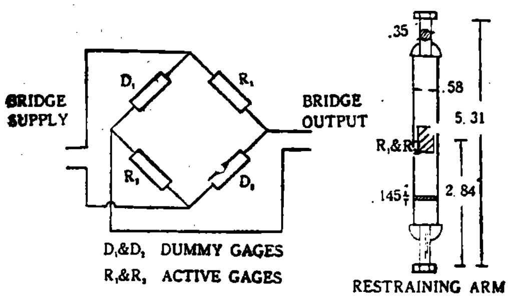

Fig. 2. Strin gage location and wiring diagram used for sensing torque in the Brabender hardness tester.

drive shaft. Two strain gages were mounted on the restraining bar. To improve the bridge null-balance, two dummy gages were later attached to an unstrained piece of bar, which was placed within a shielded connector box. The pysical and electrical arrangements of the four strain gages are shhown in Fig 2. The modified system is shown in Fig 3.

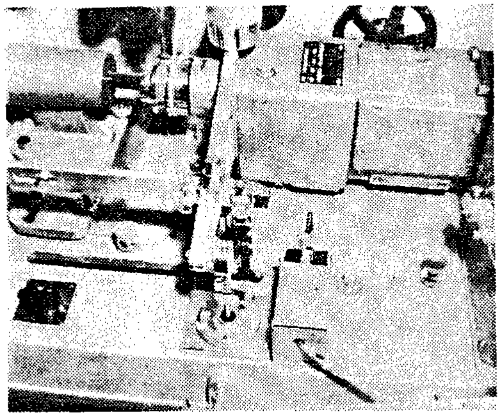

Fig. 3. The modified Brabender system with the restraining tension bar on which strain gages were mounted.

Strain gages used for sensing torque output from the hardness measuring system were connected to a strain gage amplifier-indicator. The system used in this study was the Daytronic Model 300 D transducer amplifier-indicator. The

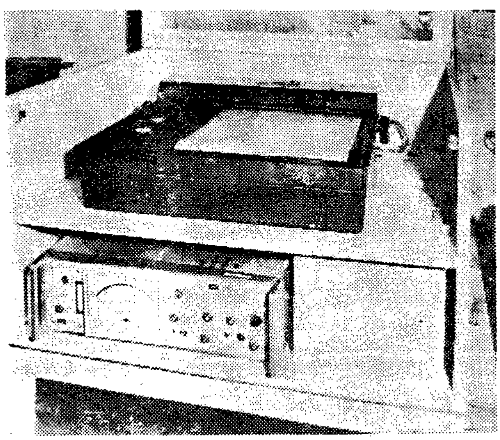

Fig. 4. The Daytronic Model 300 D tansducer amplifier-indicator (lower) and Beckman Model 100500 Recorder (upper).

electric signal from the Daytronic system was fed into a recorder, the Beckman Model 100500, which utilizes a standard 10-inch cartesian coordinate recording chart. The recorder was equpped with an integrator unit. An overall view of the Daytronic amplifier-indicator and the Beckman recorder system is shown in Fig 4.

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

Experimental Material

Wheats used in this investigation ranged widely in variety, region, and history of growth. The wheats were grown in experimental plots in various locations of the United States and were obtained through the Office of Market Quality Research Division, ARS, USDA, Manhattan, Kansas. Table 2. summarizes the wheats used in this study. A more detailed description of the wheats including variety, location of growth, and kernel size are given in the reference[7].

Table 2. Wheats tested in the Brabender hardness tester

Wheat Class	Region of Growth	Number of Varieties and/or Location	Year of Growth
SWW	Washington	18	1970
	Oregon	4	1970
SRW	Ohio	1	1969
HWW	Washington	4	1970
HRW	Washington	6	1970
	Oregon	1	1970
	Kansas	19	1970
	Oklahoma	2	1970
HRS	North Datota	11	1970
	Montana	6	1970
	Minnesota	2	1970
	South Dakota	5	1970
Durum	North Dakota	2	1970

Experimental Procedure

Each time about 400 grams of individual wheat samples were taken from a bulk sample. The row materials contained fines, broken kernels, and foreign material which varied considerably with the individual entries. To insure that the initial samples for each test were nearly uniform, the fines and foreign materials were screened out by using No. 10 Tyler sieves and about one minute of hand shaking. As an additional check on the preparation of samples, the remaining broken kernels were separated out from sound kernels by inspection.

For a given charge it is possible to alter the particle size distribution of 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. The former is related to the degree of grinding, while the latter to the rate of grinding.

The degree of grinding was selected such that the amount of under size passing through the No. 200 Tyler sieve would be relatively small, preferably a few percent of the whole product so as to eliminate the need for employment of any fine particle sizing technique other than sieve analysis. On this basis, no reason was found to change the clearance index of "9" that has been standardized for the operation of the Brabender hardness tester.

The rate of grinding was conveniently selected with a mill shaft speed of 20 Rpm. This speed gave a desired shape of the torque-time curve for the 100 grams charge and the 5 Rpm. of recorder chart-speed.

The particle analysis for the ground material in the Brabender machine was performed with 8-inch Tyler sieves and a Ro-Tap Shaker. To give the balanced picture of particle size distribution, an adequate combination of sieves was No. 14, 20, 28, 35, 48, 65, 100, 150 and 200 in Tyler series. A timer was used for obtaining accurate shaking time. The total shaking time was 20 minutes. Shaking was interrupted after 10 minutes to brush the undersides of the sieve to remove fine particles clinging to them.

Analysis of Experiments

Defining Comminution Parameters

1. Particle Characteristics

A logical starting point for measuring wheat hardness by using the characteristic of particle assemblies resulting from the comminution process would be the capacity for the contiuum of solid matter to withstand the external forces. For uniform grinding condition, a harder wheat may be exected to remain in coarser particulate state because of higher bonding strength compared to weaker wheats.

Parameters actually selected as a measure of wheat hardness have been dependent upon the grinder used and the manner in which the emerging particulate materials are measured and represented. It may be desireable to differentiate the difference of the particulate states of the ground product as great as possible when the grinder is being used to measure wheat hardness. In this sense, investigation of a better grinder could be a good approach for improving the wheat hardness measurement. However, this study was only concerned with representing the characteristics of the particulate material from the Brabender mill.

The following are the quantities used for characterizing the particle size and so wheat hardness.

Flour yield; The quantity was defined by the previous researcher[14,22] as the cummulative percentage of material passing through the No. 100 Tyler sieve of the ground product from the Brabender hardness tester. The flour yield may be considered as an equivalent technique to the particle size index because of measuring the same particle characteristcs, although the grinder, the amount of charge and sieve are different in each techniques.

Two parameters of the particle size distribution; Although representation by a single parameter such as the flour yield or mean size are acceptable in some cases, two or more parameters are required to adequately describe the whole range of particle size distribution. An attempt was made to find out an appropriate representation for the Brabender mill products, among which were log-normal, the Rosin-Rammler equation[16], and the Gaudin-Schuhmann equation [8,20]. For a wide range of wheat varieties, the best fit among these equations was the Gaudin Schuhmann equation, for which about 20 percent of the undersized fractions was fitted reasonably well as shown in Fig 5.

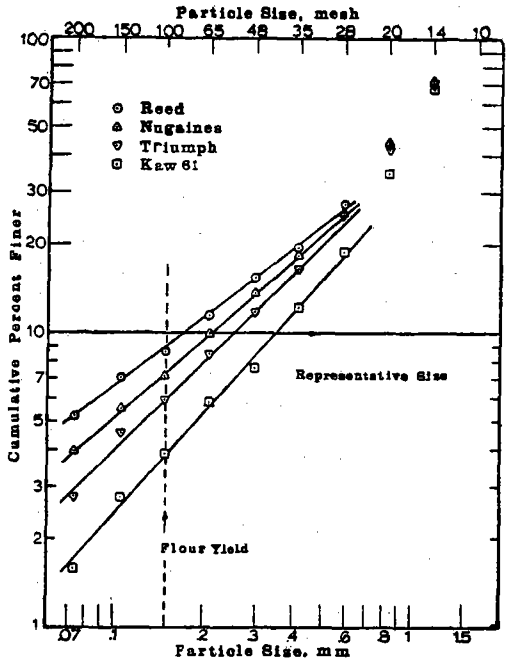

Fig. 5. Particle size distributions of ground wheats with illustrations for obtaining the representative size and flour yield.

For reference, recall the Gaudin-Schuhmann equation

$$Y=100\left(\frac{X}{K}\right)^{\beta} \tag{2}$$

where Y = cummulative weight percent finer than size X

X = particle size

K = product size modulus

β = distribution modulus

Eq. (2) was modified in this study for convenience of analysis to give

$$Y=A_1X^{\beta} \tag{25}$$

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

A linear regression analysis was performed to obtain two parameters A and by using the data for the cumulative undersizes and the corresponding sieve opening of Tyler sieves of #200,150 100, 65, 48, 35, and 28. The result of the analysis for various wheats are summarized in the reference [7].

Representative size from the Gaudin-Schuhmann equation; Although representation of particle size characteristic by two parameters allows to specify it for a wide range distribution, it has the disadvantage that two parameters, the size and distribution modulus, should be taken into account for comparisons with other kinds of wheats. It is necessary to have another representation that accommodates these two parameters. For this purpose and the other reason, the particle size corresponding to the 10% cumulative weight for a given distribution was considered and designated by X_{10}. This particle size was obtained by substituting the 10% cumulative weight into Eq. (25) which is completely defined by the two previously defined parameters. The values of X_{10} for different varieties are shown in the reference [7].

2. Energy of comminution

Brabender burr mill is a single pass or open circuit type of grinding, the action of which is classified as a combination of compression and shear. Therefore the prime resistance of the rotating shaft of the burr mill while grinding may indicate the rupture strength of wheat kernels from compreasive and shear stresses. Gross energy input to the burr mill would not be expected to convert completely into useful work. Some of the energy input would go into transmission losses, losses in grinding media and losses at the surface of working tool, fruitless stresses(stresses with insufficient energy to induce breakage), and the energy converted into kinetic energy(to induce the motion of whole kernels and broken particles). However, these energies may be maintained relatively constant under strictly identical operating conditions of the mill (amount of charge, rate and degree of grinding).

Fig 6 shows a typical torque-time curve measured and the terminology that is used in connection with the chart. The following quantities shall be used to rate the energy characteristics of the comminution:

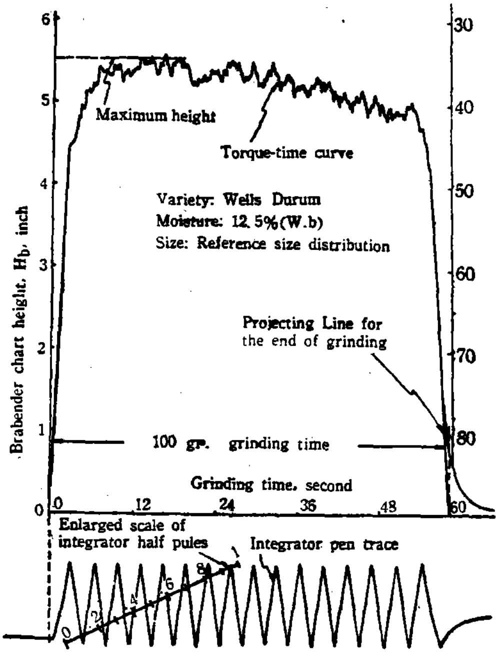

Fig. 6. A typical torque-time curve and integrator pen trace from the Brabender hardness tester.

Maximum rupture resistance(TBM); Maximum rupture resistance is defined as the maximum torque in kg-m that are required to rotate the burr mill shaft while grinding 100 grams of wheat under the operation conditions specified earlier. The quantity can be obtained by converting the maximum chart height of the Brabender torque-time curve into torque using the calibration equation. Researchers have termed similar quantity measured from the Brabender Fairnograph system as the H-value[22] and wheat hardness peak [41] The measured values of maximum rupture for different wheats are given in the reference[7].

Average rupture resistance (TBA); The average rupture resistance is defined as the torque averaged over the 100 gram grinding time. The average rupture resistance is different from the maximum rupture resistance mainly because of variation of the 100g grinding time as wheat variety varies.

Grinding energy (EB); Grinding energy is defined as the gross energy input to the Brabender burr mill while grinding 100 grams of wheat. The quantity can be obtained by converting the area underneath the torque-time curve into the energy. Researchers termed a similar quantity as the Ae-value[13].

3. Energy-size reduction relationship

As reviewed in literature survey, Agar and Charles[1] suggested that a grindability parameter that resulted from the energy-size reduction relationship, could be used for rating the material characteristic in connection with comminution. Later, Hansen and Steward[18] did the same thing in connection with cereal grain comminution. As previously mentioned, Charles law is given by

$$E = AK^{-\beta} \qquad (14)$$

where E = energy per unit mass

A = constant

K = product size modulus

β = a constant

The basic requirement of Charles law is that the product size distribution must obey the Gaudin-Schuhmann equation

$$Y = 100\left(\frac{X}{K}\right)^{\beta} \qquad (2)$$

the variables being defined earlier as in Eq.(2).

Substituting Eq.(2) into Eq. (14) to eliminate K gives

$$E = A\left(\frac{Y}{100}\right)X^{-\beta}$$

and finally the grindability was defined as

$$G_i = \frac{1}{A} = \frac{G1mm}{E} \qquad (26)$$

where G_i = grindability in unit weight per unit energy

G1mm = the value of Y corresponding to X = 1mm

or the weight fraction smaller than 1mm

No explanation was given as to why X was taken specifically at 1 mm in either paper, although, with X=1 mm, the constant for any definite value may be eliminated from the defining equation of grindability. To ignore the specific case of X=1 mm, and take into accout the constant, the energy-size reduction equation for steady-state grinding process was derived by the author to define a new grindability index.

For this purpose, the energy-size reduction equation for the steady-state grinding process was derived by the author as given in Eq. (23). Based on the newly developed equation, the toughness index was defined as:

$$TI = \bar{A} = EX_r^{\beta} \qquad (26)$$

AS Eq. (26) indicates, the toughness index $\bar{A}$ increases as grinding energy E, the representative size X_r, and the distribution modulus increase. Underthe identical conditions of the Brabender burr mill operation, more torque input to the grinder shaft is required to grind harder wheats than softer ones. Therefore the toughness index increases in accordance with the increased E for harder wheat. As illustrated in Fig 5, the particle size distribution parameters A_1 and β generally increase as wheat is getting harder. Therefore the toughness index includes two factors, the energy input and the particle size characteristics, in such away that the toughness index is a multiple of two factors which increase as a function of hardness.

The size X_r could be represented by any value within the distribution. For convenience, X_r was selected in this study as the particle size corresponding to the 10 percent undersize. The distribution modulus and the representative size X_r were obtained from the analysis of the particle size distribution. Obtaining the energy input E required to produce β and X_r for the product is the final step necessary to compute the toughness index $\bar{A}$ for a given wheat. The values of $\bar{A}$(=TI) so obtained for 82 different kinds of wheats are given in the reference[7].

To define another hardness indicating parameter from the energy-size reduction relationship, Rittinger's equation was considered.

$$E \propto \left(\frac{1}{X_2} - \frac{1}{X_1}\right) \qquad (8)$$

When $X_1 \gg X_2 = X_r$

$$E \propto \frac{1}{X_r} \qquad (13)$$

or $GI = EX_r$ (27)

where GI is the proportionality constant and was termed the grindability index. Since $1/X_r$ in Eq.(13) is also proportional to the specific surface area (refer to Eq. (9)), the grindability index could be considered as the grinding energy divided by specific surface. It may be noted that the grindability index is equivalent to the inverse of the flour surface area per unit work which was defined by Anderson, et al. [8] The value of the grindability index obtained for 82 different kinds of wheats are given in the reference[7].

Result and Discussion

Analyses of comminution parameters in the Brabender burr mill resulted in various quantities, which all represent different segments of wheat properties regarding different versions of wheat hardness. For convenience of comparison, the quantities are classified in three categories: the quantities from the torque-time curves are in the first category, those related only to the particle characteristic in the second category, and those obtained from the energy-size reduction relationship in the third category. These are shown in Table 3.

All the quantities were intended for representing the common characteristic-wheat hardness. However, the responses of quantities for different wheats would not be the same, both in the extent and direction of the variations, because of differences in method of measurement and subsequent data analysis. In other words, the ranks of wheat hardness measured by a technique may not be the same by the other techniques. However, if the responses are about the same, the quantities must be closely related. To show how each of the quantities listed in Table 3 relates to the others, a linear correlation analysis was performed. The results are shown in Table 4. The data in the table form a symmetric matrix, each element of which represents the correlation coefficient between the quantities which are common to the element.

The correlation coefficients clearly indicate how one quantity is related to the others. In general, the parameters within the same category correlated closely. Quantities from the energy or strength measurements (category 1) did not

Table 3. Wheat hardness paramters from the Brabender hardness tester.

Parameter	Symbol	Unit	Nature of Date
Maximum rupture resistance	T_{BM}	kg-m	Energy or Strength
Average rupture resistance	T_{BA}	kg-m	(Category 1)
Grinding Energy	E_B	kg-m	
Flour yield	FY	%	Particle Characteristics
Modified size modulus	A_1	—	(Category 2)
Distribution modulus	β	—	
Representative size	X_{10}	mm	
Grindability index	GI	—	Energy-Size reduction
Toughness index	TI	—	relationship (Category 3)

Table 4. The Correlation Coefficients for the parameters from the Brabender burr mill comminution.

	FY	A_1	B	X_{10}	T_{BM}	T_{BA}	E_B	GI	TI
FY	1,000								
A_1	.864	1,000							
B	−.94	−.693	1,000						
X_{10}	−.98	−.883	.949	1,000					
T_{BM}	−.665	−.611	.577	.626	1,000				
T_{BA}	−.673	−.602	.585	.631	.995	1,000			
E_B	−.684	−.864	.623	.656	.921	.927	1,000		
GI	−.964	−.864	.933	.981	.740	.744	.784	1,000	
TI	−.864	−.923	.740	.881	.807	.809	.848	.932	1,000

correlate closely with the parameters from the particle characteristics (category 2). On the other hand,the parameters from the energy-size reduction relationships (category 3) in general correlated strongly with the parameters in category 1 and 2. These results indicate that two fundamental techniques, particle characteristic and energy or strength measurements, may measure different phenomena in a rigorous sense, although there exists a good correlation between them.The quantities from the energy-size reduction relationships merely compromise these two techniques. Therefore, the selection of a particular technique for measuring wheat hardness may depend upon the point of view as to which characteristics are most important for practical use.

Greenaway[14] discussed the basis of applicability and usefulness of grain hardness to (1) the degree of correlation with flour quality factors (such as protein content, sedimentation value, flour yield,etc.); (2) the estimation of the power consumption and milling cost; and (3) the classification of wheat with respect to millability. Mepplink[22] attempted to correlate these flour quality factors with the hardness indicating parameters. This approach seems to place more emphasis on the flour quality such as particle characteristics, although their attempt was a result of efforts to improve the existing hardness measuring device.

Kuprits[11] characterized hardness strictly by classical definitions used in the materials engineering, which are definitely not related to the flour quality factors.

There are many reasons for not considering particle characteristics as a prime factor over the strength or grinding energy in connection with the wheat hardness measurement. First of all, the particle characteristics are an indirect measure of hardness chacteristic; therefore they could not be represented explicitly by physical quantities related to strength. In addition, a unique technique is not presently available for satisfactorily charaterizing the whole of particles by a single parameter. The use of two or more parameters to represnt wheat hardness as a single characteristic is obviously undesirable. Particle measurement is also very tedious compared to direct strength or energy measurements, and is very susceptible to an undesirable variation due to the grain moisture effect[22].

Therefore the results of correlation analysis were discussed by stressing the direct measurement of strength quality the most.

The following are the points which received special attention in the correlation analysis.

1. Researchers[22,28] indicated the particle size index (which is an equivalent technique to the flour yield) as one of the most practical methods of kernel hardness measurements. Their arguments are based on the supposition that kernel hardness measurements have a greater differentiating ability between the hard and soft wheat, and are simpler to perform. For referece purposes, Fig 7 shows that the Brabender grinding energy is related to the flour yield. Although the flour yields for hard and soft wheats were quite different, the flour yield correlated very poorly with the energy parameters from both machines. Therefore the flour yield may be used only for rough estimation, such as two classifications soft and hard but not for the rigorous measurement of the degree of hardness.

2. The distribution and size moduli in Gaudin-Schuhmann equation were compared to the flour yield in reference to the energy parameters. Compared to the flour yield, the two moduli correlated poorly with the energy parameters. However, the representative size X_{10}, which accommodates these two moduli, as explained previously, had in general about the same correlation with the energy parameters. Therefore the particle characteristic could be represented better by either flour yield or the representative size X_{10} than by distribution or size moduli. Since the flour yield is much simpler to determine, the flour yield appears to be the best particle parameter for characterizing wheat hardness.

3. A comparison of the grindability index and toughness index in relation to the other hardness parameters showed that the toughness index

correlated better with the energy parameters than the grindability index. The grindability index generally correlated more strongly with the particle parametes than the toughness index. Since high correlations exist with regard to both particle and energy parameters, either index could be used satisfactorily for rating wheat hardness.

Importance of these indices is that the particle characteristic and energy requirement are formulated based on the physical law—energy—size reduction relationship;thus two versions of wheat hardness measurements are taken into account.

The variation of data in accordance with the transformation from the defining equations of the toughness and grindability indices are noticeable, as seen from Fig 8. A special feature of the relation between the grinding energy and the toughness index is that, in addition to relatively strong correlation, the data of the soft wheats (SRW and SWW) behaved differently than the harder wheats.

Another possible advantage of these indices seems compensation characteristic of the moisture effect. As Mepplink indicated, the grinding energy increases as the grain moisture increases. On the other hand, X_r and X_r^{β} in the defining equations of both indices, Eq. (26) and Eq.(24), apparently decreases due to the increased granulation as grain moisture increases. Therefore it is obvious that variations in opposite directions between the grinding energy and X_r or X_r^{β} should have a small effect on the indices. No attempt was made in this study to test the variation of the indices due to the change of grain moisture.

Summary and Conclusions

Comminution theory was applied to the Brabender burr mill grinding process in an effort to investigate a better hardness indicating parameter. The energy-size reduction relationship for the steady-state comminution process was derived and the toughness index was defined from the relationship. The paramters from the Brabender system included flour yield, distribution and size moduli for the Gaudin-Schuhmann equation, the representative size, maximum rupture resistance, average rupture resistance, Brabender grinding energy, grindability index, and toughness index. Experiments were performed for 82 different wheats. All the parameters were compared by simple, linear correlation analysis techniques.

The following conclusions were drawn from the comparisons of the various techniques for measuring wheat hardness.

1. The hardness indicating parameters obtained from the measurement of particle characteristics are in general very different from the parameters obtained from the direct measurement of str ength or grinding energy, even though a good corrlation exists between them.

2. Among the parameters from the particle characteristics, flour yield seems to be the best for indicating wheat hardness. It may, however, be used only for hard and soft classifications.

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

$$E=\overline{A}\ X_r^{-\beta}$$

where E= grinding energy per unit weight

X_r=the particle size corresponding to the 10 per cent cumulative fractional weight

β=the distribution modulus in Gaudin-Schuhmann equation.

From this equation, the toughness index, TI $(=\overline{A})$, was defined.

$$TI=\overline{A}=EX_r^{\beta}$$

The defining equation includes factors from both particle charactristics and grinding energy. Experimental results showed that the toughness index is strongly coorelated with both energy and particle parameters. It could therefore be used satisfactorily to project these two properties.

4. The defining equation of the grindability index, GI, is $GI=EX_r$.

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 provided almost the same result as the toughness index, having better correlations with particle 'parmeters and poorer correlations with grinding energy.

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