Measuring Kernel Hardness Using the Tangential Abrasive Dehulling Device[1]

J. W. LAWTON and J. M. FAUBION[2]

ABSTRACT

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A test is described that uses the Tangential Abrasive Dehulling Device (TADD) to measure grain hardness. Percent kernel weight loss during milling follows a first-order decay model. The rate constant from the model is used as a measure of kernel hardness. The rate constant was shown to discriminate kernel hardness in sorghum, wheat, and corn samples. Kernel moisture above 12.5% was shown to raise the rate constant significantly; however, this effect could be reversed by drying the grain before testing. Kernel size also raised the rate constant, but this effect was significant only for very small kernels.

Kernel hardness, or a mechanical property related to endosperm hardness, has been used as a predictor of numerous end-use properties, including milling yield, handling properties, and starch damage (Moss 1978, Baker and Dyck 1975, Stenvert 1972, Symes 1969). Some objective predictions of kernel hardness often fail to match empirical estimates. Worse, the methods fail to discriminate between varieties with different milling properties.

Abrasive milling is one method of determining kernel hardness. Kernel hardness determination using an abrasive type mill was suggested first by Taylor et al (1939), who used a Strong-Scott barley pearler to abrasively mill wheat. In standardizing the technique for determining kernel hardness with the barley pearler, McCluggage (1943) pointed out that both kernel and sample sizes affect the results obtained. McCluggage (1943) found no significant difference in the pearling indexes of samples due to differences in their moisture content. However, this was contradicted by later work (Kramer and Albrecht 1948, Mepplink 1966). Mepplink (1966) found that the pearling index of wheat decreased linearly at a rate of 1.5-% per 1.0% increase in kernel moisture content.

A mill using a tangential abrasive action to accomplish the milling was described by Hogan et al (1964), who found that rice kernels milled with a rapidly moving abrasive surface would lose successive layers of the kernel without themselves being broken. Normand et al (1965) used this type of mill to remove peripheral layers from barley, rice, sorghum, and wheat in work designed to study protein distribution within the kernel of these cereals.

Oomah et al (1981) developed a prototype Tangential Abrasive Dehulling Device (TADD) that was faster and gave more reproducible results than other types of tangential abrasion mills. The design of the TADD was further refined by Reichert et al (1981, 1986). They also showed that the TADD could be used to assess hardness characteristics of sorghum. The abrasive hardness index derived from TADD data had a very high linear relationship with high correlation coefficients for sorghum varieties when retention times were plotted against percent of the kernel removed by milling.

Plots of percent kernel removed versus retention time in the TADD (milling curves) were shown to be nonlinear, provided the retention times inside the TADD were long enough (Saunders 1987). Use of short milling times or a small number of data points could lead to the incorrect conclusion that the curve is in fact linear. There are two primary reasons for this phenomenon. First, most of the milling curves presented in the literature were created by milling the cereal with the bran still on the kernel. This will result in a different slope for the early part of the curve due to the difference in the physical properties of the bran versus the endosperm. Secondly, a small number of data points will obscure the nonlinearity of the plotted results.

The objective of the following study was to model the nonlinear milling curve produced by the TADD and to test the subsequent model for its applicability as a tool for hardness determination. As a part of this objective, the physical constraints to performing such a hardness determination using the TADD were assessed. Finally, a milling test procedure was developed that used the rate constant obtained from the model as a predictor of cereal kernel hardness.

MATERIALS AND METHODS

Grain Samples

Sorghum samples 8222, 8515, 8790, and 894 were the gift of Gene Dalton, Pioneer Hi-Bred International, Inc. (Plainview, TX). Additional sorghum samples (Asgrow, DK41Y, Cargil, Funk, DK42Y, NK2278, and Golden) were from Jean Heidker, Department of Grain Science and Industry, Kansas State University (KSU). Wheat samples (durum, Eagle [hard red winter, HRW], Baca [HRW], Augusta [SWW], and two HRW wheats of unknown variety) were from Steve Curran, Department of Grain Science and Industry, KSU. Corn samples were from Keith Behnke, Department of Grain Science and Industry, KSU.

Milling

Abrasive milling was done on a model 4E-115 TADD mill. Details of machine design and operation were described by Reichert et al (1986). The 12-cup cover plate was used for all milling trials. The abrasive grits used were 50-, 120-, and 180-grit abrasives manufactured by Merit Abrasive Products Inc. (Los Angeles, CA). The stone supplied with the TADD mill was designated A24-LSVBE.

Before each milling, the gap between the abrasive grit and the cup wall was adjusted to approximately 0.0254 cm, as described by Saunders (1987). A preweighed grain sample was placed into each of the 12 cups and milled on either the 50-, 120-, or 180-grit abrasive or an A24 stone. After milling, the grain was removed from the cups by vacuum aspiration, which also separated the grain from the fines.

To generate milling curves, grain was milled for successive time intervals of 3 min until milling time totaled 24 min. For each sample, millings were replicated three times. Continuous milling was done in the same way, except the milling runs were for the entire time indicated (3, 6, 9, 12, 15, 18, 21, or 24 min) without 3-min intervals.

Tempering, Drying, and Sizing of Grain

Sorghum was rapidly tempered by adding enough distilled water to a preweighed lot of grain to increase its moisture content to the desired level. The sorghum and the water were thoroughly mixed, covered, and left overnight at 4°C. Sorghum was slowly tempered to 17% moisture by placing the grain in a constant humidity chamber over a saturated potassium chloride solution until its weight remained constant (about two weeks). A small amount of cupric sulfate also was added to the KCl solution

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[1] Contribution no. 89-191-J. Kansas Agricultural Experiment Station.

[2] Graduate research assistant and associate professor, respectively, Department of Grain Science and Industry, Kansas State University, Manhattan 66506.

to inhibit mold growth. Dry grain was produced by drying the grain at 44°C in a forced-air oven for 24 hr. Moisture content of whole sorghum before or after tempering was obtained by the method of Hart et al (1959).

Sorghum kernels were separated according to size by the use of a Ro-Tap testing sieve shaker (W.S. Tyler Inc., Mentor, OH), using the 9, 8, 7, and 6 Tyler screens. The samples were shaken for 5 min.

Statistical Analysis

Milling curves were statistically analyzed by the nonlinear (NLIN) procedure of SAS (SAS 1985) using the Gauss-Newton iterative method. The rate constants obtained from the milling curves were analyzed by the general linear model (GLM) procedure of SAS.

RESULTS AND DISCUSSION

Modeling Milling Loss in the TADD

The milling data, when graphed as weight loss against time, resulted in the plot shown in Figure 1. Sorghums that were generally considered to be softer had higher rates of loss than did harder sorghums. Figure 1 also appears to indicate that the kernel becomes harder as the endosperm is removed. This is contrary to the accepted view of sorghum endosperm physical properties. One approach to understanding this unusual phenomenon involves calculating the percent cumulative interval loss. Graphing this loss along with the percent loss (Fig. 2) shows that the cumulative curve approaches linearity. These data were obtained by taking the interval loss at every 3-min interval of milling, dividing the preceeding interval weight into it, and expressing that figure as a percent. This is shown numerically by equation 1,

$$\text{Percent interval loss} = L_t / \text{Wt}_{(t\text{-}3)} \times 100 \qquad (1)$$

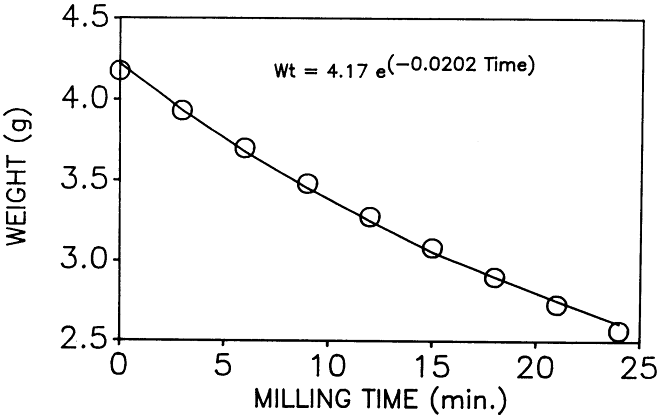

Fig. 1. Milling loss of sorghum (variety Golden).

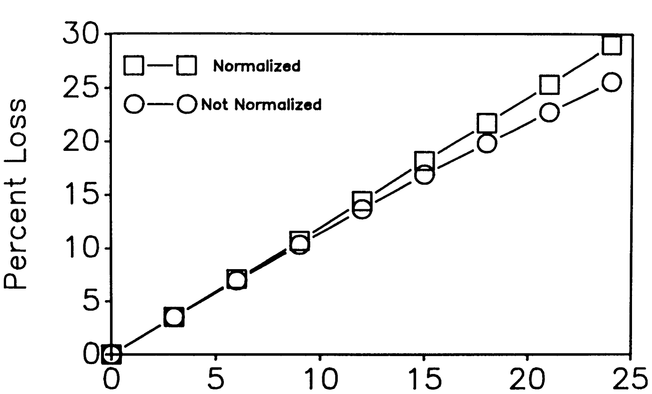

Fig. 2. Percent milling loss of sorghum (variety 8515). Data is presented as normalized and not normalized for interval milling time.

This demonstrates that the rate of loss over time is constant, regardless of the position in the endosperm, and consequently, the kernel is not getting harder as the milling goes deeper into the endosperm. If the instantaneous weight loss of the grain could be graphed, its slope in all likelihood would be linear as well.

The nonlinear region of Figure 1 is due, most likely, to the design of the TADD mill. As described by Reichert et al (1986), kernels in the mill are pulled by the abrasive grit until they hit the wall and are recirculated back to the top of the grain mass by kernels following behind. Because of the behavior of the grain mass in the TADD, the milling system is very similar to the classical physics model for the determination of coefficient of dynamic friction. The classical model has been altered slightly to more closely resemble the TADD, in which a force is applied to the surface instead of an object. In the altered model, a force is applied to the surface, and the surface is moved under the object (Fig. 3A). In the classical system there is a frictional force that opposes the movement of the surface (Fig. 3A), abrading the object and the surface. In the mill (Fig. 3B), the frictional force opposes the movement of the abrasive grit. This frictional force can be related to the normal force acting on the surface by equation 2,

$$f = uN \qquad (2)$$

where f is the friction force, u is the coefficient of friction, and N is the normal force, in this case, equivalent to the weight. The coefficient of friction is a constant for any two solid surfaces.

Equation 2 explains the curve-linearity of the graph in Figure 1 by stating that the frictional force (responsible for the milling) is directly proportional to the weight of the grain. As the grain is milled, its weight decreases thereby decreasing the frictional force. It is this interaction between the weight of the grain and the frictional force that accomplishes the milling.

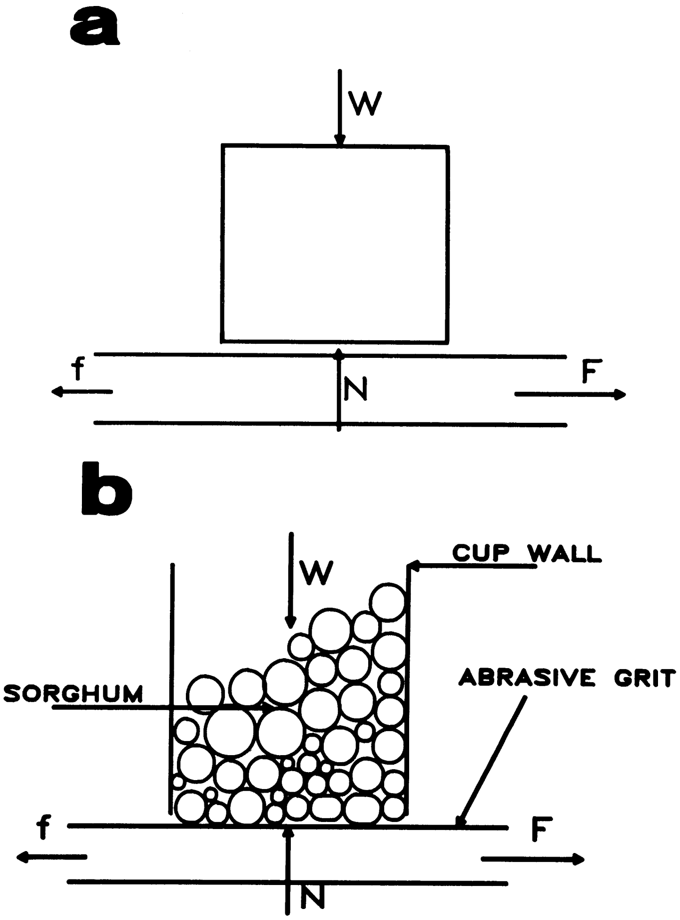

Fig. 3. A, Forces affecting a moving object. **W** = weight, **N** = normal force, **f** = friction, and **F** = force to move surface. **B,** Forces affecting the milling of samples in the TADD.

The curve generated from the sorghum milling data (Fig. 1) approximated the first-order rate law, which states in this case that the rate loss is exactly proportional to the weight of the sample. The equation for a first-order rate loss function is

$$d(\mathrm{Wt})/dT = -b(\mathrm{Wt}) \tag{3}$$

and its integrated form is

$$\mathrm{wt} = \mathrm{wt}_0 e^{(-b\ \mathrm{time})} \tag{4}$$

In equation 4, wt is the sample weight, wt_0 is the initial weight, and b is the rate constant. Because both frictional force in equation 2 and the rate constant in equation 4 are proportional to the weight of the sample, the equations can be combined to give

$$f/u = \mathrm{wt}_0\, e^{(-b\ \mathrm{time})} \tag{5}$$

which relates the rate constant and the coefficient of friction in the same expression. Relating the rate constant to the coefficient of friction in this way allows the rate constant to be used as a measure of endosperm hardness.

To test whether the milling loss was a first-order process, the integration test and the half-life test (Chang 1977) were applied to the data. The integration method substitutes the data into the integrated equation of several models. The equation resulting in the most constant value for the rate constant over a series of initial sample weights is the most suitable model. In the half-life test, the amount of time needed for half the grain to be milled away is predicted from several models. In this case, the model that gives half-lives that most closely fit the data is the most suitable model. A zero-order model in which the rate does not depend on the weight of the sample was used for the comparison.

The results (Table I) of this analysis showed that the first-order model closely approximates the milling loss in the TADD. The rate constants of the first-order model were unchanging, regardless of the initial sample weight. The rate constants obtained with the zero-order model varied with initial weight. Likewise, time needed to mill away half of the sample was predicted by the two models (Table II). The first-order model predicted a half-life that was very close to that determined experimentally. A first-order model has an unique half-life that does not depend on the initial weight of the grain. The zero-order model, on the other hand, only predicted the half-life correctly when the initial weight was about 5 g. This would be expected, because 5 g of sorghum was used to generate the rate constant used in the prediction model.

TABLE I
Comparison of Integrated Rate Constants of Zero and First-Order Models

Sorghum Sample	Starting Weight (g)	First-Order Rate Constant[a]	Zero-Order Rate Constant[b]
NK2278	15	0.0179	0.1852
NK2278	10	0.0180	0.1249
NK2278	5	0.0184	0.0642
NK2278	8[c]	0.0181	0.1040
DK41Y	15	0.0163	0.1580
DK41Y	5	0.0170	0.0565

[a] Calculated per minute.
[b] Calculated in grams per minute.
[c] 250 kernels.

TABLE II
Predicted Half-Lines and the Percent Loss at the Predicted First-Order Half-Life

Sorghum Sample	Starting Weight (g)	Zero-Order[a] Predicted Time (min)	First-Order[b] Predicted Time (min)	Percent First-Order Time (min)
8515	5.7780	57.4	52.1	47.8
8515	10.2761	102.1	52.1	46.5
8515	14.3453	142.6	52.1	47.1
Golden	4.2917	27.3	32.7	47.9
Golden	8.4586	53.7	32.7	47.5
Golden	12.3161	78.2	32.7	47.6
Funk	4.5729	31.9	39.4	49.5
Funk	8.5579	53.7	39.4	47.2
Funk	12.7644	78.2	39.4	47.5
8222	5.2542	42.9	43.9	47.8
8222	9.8780	80.7	43.9	46.5
8222	13.8076	112.8	43.9	47.1

[a] Zero-order rate constants are 0.0503, 0.0787, 0.0701, and, 0.0612 g/min for 8515, Golden, Funk, and 8222, respectively.
[b] First-order rate constants are 0.0133, 0.0212, 0.0176, and 0.0158/min for 8515, Golden, Funk, and 8222, respectively.

Effect of Different Abrasive Grits on the Rate Constant

Further support for the first-order model came from TADD milling using different abrasive grits. Grit coarseness affected the rate constants (Table III) such that the coarser the abrasive grit, the higher the rate constant. However, milling data from the TADD mill always followed a first-order model, no matter what abrasive grit was used.

Data from trials using different abrasive grits indicate that kernel shape is an important factor in the milling. When the rate constants for these sorghum samples were compared (Table III), the samples always had the same ranking. In contrast, the wheat sample changed its ranking, relative to the sorghums, when different abrasive grits were used. Because the wheat sample changed its ranking depending on the abrasive grit used, hardness using the rate constant should not be measured between kernels with grossly different shapes.

Effect of Kernel Size

As kernel size decreased, the rate constant increased (Table IV). This trend was only significant for the smallest kernel size milled. This implies that smaller kernels have softer endosperms, a generality that has no basis in fact. The trend can be explained by the milling action of the TADD. As shown in Figure 3B, the sorghum to be milled is a mass inside the cup, with the kernels above increasing the force on the kernels below. Consequently, kernels below (at the abrasive surface) act like they have the

TABLE III
Effect of Different Abrasive Grits on the Rate Constant

Abrasive Grit	Rate Constant (per minute)			
	Asgrow	DK41Y	Golden	Wheat
50	0.0834	0.0936	0.1997	0.0688
120	0.0264	0.0311	0.0404	0.0330
180	0.0153	0.0170	0.0212	0.0224
Stone	0.0258	···	0.0414	0.0164

TABLE IV
Effect of Kernel Size on the Rate Constant

Sorghum Sample/ Kernel Size (mm)	Rate Constant[a]	Duncan Groupings[b]
Asgrow		
over 4	0.0138	A
3.35–4	0.0142	A
2.80–3.35	0.0150	A
2.36–2.80	0.0208	B
DK41Y		
3.35–4	0.0151	A
2.80–3.35	0.0163	A
2.36–2.80	0.0263	B
NK2278		
3.35–4	0.0184	A
2.80–3.35	0.0194	A
2.36–2.80	0.0231	B

[a] Per minute.
[b] Means within a variety with the same letter are not significantly different at $P < 0.05$.

weight of the kernels above added to their own weight. Presuming that the hardness of the endosperm does not change with the size of the kernel, their deformation should be the same as long as the normal force acting on them is equal.

Assume at start-up the normal force acting on the kernels at the abrasive surface is the same, regardless of the kernels' size. Their deformation will be the same, no matter what their size. The piece sheared off by this deformation will be the same; however, the percent kernel loss represented by this piece will be greater for the small kernel than for the large kernel.

Although this explanation accounts for the nonsignificant variation in the rate constant due to kernel size, it probably does not account for all the variation in the rate constant of the smallest kernels. Two additional factors may be responsible. First, the gap between the cup and the abrasive grit was critical for small kernels. Because the gap (0.0254 cm) was constant for all trials, its size, as a percent of the kernel, was larger for small kernels. Smaller kernels will be lost from the cup in less milling time than larger kernels. Kernel breakage also affects the smaller kernels more, in that the pieces of a small kernel are more likely to pass under the cup. Premature loss of kernels and their fragments for either reason would give an artificially higher rate constant.

Secondly, the small kernels may be nonrepresentative of the entire grain sample. To obtain a size distribution, the bulk sorghum sample was sifted over a series of Tyler screens. The sample contained no broken kernels but did contain shrunken and/or immature kernels. The rate constant derived from testing such kernels might be expected to be different than the rate constant for sound grain.

Effects of Moisture Content

Grain moisture content had a significant effect on the rate constant (Table V). No significant difference existed between sorghum samples with moisture contents of ≤12.5%. This is fortunate, because most grain samples to be tested normally will be under 12.5% mc. Higher moisture content resulted in significantly higher rate constants. This is explained by referring to Figure 4. The high-moisture sorghum broke apart during milling, whereas the lower moisture samples rarely broke.

The small pieces resulting from such breakage will be lost from the cup and produce an inflated rate constant. This does not address whether the endosperm is actually softened by the water or just made more friable. Sullins and Rooney (1971) and Heidker (1984) contend that there is a disruption of the endosperm matrix in high-moisture reconstituted sorghum caused by the swelling of starch granules. This disruption could lead to a more friable kernel and account for the way the high-moisture sorghum responded to milling.

Effects of Hydration Rate

Moisture levels of the high-moisture samples increased quickly with overnight tempering. Rapid hydration of endosperm could induce diffusion cracks or some other type of physical damage that promoted breakage. To test this, moisture levels of sorghum were slowly increased in a constant humidity chamber before being milled. Regardless of tempering rate, high-moisture samples had higher rate constants (Table VI) and were more friable than their controls (Fig. 4).

The tendency of the high-moisture grain to break apart may explain the high coefficients of variation associated with the high-moisture sorghum. There was a significant difference in the rate constants between the rapidly tempered grain and the control samples. Differences were significant at an alpha level of 0.05 between the slowly tempered Asgrow and DK41Y and their controls.

Sample NK2278 was significantly different at an alpha level of 0.1, a result that may be due to its high coefficient of variation within the repetitions. There was also a significant difference between the types of tempering for DK41Y and NK2278. To show a difference in tempering methods for Asgrow, the alpha level must be raised to 0.1. This difference in tempering indicates that more disruption of the kernel is caused by rapid than by slow tempering. Consequently, it is probable that tempering, particularly to high moisture content, may result in underestimation of endosperm hardness.

To test whether the endosperm disruption due to high moisture content could be reversed, grain that had been rapidly tempered was dried for 24 hr at 44°C before testing. The lack of a significant difference (Table VI) in the rate constant between the tempered and dried sorghum and its control indicated that the endosperm disruption (or at least its physical consequence) can be reversed for sorghum. This could be beneficial, since high-moisture sorghum does give significantly different rate constants within a variety.

Hardness Determination Using the Rate Constant

Applying the first-order model to the TADD milling results separated 13 varieties of sorghum (Table VII) into seven "hardness groups." All the sorghums tested followed the first-order model quite well. However, the softer the sorghum, the less it followed the model. This may be explained by the tendency of the softer sorghums to break apart during milling.

The results from milling wheat and corn (Table VIII) followed the first-order model as well. Six varieties of wheat were separated into four groups based on "hardness." The model differentiated the durum and the soft wheat and separated the hard red winter wheats into two groups.

TABLE V
Effect of Kernel Moisture on the Rate Constant

Sorghum Sample/ Moisture (%)	Rate Constant[a]	Duncan Groupings[b]
DK41Y		
3.6	0.0158	A
10.5	0.0159	A
13.7	0.0206	B
18.0	0.0268	C
NK2278		
4.5	0.0172	A
12.4	0.0194	A
15.4	0.0229	B
18.1	0.0271	C
19.6	0.0280	C

[a] Per minute.

[b] Means within a variety with the same letter are not significantly different at $P < 0.05$.

TABLE VI
Effect of Tempering Method on the Rate Constant

Sorghum Sample/ Method	Moisture (%)	Rate Constant[a]	Duncan Grouping[b]
Asgrow			
Control	9.7	0.0148	A
Dried[c]	8.6	0.0155	A
Slow[d]	17.1	0.0213	B
Quick[e]	16.3	0.0238	B
DK41Y			
Control	10.2	0.0167	A
Dried	8.6	0.0193	B
Slow	17.5	0.0235	C
Quick	15.3	0.0281	C
NK2278			
Control	12.4	0.0205	A
Dried	8.4	0.0208	A
Slow	17.3	0.0253	A
Quick	17.8	0.0322	B

[a] Per minute.

[b] Means within a variety with the same letter are not significantly different at $P < 0.05$.

[c] Sample was quickly tempered and dried.

[d] Sample was tempered in a constant humidity chamber.

[e] Sample was tempered overnight.

Hardness Determination at a Single Milling Time

The rate constant that resulted from the milling data was a good indicator of endosperm hardness, but the milling process to perform the test was too time-consuming and labor intensive to make the test useful. Because the milling data always followed the first-order model, a test could be designed that uses the integrated form of the rate model (equation 4), solved for the rate constant.

$$b = [-LN\,(\mathrm{Wt}/\mathrm{Wt}_0)]/\mathrm{Time} \qquad (6)$$

Using equation 6, the rate constant can be found with only one milling time interval.

A rate constant was found for each of three sample weights and eight individual milling intervals (Table IX). A rate constant also was found from the same data using the SAS NLIN procedure. The test worked well up to 12 min of milling, when there was an apparent decrease in the rate constant. The drop in the rate constant may have been caused by the accumulation of fine particles in the cup. This problem, which did not occur in the original milling trials because the cups were aspirated every 3 min when the grain was reweighed, could be eliminated with the use of an aspiration device in place of the collection bag.

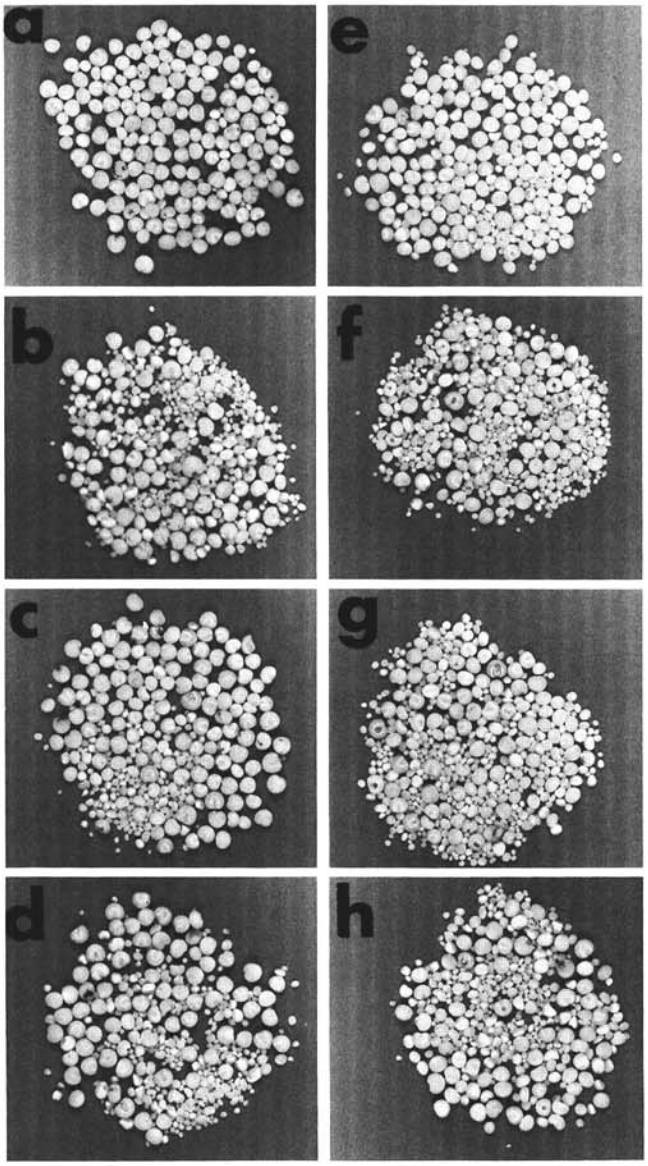

Fig. 4. TADD milled sorghum samples: Asgrow control (**a**), quickly tempered Asgrow (**b**), dried, quickly tempered Asgrow (**c**), slowly tempered Asgrow (**d**), Golden control (**e**), quickly tempered Golden (**f**), dried, quickly tempered Golden (**g**), and slowly tempered Golden (**h**).

CONCLUSIONS

TADD milling results could be used to determine endosperm hardness of cereal grains. Loss from milling over time was found to follow a first-order model whose rate constant was determined by modeling the milling results with the NLIN procedure of SAS. This procedure was successfully applied to the analysis of sorghum, wheat, and corn samples.

By using the integrated form of the first-order model, the rate constant could be determined by milling a weighed lot of grain

TABLE VII
Rate Constants of Sorghum Samples

Sorghum Sample[a]	Rate Constant[b]	Duncan Grouping[c]
8515	0.0133	A
Asgrow	0.0153	B
8222 P	0.0155	B
8222	0.0158	B
8790	0.0162	CB
KL41Y	0.0170	CD
Cargill	0.0176	D
Funk	0.0176	D
DK42Y	0.0191	E
8222 H	0.0196	FE
NK2278	0.0198	FE
894	0.0207	FG
Golden	0.0212	G

[a] Sample moistures were from 10 to 12%.
[b] Per minute.
[c] Means with the same letter are not significantly different at $P < 0.05$.

TABLE VIII
Rate Constants of Wheat and Corn

Sample[a]	Rate Constant[b]	Duncan Groupings[c]
Wheat		
Durum	0.0147	A
HRW Wheat	0.0224	B
Eagle (HRW)	0.0235	B
HRW (Mont.)	0.0259	C
Baca (HRW)	0.0272	C
Augusta (SWW)	0.0498	D
Corn		
Popcorn	0.0137	A
White corn	0.0191	B
Yellow dent	0.0239	C

[a] HRW = Hard red winter; SWW = Soft white winter.
[b] Per minute.
[c] Means within a cereal group with the same letter are not significantly different at $P < 0.05$.

TABLE IX
Rate Constants of 5-g Samples Found Using One-Time Milling[a]

Milling Time (min)	Rate Constant (per min)			
	Asgrow	DK41Y	Golden	Wheat
3	0.0146	0.0174	0.0241	0.0229
6	0.0147	0.0181	0.0223	0.0237
9	0.0140	···	0.0224	0.0233
12	0.0142	0.0163	0.0224	0.0230
15	0.0136	0.0155	0.0193	0.0216
18	0.0128	0.0140	0.0178	0.0194
21	0.0130	0.0151	0.0195	0.0217
24	0.0131	0.0148	0.0181	0.0207
Model[b]	0.0133	0.0155	0.0193	0.0216

[a] Rate constants of 10- and 15-g samples were not significantly different. The rate constants from the model for 10- and 15-g samples are 0.0211 and 0.0209 for wheat, 0.0130 and 0.0131 for Asgrow, 0.0149 and 0.0154 for DK41Y, and 0.0196 and 0.0199 for Golden.
[b] The rate constants found from the model were obtained from the same data used to obtain the above individual rate constants.

for a single time interval. Because loss due to milling followed a first-order model, any initial charge weight or milling time could be used to assess endosperm hardness. This is an advantage over the pearling index, which requires both a specified milling time and initial charge weight.

Grain moisture content above 12.5% raised the rate constant of the tested grain significantly. This artificial raising of the rate constant could be corrected by drying the grain before testing.

Reduced kernel size appears to raise the rate constant, but this trend was only significant for very small kernels. This trend was thought to be caused by the fact that loss from a small kernel would be larger on a percent basis than the same loss from a larger kernel.

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