Mechanical Behavior of Corn Kernels: Development of a Laboratory Friability Test That Can Predict Milling Behavior

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ABSTRACT

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A friability test for maize grains has been developed. It is a particle size index test that has been optimized to enhance discrimination between samples. It has been tested on kernel samples from 18 maize cultivars. From these results, a classification table with four classes has been proposed. Highly significant correlation coefficients have been found between kernel friability and yields of milling products, which were determined by using semi-wet and dry milling pilot devices. Other physical attributes of maize kernels, such as kernel size, shape and vitreousness, are not clearly related to friability and grain milling performances.

In many African countries, maize is the primary staple food, and consumer preference for maize quality is very strict (Kydd 1989, Tchamo 1993). For example, in the countries of the Guinean zone of West Africa, people generally prefer soft grains, mainly because grinding hard grains is more difficult and/or more expensive (Koudokpon 1991, Tchamo 1993). But grain quality is a criterion often underestimated in local maize research programs, which leads to new cultivars with inadequate grain characteristics and, consequently, to their failure to be adopted by local producers (Koudokpon 1991, Kydd 1989). Therefore, there is a trend toward breeding African maize cultivars for their kernel qualities and physical properties (Raju et al 1991, Tchamo 1993).

The quality of maize grain has also come under scrutiny in developed countries in the past decade for two primary reasons. First, commercial handling of grain induces kernel breakage, which increases losses and costs of aeration and of removal of fines, which also increases mold and insect infestation and risks of fires and explosions (Watson et al 1993). Second, corn processors in developed countries (who transform a quarter of the world maize grain production) have specific demands; dry millers prefer hard grain, which yields higher prime products, whereas wet millers prefer soft grain because it requires less steeping time and gives better starch-protein separation (Wu and Bergquist 1991).

In all cases, it is first the mechanical, or viscoelastic, behavior of maize kernel, generally called hardness, that is in question. But there is no general agreement on the definition of hardness in terms of fundamental physical units. Some authors (Jindal and Mohsenin 1978, Tran et al 1981, Waananen and Okos 1988) have proposed several methods for measuring static and dynamic hardness on individual kernels by using compression and impact tests. They have demonstrated that the kernel becomes ductile or plastic when moisture content increases: at high moisture content kernel can absorb higher deformation value before breakage. On the other hand, lower stress values are necessary for breaking the kernel at high moisture content. Kernel hardness depends on whether constant stress or strain is applied. In addition, tests performed on individual kernels are not practical for routine analysis, so many practical tests performed on kernel populations have been proposed. For example, not less than eight devices to measure corn breakage susceptibility have been studied by Watson and Herum (1986), who selected the Wisconsin Breakage Tester as a standard device. But it was later rejected (Watson et al 1993) for the Modified Stein Breakage Tester (Watson and Keener 1993), which has been partly automated (Watson et al 1993). A number of laboratory tests have been used to evaluate the milling ability of maize kernels, ranging from time, force, or work required to grind maize kernels (Tran et al 1981, Pomeranz et al 1985), to average particle size after grinding measured by sieving, or by using near-infrared reflectance at 1,680 nm (Wu 1992, Pomeranz et al 1984). These studies show that the coarser the particles after grinding, the harder the grain. Breakage susceptibility tests and grinding tests that can predict the behavior of maize kernels during transportation (Paulsen and Hill 1983) and industrial milling (Pomeranz and Czuchajowska 1987) reflect mechanical kernel properties and are therefore generally correlated (Pomeranz et al 1984, 1986).

There are many indirect methods for evaluating the mechanical properties of maize kernels. They are generally based on the evaluation of the endosperm texture, i.e., vitreousness. Vitreousness can be visually estimated on grain cross-sections (Paulsen et al 1983), calculated by the respective areas of vitreous and floury endosperm parts (Louis-Alexandre et al 1991, Pordesimo et al 1991, Gunasekaran et al 1988), or evaluated by the opacity of whole kernels using image analysis (Felker and Paulis 1993). Another way to evaluate vitreousness is to measure kernel density because vitreous endosperm is dense whereas floury endosperm is lighter and full of air spaces (Robutti et al 1974, Watson 1987b). The apparent density can be measured using a pycnometer or evaluated by using a floating test in sodium nitrate solution of 1.275 specific gravity. Measured vitreousness and maize kernel specific density are highly correlated (Mestres et al 1991). Both of these factors are correlated to milling abilities of maize and particularly to the yield of fine products (Mestres et al 1991, Wu and Bergquist 1991). But the measurement of specific density or vitreousness is time consuming and is not practical to use as routine test. Furthermore, endosperm texture characteristics are not clearly related to the results obtained by various mechanical laboratory tests (Abdelrahman and Hoseney 1984) and to the yield of prime products during the dry-milling procedure (Mestres et al 1991, Peplinski et al 1992).

In addition, other characteristics linked to the shape and size of maize kernels are often determined, such as kernel weight, test weight, sphericity, and dent kernel percentage. But there is no clear relationship between these parameters and mechanical properties or endosperm texture of maize kernels. For example, Mestres et al (1991) did not find any significant correlation between kernel shape factors (sphericity or dent kernel percentage) and endosperm texture (vitreousness or specific density) for 18 culti-

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vars. Nor was there any correlation between kernel weight and endosperm texture (Mestres et al 1991, Pomeranz et al 1986) or grain mechanical properties (Pomeranz et al 1986). Test weight is also not a precise indicator of any specific grain quality attribute (Dorsey-Redding et al 1991).

There is a need for a rapid standard laboratory test that can be routinely used by breeders to predict maize milling abilities. Current breakage susceptibility tests under development predict maize kernel behavior during handling rather than milling behavior. Until now, laboratory grinding tests have used specific devices such as a micro hammer mill for the Stenvert Hardness Test (Pomeranz et al 1985). A standard routine test should use a widely used grinding device such as a KT-3303 (Falling Number), which is already recommended for other hardness tests such as wheat (AACC 1983) or sorghum (Fliedel et al 1989).

We set out to develop a routine test that can be used by maize breeders in African countries. Furthermore, because maize breeders currently judge grain quality from kernel shape (dent or flint character) and aspect (translucency), we wanted to clearly establish the relationships existing between the mechanical properties of the maize endosperm and the other physical properties of maize grains, particularly endosperm texture and kernel shape.

MATERIALS AND METHODS

Maize

For the development of the grinding test, seven samples (from cultivars IRAT 39, 81, 100, 102, 148, 200, and 275) that ranged from floury to very vitreous endosperm texture were used (Louis-Alexandre et al 1991). For physical and milling tests, 18 maize samples (10–20 kg) were collected from several seed farms in African countries and French West Indies (Table I). They were chosen to represent the highest phenotypic variation of endosperm texture encountered in West and Central Africa. The samples were harvested in 1988 or 1989 and air-dried at ambient temperature (25–40°C). Final moisture content ranged from 9.8 to 15.1% (wb). Each sample was stored at 4°C and brought up to ambient temperature one day before analyses were performed.

Physical Analysis

Thousand-kernel weight, dent kernel percentage, specific density, and vitreousness were measured as described elsewhere (Mestres et al 1991, Louis-Alexandre et al 1991).

The laboratory grinding test was performed using a KT-30 disc mill (Falling Number, Stockholm, Sweden) device (similar to KT-3303 from the same supplier) using fine or coarse burr. Grain samples of 20 or 50 g were rapidly introduced into the grinder already working, and the product was sieved during 5 min using an air jet sifter (Alpine 200 LS, Duisburg, Germany) with various sieves (openings from 125 to 400 μm). Overs were weighed and their dry matter content determined (DMO, %, wb). A particle size index (PSI) was calculated for each sieve using the formula: PSI (% db) = 100 − 100 × [(Overs × DMO)/(Sample weight × DM)] where DM is the dry matter content (% wb) of initial sample and overs is the weight of overs collected on top of the sieve.

TABLE I
Characteristics of the 18 Corn Cultivars Used for the Physical and Milling Tests

Cultivar	Type	Origin	Kernel Color
IRAT 48	Composite	Guadeloupe	Yellow
Kolaribougou	Ecotype	Guadeloupe	Yellow
Poza rica 7429	Composite	Guadeloupe	White
Across 8149	Composite	Guadeloupe	White
Guatemala	Population	Guadeloupe	White
Jaune de Bambey	Single hybrid	Sénégal	Yellow
HVB1	Single hybrid	Sénégal	White
Synthétic C	Single hybrid	Sénégal	White
Mali 2	Ecotype	Mali	Yellow
E 211	Composite	Mali	Yellow
Tiemantie	Ecotype	Mali	Yellow
TZ-ESR-W	Variety	Mali	White
Tuxpenio	Variety	Mali	White
SR 22	Composite	Burkina Faso	White
Massayomba	Ecotype	Burkina Faso	White
IRAT 171	Composite	Burkina Faso	White
IRAT 80	Composite	Burkina Faso	Yellow
Jaune de Fô	Ecotype	Burkina Faso	Yellow

Tempering

Before being used for the grinding test, maize lots were tempered at fixed water content (from 10.5 to 17.5 % wb). For this, two alternative methods were used: 1) grains were soaked in distilled water for one hour then brought to 11.5 or 15.5 ± 0.5% water content (wb) by holding at 30°C over saturated solutions of $Mg(NO_3)_2$ (aw = 0.51) and KBr (aw = 0.80), respectively (Louis-Alexandre et al 1991) or 2) just enough distilled water was added to raw or pre-dried (to 10.5% water content by storing for one week at room conditions: 20°C, 30–50% rh) grains that were then held at 20°C in an hermetic container for seven days.

Experimental Design for the Grinding Test

A factorial design was used to optimize sample discrimination of the grinding test. Four experimental parameters were studied, each one at two levels: maize grain water content (11.5 and 15.5% wb), sample mass (20 and 50 g), burr type (fine and coarse), and burr setting (1 and 4 from contact, i.e., spacing of 0.18 and 0.72 mm, respectively). A half replicate of a 2-fourth design was chosen (Mullen and Ennis, 1985, Table II); in this configuration, the fourth-order interaction is lost, the main effects are aliased with three-order interactions, and second-order interactions are aliased among each other. Three-order interactions are negligible and can thus be ignored. This fractional factorial design was applied to the first set of seven IRAT cultivar samples. For each experimental grinding condition, five PSI measurements were successively made by weighing sieve fractions remaining over sieves with openings of 125, 180, 250, 315, and 400 μm.

Dry and Semi-Wet Milling

Dry milling was performed using an experimental fragmentation device that had been adapted for use as a maize flaking grits tester (Chaurand et al 1993). Maize grains are thrown by an impeller rotating at 1,000 rpm against a cylindrical stator composed of two half linings, one a Carborundum corrugated surface and the other a wire sieve with circular openings of 0.8 mm in diameter. Overs, representing 70–80% of maize sample, were collected and sieved using a rotating shaker (Tripette et Renaud, France). The flaking grits, with a particle size over 4 mm, were collected and weighed. Each maize lot (2.5 kg) was tempered at 13.5%

TABLE II
Half-Replicate 2-Fourth Design Used for Testing the Parameters of the Grinding Test (adapted from Mullen and Ellis 1985)

Experimental Condition[a]	Water Content[b] (% wb)	Sample Mass (g)	Burr Type	Burr Setting
1	11.5	20	Fine	4
2	11.5	20	Coarse	1
3	11.5	50	Fine	1
4	11.5	50	Coarse	4
5	15.5	20	Fine	1
6	15.5	20	Coarse	4
7	15.5	50	Fine	4
8	15.5	50	Coarse	1

[a] Each experimental condition was applied to 7 cultivars: IRAT numbers 39, 81, 100, 102, 148, 200, 275.
[b] Each sample was tempered at the desired water content by holding with saturated solutions of $Mg(NO_3)_2$ or KBr.

water content (wb) by storing in an air-conditioned room (20°C, 65% rh) seven to 15 days before testing.

Semi-wet milling was performed on a pilot roller-mill on 4- to 5-kg maize lots (Feillet and Redon 1975). Twenty-four hours before testing, maize lots were conditioned at 15.5% water content (wb) by addition of water and then brought to 18% water content (wb) just before milling. After four extraction steps, regular and coarse grits (particle size between 0.75 and 2.3 mm) were collected whereas fine products (cornmeal and corn flour with particle size under 0.75 mm) were pooled.

TABLE III
Analysis of Variance of Fraction Yields Obtained with 315-µm Sieve: 56 Experimental Datas for Seven Maize Cultivars Using the Half-Replicate 2-Fourth Design

Source of Variation	Degree of Freedom	Mean Square	*F* Ratio	H_0 Probability
Main effects				
A: Cultivar	6	51.5	9.6	0.0001
B: Water content	1	0.28	0.05	0.83
C: Sample mass	1	23.4	4.4	0.051
D: Burr type	1	1,821	340	<0.0001
E: Burr setting	1	6,024	1,125	<0.0001
Interactions				
AB	6	3.7	0.69	0.66
AC	6	5.5	1.0	0.44
AD	6	7.6	1.4	0.26
AE	6	3.4	0.64	0.70
BC – DE[a]	1	1,030	192	<0.00001
BD – CE[a]	1	51	9.6	0.006
BE – CD[a]	1	0.17	0.03	0.86
Residual	18	5.4		

[a] Second-order interactions are aliased among each other.

TABLE IV
Particle Size Index Values (%) Obtained for the Seven Cultivars Using the Half-Replicate 2-Fourth Design[a]

Cultivar IRAT Number	Sieve Opening (µm) 125	180	250	315	400
148	12.3	16.4	23.3	31.8	44.2
39	7.8	11.8	17.8	25.9	40.2
200	8.0	12.3	19.0	27.0	39.5
275	7.3	11.0	17.5	25.7	39.2
102	7.1	11.1	16.6	25.1	39.0
100	7.5	12.0	17.1	24.6	37.0
81	7.5	11.4	17.1	24.4	36.8
F value	27.2**[b]	8.4**	12.1**	9.6**	6.5**
LSD[c]	1.03	1.93	1.97	2.43	2.87
Range	4.8	5.4	6.2	7.4	7.4

[a] Mean values for the eight operating conditions.
[b] * = Significant at $P < 0.05$; ** = significant at $P < 0.01$.
[c] Least significant difference at $P < 0.05$.

TABLE V
Influence of Grain Water Content (GWC) on Particle Size Index (PSI) Values (% db) Obtained for the Seven Cultivars Using the Half-Replicate 2-Fourth Design

Sieve Opening (µm)	11.5% (wb) GWC	15.5% (wb) GWC	*F* Value of g wc Effect
125	8.9	7.6	28.0**[a]
180	12.9	11.6	6.8*
250	18.6	18.1	2.7
315	26.4	26.3	0.05
400	39.5	39.3	0.09

[a] * = Significant at $P < 0.05$; ** = significant at $P < 0.01$.

RESULTS AND DISCUSSION

Development of a Friability Test

Definition of Operating Conditions. The PSI values obtained for the fractional design were analyzed using variance analysis. The five main factors (cultivar factor and four experimental grinding conditions) were controlled, and main factors and interactions were tested through *F*-test using a global residual (experimental error). For the five sieves, the utilization conditions of the grinding device (burr type and burr setting) gave the highest *F* values (see Table III, for example for the 315-µm sieve). In addition, a highly significant interaction was observed for all sieve fractions between factors BC or DE. Due to alias among two-order interactions, these two effects could not be separated. But, it is very unlikely that PSI value was influenced by the interaction between grain water content and sample mass. This effect can be interpreted by an interaction between burr type and burr setting.

There was no interaction between cultivar and grinding experimental conditions. The effect of cultivar was interpreted; it was significant for all sieve fractions (Table IV). The precision of the methodology decreased when sieve opening increased (threefold increase of LSD from 125 to 400 µm sieve) whereas

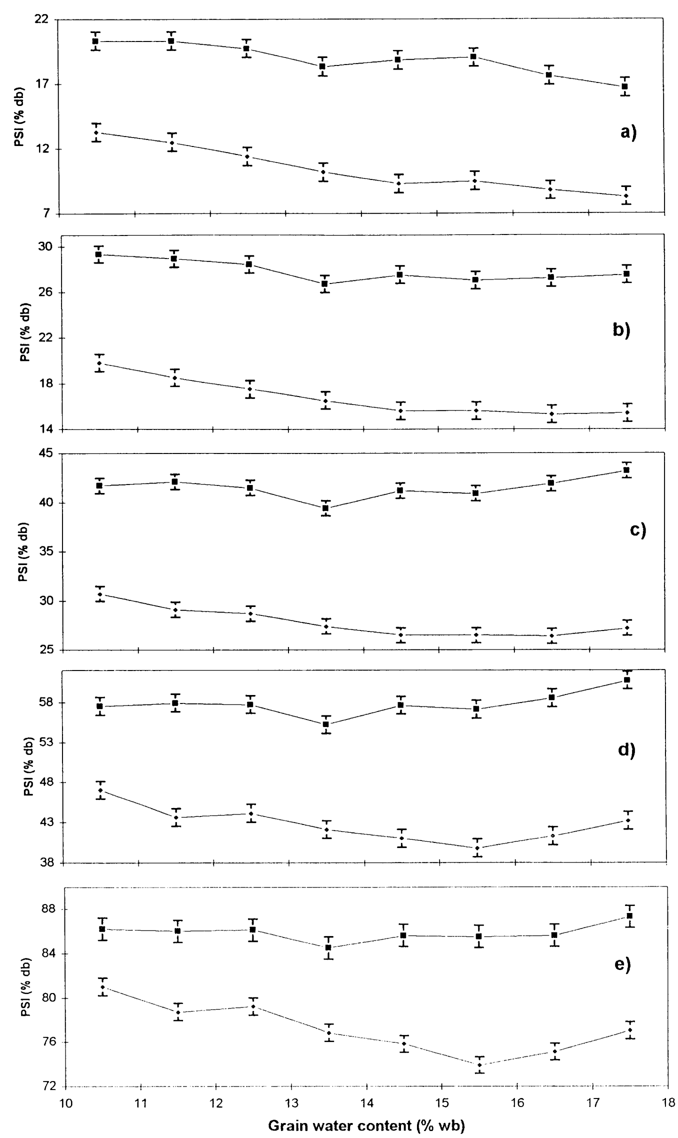

Fig. 1. Influence of grain water content on the particle size index (PSI) of two cultivars, E 211 (■) and Jaune de Bambey (◇), measured with a 125- (a), 180- (b), 250- (c), 315- (d), or 400-µm (e) sieve. Error bars indicate standard deviation.

the range increased (it was almost doubled). But the ranking of the seven cultivars was very similar for all sieve fractions.

The effect of grain water content was significant only for the finest sieves (125 and 180 μm); PSI values were higher at low moisture content (Table V). This means that more fine products are formed when grain moisture content is low, whereas more coarse products are formed at higher water content. This result agrees with the experience of the milling industry where grain is tempered at intermediate moisture content to improve yield of coarse particles. But this relation is not clearly observed with the Stenvert Hardness Test: at low water content, lower time is required to grind (grain is more friable), but no difference is observed for the mass ratio of coarse to fine products; volume fractions of coarse and fine products indicate that grain is harder (Pomeranz et al 1986, Dorsey-Redding et al 1990).

We further investigated the effect of grain water content on particle size distribution after grinding for two cultivar samples (E 211 and Jaune de Bambey) with a larger range of grain water contents—from 10.5 to 17.5% with intervals of 1%. In this case, the analysis of variance showed that the interaction between cultivar and water content was highly significant for all sieve fractions except 125 μm. In this case, water content effect was significant, and the lowest PSI value was observed for the highest water content (Fig. 1a). For the coarsest sieve (400 μm), only the grain with low PSI value appeared sensitive to grain water content; a minimum PSI was observed for intermediate water content (15.5%, Fig. 1e).

The sample mass effect was significant only for the coarsest sieve (400 μm openings). Because we wanted to define a grinding test that enhanced sample discrimination and lowered the influence of operating conditions, we eliminated the 400 μm sieve. Nevertheless, we fixed mass sample to 20 g. Because grain water content has an influence on grinding behavior, we fixed it at 15.5% (wb), which is easier to obtain. Also because we wanted to characterize the major fraction of the kernel, we chose the procedure parameters giving the PSI value nearest to 50%—fine burr at setting 1 and 315-μm sieve. Finally, the friability index was defined as the PSI measured after grinding 20 g of grain (tempered at 15.5%, wb) with a KT 30 disc mill using fine burr at setting 1 and sieving with 315-μm sieve for 5 min on an air jet sifter. These operating conditions were quite different from those of Pomeranz et al (1984), who used a high setting value at 3 (giving coarser products) but a less efficient sifter.

Validation. Using these operating conditions, the friability indexes of 18 samples, representing a fairly good collection of high-yield maize cultivars in use in West African countries, were measured. To simplify the methodology, friability indexes were also measured after adjusting grain water content to 15.5% (wb) by addition of water and holding grains in hermetic containers for one week before grinding. Analysis of variance showed (Table VI) that there was no interaction between cultivar and methodology effects. The methodology of tempering had a significant effect on the friability indexes; but the difference between the two methodologies remained very small (0.4%). Multiple mean comparisons showed six homogeneous groups among the 18 cultivars (Table VI). From these results, we proposed a maize kernel classification table based on grain friability indexes. The classification is as follows: kernels with >46 % db were considered very friable, between 46 and 43 was considered friable, between 43 and 41 was medium, and under 41 was considered coherent or solid.

TABLE VI
Friability Indexes (% db) of 18 Maize Cultivars[a]

Cultivar	Standard Methodology[b]	Practical Methodology[c]	Mean[d]
E 211	51.4	52.0	51.7 a
Tuxpenio	47.0	47.0	47.0 b
Jaune de Fô	45.9	45.2	45.5 c
Kolaribougou	45.3	45.2	45.2 c
Massayomba	44.7	44.2	44.5 cd
Guatemala	43.8	44.1	44.0 d
Mali 2	42.9	44.1	43.5 d
IRAT 80	44.4	42.6	43.5 d
IRAT 171	43.0	43.6	43.3 d
Poza Rica 7429	42.5	42.0	42.2 e
Across 8149	42.2	41.3	41.7 e
Tiemantié	41.9	41.2	41.5 e
TZ-ERS-W	41.4	41.2	41.3 e
Synthetic C	41.5	40.8	41.2 e
SR 22	41.4	40.9	41.1 e
HVB 1	39.5	39.1	39.3 f
Jaune de Bambey	39.8	38.3	39.0 f
IRAT 48	39.3	39.7	38.5 f
Mean	43.2	42.8	43.0
F ratio (df)	Sample effect (df = 17)		86.2**[e]
	Methodology effect (df = 1)		6.3*
	Interaction (df = 17)		1.3
Standard deviation of residual (df = 36)			0.7

[a] Grain tempered at 15.5% water content ; sample mass, 20 g ; fine burr ; burr setting of 1 ; 315 μm-sieve. All measurements were duplicated.
[b] Tempering over saturated solution of KBr at 35°C.
[c] Tempering by water adjunction and holding for one week in an hermetic container.
[d] Different letters denote statistically significant differences (at $P = 0.05$) using Newman-Keuls multiple range test.
[e] * = Significant at $P < 0.05$; ** = significant at $P < 0.01$.

TABLE VII
Kernel Physical Properties of 18 Cultivars[a]

Cultivar	1,000 Kernel Weight	Dent Kernel Percent	Vitreousness (%)	Specific Density (g/cm³)
E 211	225	2	35	1.251
Tuxpenio	347	100	72	1.334
Jaune de Fô	239	4	50	1.316
Kolaribougou	315	31	63	1.344
Massayomba	249	12	52	1.303
Guatemala	285	52	66	1.319
Mali 2	261	12	51	1.309
IRAT 80	258	6	58	1.308
IRAT 171	297	68	73	1.323
Poza Rica 7429	309	75	82	1.359
Across 8149	303	84	87	1.344
Tiemantié	263	0	52	1.349
TZ-ERS-W	249	21	67	1.322
Synthetic C	240	4	64	1.327
SR 22	277	58	66	1.319
HVB 1	193	3	59	1.339
Jaune de Bambey	212	26	72	1.353
IRAT 48	279	2	78	1.401
LSD[b]	17	6	7	0.007

[a] Maize samples are listed from the the most to least friable.
[b] Least significant difference at $P < 0.05$.

TABLE VIII
Correlation Coefficients Among Physical Properties of Maize Kernel

	1,000-Kernel Weight	Dent Kernel Percent	Vitreousness	Specific Density
Dent kernel percent	0.76 ***[a]			
Vitreousness	0.53 *	0.68 **		
Specific density	0.28	0.16	0.71 ***	
Friability	0.23	0.13	–0.54 *	–0.69 **

[a] * = Significant at $P < 0.05$; ** = significant at $P < 0.01$; *** = significant at $P < 0.001$.

TABLE IX
Yields of Semi-Wet and Dry Milling Products for 18 Maize Cultivars[a]

Cultivar	Semi-Wet Milling Yields		Dry Milling Yield
	Regular and Coarse Grits	Cornmeal and Flour	Flaking Grits
E 211	64.2	15.5	
Tuxpenio	62.9	12.4	27.8
Jaune de Fô	70.1	11.2	
Kolaribougou	70.1	11.4	32.9
Massayomba	68.2	12.5	26.7
Guatemala	66.1	11.3	40.0
Mali 2	67.0	11.0	26.6
IRAT 80	72.6	10.4	39.2
IRAT 171	72.0	9.7	
Poza Rica 7429	67.8	10.0	41.0
Across 8149	66.8	10.2	
Tiemantié	72.0	10.1	36.6
TZ-ERS-W	69.5	10.5	37.9
Synthetic C	72.1	8.9	45.5
SR 22	71.0	9.9	43.9
HVB 1	71.0	8.3	
Jaune de Bambey	69.2	9.1	
IRAT 48	71.4	8.1	48.1
LSD[b]	1.9	1.8	

[a] Maize samples are listed from the most to the least friable.
[b] Least significant difference at $P < 0.05$.

Relationship Between Friability and Other Physical Properties of Kernels

For the 18 cultivars, we also measured 1,000-kernel weight, dent kernel percentage, vitreousness, and specific density. A high variability was observed for all parameters (Table VII). Kernel attributes of African maize cultivars vary more than do those of maize hybrids of developed countries (Mestres et al 1991)

There was a significant correlation between endosperm texture parameters (vitreousness and specific density) and grain friability (Table VIII). But endosperm texture could explain only 50% of the variability of grain friability. This result confirms the observations made for many cereal grains that kernel vitreousness and mechanical properties are not tightly bound physical characteristics (Abdelrahman and Hoseney 1984, Fliedel et al 1989). There was no correlation between friability or vitreousness and shape factor. Because of this, a flint corn cannot be considered as hard as it was generally thought (Watson 1987a).

Grain Physical Properties and Milling Behavior

After semi-wet milling, the yield of regular and coarse grits ranged from 62.9 to 72.6%, whereas cornmeal and flour yield ranged from 8.1 to 15.5% (Table IX). After dry milling, the yield of flaking grits ranged from 26.6 to 48.1%.

The correlation matrix between milling product yields and physical properties of maize kernel (Table X) shows that the friability index is the best descriptor of maize milling ability: it explains 40–75% of milling product yield variability. On the other hand, endosperm texture (vitreousness and specific density) and shape factor are not clearly related to milling performances, confirming previous results (Mestres et al 1991). It has a direct consequence on maize breeding programs because for breeders, dent kernel factor and horny aspect are used to classify maize grains—this classification being generally considered as an image of grain quality.

The friability index should be a good breeding test for grain quality. But before using it, we must confirm that the friability index is mainly an inherited factor, as are many other physical properties of kernels (Shumway et al 1992).

CONCLUSIONS

The friability test developed is discriminant and precise. A classification table with four classes has been proposed. The friability is a good descriptor of maize milling performance and could therefore be used in grain quality maize breeding programs as soon as its inheritability has been studied.

On the contrary, the other physical attributes of maize kernels, kernel size, shape, and vitreousness (and consequently their dent or flint character) are not clearly related to the friability and grain milling performance.

TABLE X
Correlation Coefficients Between Maize Kernel Physical Properties and Yields of Milling Products

	Semi-Wet Milling		
	Regular and Coarse Grits	Cornmeal and Flour	Dry Milling Flaking Grits
1,000-kernel weight	–0.36	0.13	–0.20
Dent kernel percent	–0.56*[a]	0.10	–0.16
Vitreousness	–0.03	–0.47	0.56
Specific density	0.33	–0.68**	0.50
Friability	–0.66**	0.86***	–0.80**

[a] * = Significant at $P < 0.05$; ** = significant at $P < 0.01$; *** = significant at $P < 0.001$.

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