Effects of Hardness and Drying Air Temperature on Breakage Susceptibility and Dry-Milling Characteristics of Yellow Dent Corn[1]

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Cereal Chem. 67(6):523-528

ABSTRACT

Kernel density, test weight, Stein and Wisconsin breakage susceptibilities, stress cracking, and Stenvert hardness were determined for three corn hybrids that were classified as soft, hard, and of intermediate hardness. A stress crack index was developed for quantifying degree of stress cracking. Severity of stress cracking was directly related to hardness with the hardest hybrid showing the most severe cracking. Surprisingly, stress cracking was most severe at the intermediate (60°C) drying temperature. Stein breakage was greatest for the soft hybrid and least for the hard hybrid, whereas Wisconsin breakage was greatest for the hard hybrid and least for the hybrid of intermediate hardness. Stein breakage susceptibility was primarily influenced by hardness, whereas Wisconsin breakage susceptibility was correlated with stress cracking. Milling quality, as measured by a milling evaluation factor (MEF), decreased linearly with increasing drying temperature. For all drying temperatures, the hard hybrid had the highest MEF and the soft hybrid had the lowest MEF. Kernel density was the best single predictor of MEF ($R^2 = 0.773$). A two-variable model that combined test weight and kernel density improved the prediction of MEF ($R^2 = 0.907$). Incorporation of additional variables into the model did not significantly improve the two-variable MEF prediction model.

In the past decade, corn dry millers and food corn processors have become increasingly aware of the variations in quality among shipments of shelled corn arriving at their facilities. Corn dry millers seek a maximum amount of endosperm recovered as large grits. Recent studies by Paulsen and Hill (1985) and Litchfield and Shove (1989) demonstrated that selection of corn lots on the basis of kernel density, breakage susceptibility, or test weight can significantly improve flaking grit yields. Similarly, varietal differences in dry-milling quality among commercial hybrids have been demonstrated, with "hard" hybrids exhibiting more desirable milling characteristics (Stroshine et al 1986, Peplinski et al 1989). Food corn processors also prefer "hard" hybrids (Ellis et al 1984, Pflugfelder et al 1988), which are low in breakage susceptibility (Jackson et al 1988).

Drying temperature has substantial effects on breakage susceptibility, stress cracking, and dry-milling quality. Increasing drying temperature increases breakage susceptibility and stress cracking (Peplinski et al 1975, Gunasekaran and Paulsen 1985, Gunasekaran et al 1985). Brekke et al (1973) found that as drying air temperature increased from 15 to 143°C, yield of first-break grits decreased from 42 to 12%, respectively. Similarly, percentage of kernels with stress cracks increased from 7 to 84%. Examination of milled products revealed that corn dried at 143°C had more germ attached to the large flaking grits than that dried at 15°C. Peplinski et al (1989) dried six hybrids at two temperatures (25 and 60°C). Corn dried at 60°C had the highest breakage susceptibility and stress cracking and gave the lowest grit yields. They observed genotypic differences in these factors at both drying temperatures. Genotypic differences in breakage susceptibility have been demonstrated (Paulsen et al 1983, Stroshine et al 1986).

Pomeranz et al (1985) demonstrated that the Stenvert mill could be used for determining the hardness of corn dried at ambient temperature. In a later study, Martin et al (1987) tested combine-harvested corn dried at ambient temperature for relationships between breakage susceptibility and corn hardness. They reported that Stein breakage susceptibility (percent fines) was highly correlated to Stenvert grinding time. However, they found no correlations between corn hardness and Wisconsin breakage susceptibility.

Relationships among several of the quality parameters and physical properties have been studied and related to dry-milling quality. However, the interactions among drying temperature, dry-milling quality, and the more important factors have not been determined. Although hardness has been defined for other crops such as wheat, the distinction between kernel hardness and breakage susceptibility of corn has not been clearly drawn. Kernel density, test weight, and breakage susceptibility are useful screening methods for evaluating dry-milling quality. However, it has not been determined which combination of these tests is most useful for predicting dry-milling quality of corn.

This study was undertaken to investigate the relationships among corn hardness, test weight, kernel density, breakage susceptibility, stress cracking, and dry-milling quality and to identify those tests that could best be used to screen corn lots for dry-milling quality. Evaluations were performed on three corn hybrids identified as hard, soft, and intermediate types. Grain samples were dried at ambient temperature in still air or artificially dried at temperatures between 28 and 93°C.

MATERIALS AND METHODS

Materials

Three dent corn hybrids were grown on 0.2-ha field plots at Lafayette, IN, during the 1985 crop year. These hybrids were selected on the basis of kernel vitreousness and dry-milling performance in previous crop years to represent hard, intermediate, and soft endosperm types (FR23 × FR140, MBS73 × MBS847, FRB73 × MO17, respectively). Corn (approximately 20 kg of grain) was hand harvested at 23.6–26.4% moisture and stored at 2°C for a maximum of one week prior to hand shelling and drying. Control grain samples from each hybrid were placed on a laboratory bench (still air 27°C) and allowed to dry on the cob to about 15% moisture content (mc) before hand shelling. Samples for artificial drying were stored at 2°C for one week or less prior to hand shelling and drying.

The 1985 stress cracking and breakage patterns were unexpected and some of the tests were repeated on corn grown in 1986 to confirm our results. FRB73 × MO17 and FR23 × FR140 were again grown in 0.2-ha plots, harvested by hand, and hand-shelled. However, control samples were shelled prior to drying, placed in wire trays, and held at room temperatures until they reached 15% moisture.

Thin-Layer Drying

Grain from each hybrid was divided into four sublots of 1 kg each and dried in a laboratory thin-layer dryer (Stroshine and Martins 1986). Each sublot of the corn hybrids was artificially dried at one of the following temperatures in order of increasing temperature: 37.7, 60, 82.2, and 93.3°C. Final moisture contents were about 15% (range 14.6 to 15.6%). At each drying temperature the hybrids were dried in a random order. Approximate drying

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times were 8.0, 2.2, 0.8, and 0.5 hr, respectively, for temperatures of 37.7, 60, 82.2, and 93.3°C. When samples were removed from the dryer, they were immediately sealed in double plastic bags and cooled at room temperature. In the 1985 tests, air velocity in the vicinity of the drying tray was 1.53 m/sec and total airflow was 0.137 m^3/sec. The 1986 samples were dried with air velocities of either 1.53 or 0.41 m/sec to determine any air velocity effect on stress cracking and breakage susceptibility.

Proximate Analysis

Initial and final moisture contents of artificially dried grain were determined using a 72-hr, whole-kernel procedure (ASAE 1986). Fat and ash contents were determined by AACC approved methods 30-25 and 08-01, respectively (AACC 1983). Protein (N × 6.25) content was determined by an automated Kjeldahl procedure (AOAC 1980), with titanium dioxide substituted for the mercuric oxide catalyst (Williams 1973).

Physical Properties

The outer edges of 30 kernels, with the germ side facing up, were traced on a Zeiss Videoplan image analyzer (Carl Zeiss, Inc., New York). The image analyzer system was programmed to compute kernel length and width to the nearest 0.1 mm from the tracing. Thickness of the same 30 kernels was measured with an Ultra-Digit indicator (Fowler Co., Newton, MA). Percent vitreousness was determined on 20 kernels by modifying a procedure developed for sorghum (Kirleis et al 1984). In the modified procedure, embedded corn kernels were longitudinally sectioned perpendicular to the germ front for tracing total endosperm and translucent endosperm areas with a Zeiss Videoplan image analyzer. Vitreousness was expressed as the percent of total endosperm area that was translucent.

Whole kernels were individually examined over a light source for single, multiple, and checked (intersecting) stress cracks. A stress crack index (SCI) was calculated using the equation:

$$\begin{aligned} \text{SCI} &= 1(\%\ \text{single cracked kernels}) \\ &\quad + 3(\%\ \text{multiple cracked kernels}) + 5(\%\ \text{checked kernels}) \end{aligned}$$

Prior to determining kernel density, test weight, kernel hardness, and breakage susceptibility, the corn samples were conditioned to equilibrium moisture (11.1–12.3%) with circulating air at 26.7°C dry bulb and 67% relative humidity. Kernel density was determined by weighing 100 kernels and measuring the volume of 95% ethanol displaced by the weighed corn sample. Test weight (pounds per bushel) was determined by AACC method 55-10 and converted to kilograms per hectoliter using the factor 1.2872 (AACC 1983).

The Stenvert hardness test (SHT) as described by Pomeranz et al (1985) was performed on 20-g corn samples. Samples were ground in a Glen Creston Type 4 microhammer mill (Glen Mills, Maywood, NJ), using a 2.0-mm aperture screen and a hammer speed of 3,600 rpm. The time to grind 17 ml of meal, measured to the nearest 0.1 sec, was used as a measure of grain hardness.

Two devices commonly used to measure breakage susceptibility, the model CK-2M Stein (SBT) and Wisconsin (WBT) breakage testers (Singh and Finner 1983, Watson and Herum 1986), were used in this study. The Stein breakage test was conducted by AACC method 55-20 (AACC 1983). Wisconsin breakage was determined on the "standard" Wisconsin tester using a 250-g corn sample at a feed rate of 500 g/min. Broken kernels from both testers were removed with a 4.76-mm (12/64-in.) round-hole sieve and the breakage susceptibility was expressed as a percent of the sample passing through the test screen. Breakage values were not corrected for sample moisture differences.

Dry Milling

A short-flow corn dry-milling procedure was used to determine MEF, a numerical index reflecting grit and total endosperm yields. Previous work showed that MEF values are highly correlated (R = 0.92) with flaking grit yields obtained on a commercial corn dry mill (Kirleis and Cagampang 1983, *unpublished*). Prior to milling, 1,300-g grain samples were conditioned consecutively to 16% mc for 16 hr, 21% mc for 1.75 hr, and finally to 24% mc for 15 min. Tempered samples were passed through a horizontal drum type degermer, operated at 2,150 rpm, at a feed rate of 450 g/min. After the initial 15 sec (the time required to equilibrate flow through the degermer) two replicate samples were collected (each sample was collected for 1.0 min). Stock from each replicate was screened for 30 sec over a 3½W sieve on a Smico laboratory test sifter. Stock remaining over the sieve was given a second pass through the degermer, at a speed of 2,250 rpm, and combined with the stock that passed through the sieve. Combined stocks were dried for 1 hr at 45°C to a moisture content of 17 ± 1%. Dried stock was separated by screening over 3½, 5, 7, 10, and 16 W sieves on a Smico laboratory test sifter for 1 min. Fractions remaining over each sieve were aspirated on a Bates laboratory aspirator to remove hull material. After aspiration, the 5, 7, and 10 W stocks were floated in sodium nitrate solution (specific gravity of 1.275) to separate germ and endosperm pieces. All fractions were dried for 16–18 hr at 45°C and weighed. MEF was calculated using the equation:

$$\text{MEF} = (\text{EN}_{3\frac{1}{2}\text{W}} + \text{EN}_{5\text{W}} + \text{EN}_{7\text{W}})\ (\text{TEP}/100)$$

where EN is weight percentage of endosperm remaining on the indicated screen, and TEP is weight percentage of total endosperm product.

Statistical Analysis

The SAS statistical software package was used for all statistical analyses (Nie et al 1975). Correlation coefficients among factors were determined using procedure CORR. In an attempt to identify the best methods of evaluating dry-milling quality of shelled corn, stepwise regression was performed to determine the best physical properties and quality parameters for predicting milling quality. The data from all three hybrids were pooled, and the multiple regression technique was used to relate milling quality to the physical properties and quality parameters. Pooling of the data allowed development of a model applicable to corn of various degrees of hardness and dried at a wide range of temperatures. The regression was performed using the SAS STEPWISE procedure and the MAXR (maximum R^2 improvement) method. SAS STEPWISE attempts to find the best one-variable model and successively the best models that combine two or more variables. When each variable is added, MAXR chooses the variable such that the new model gives the greatest improvement in the value of R^2.

The 1985 data for each quality variable were analyzed using the analysis of variance and regression procedures (SAS 1985). Since all sublots of the hybrids were analyzed for quality in random order, a pure error (*b*) mean square term existed (no error [*a*] and usual error [*b*] terms existed, as there were no drying temperature replicates), and was used to test hybrids and their interaction with temperature in the analysis of variance procedures. Regression was used to partition the drying temperature by hybrid effects interaction by orthogonal polynomial coefficients and to develop coefficients for the best-fitting polynomial model. The least significant intervals (LSI) as described by Andrews et al (1980) were determined from the confidence interval of the predicted means given by the regression procedure.

RESULTS AND DISCUSSION

Proximate composition (protein, fat, and ash expressed on a dry matter basis) of the corn hybrids dried at ambient temperature is shown in Table I. The protein range was 11.2–12.0%, the fat range 3.5–4.5%, and the ash range 1.26–1.54%, typical of commercial dent corn. Kernel vitreousness and dimensions of the corn dried at ambient temperature are presented in Table II. The kernel vitreousness of FR23 × FR140, MBS73 × MBS847, and FRB73 × MO17 was 59, 53, and 49%, respectively. On the basis of kernel vitreousness the hybrids were ranked in the expected order, although intermediate (MBS73 × MBS847) and soft (FRB73 × MO17) hybrids were not significantly different. Kernel dimension measurements showed that kernel length and width decreased in the following order: FRB73 × MO17 > MBS73 × MBS847 > FR23 × FR140, and kernel thickness decreased in the order: FR23 × FR140 > MBS73 × MBS847 = FRB73 × MO17 (Table II). Thus the soft hybrid (FRB73 × MO17) kernels can be characterized as long and thin, whereas the hard hybrid (FR23 × FR140) kernels were shorter and thicker.

The effects of high-temperature drying on the characteristics of the hybrids are presented (Figs. 1–7) and discussed in the following sections.

Kernel Density

Density is frequently used as an indirect indicator of the corneous endosperm content in corn (Watson 1987). This is based on the fact that corneous endosperm is very dense, whereas floury endosperm is full of microfissures or void spaces and therefore, less dense. The amount of corneous endosperm is related to grit yield, a prime product in corn dry milling. The effects of artificial drying on the density of the corn hybrids is shown in Figure 1. Regardless of hybrid hardness, kernel density decreased as drying temperature increased from 27 to 93°C. However, the soft

TABLE I
Protein, Ash, and Fat Content of Corn Hybrids[a]

Hybrid	% Protein (N × 6.25)	% Fat	% Ash
FR23 × FR140	12.0	3.5	1.26
MBS73 × MBS847	11.6	4.5	1.51
FRB73 × MO17	11.2	3.6	1.54

[a] Values are averages of duplicate determinations on two field replicates reported on a dry matter basis.

TABLE II
Vitreousness and Kernel Dimensions of Corn Hybrids Dried at Ambient Temperature[a]

Hybrid	Vitreousness (%)	Kernel Dimensions (mm) Length	Width	Thickness
FR23 × FR140	59.0	11.9	7.5	4.6
MBS73 × MBS847	53.0	12.2	7.7	4.1
FRB73 × MO17	49.0	13.4	7.9	4.0
SD	4.5	0.1	0.1	0.2

[a] Average of duplicate determinations on two field replicates.

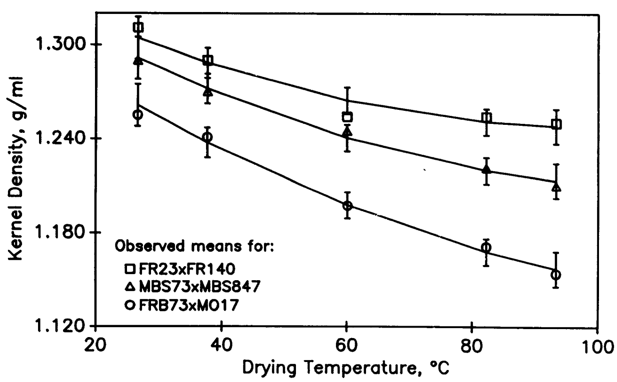

Fig. 1. The observed and predicted transformed means (—) for kernel density with the least significant interval for artificially dried hard (FR23 × FR140), intermediate (MBS73 × MBS847), and soft (FRB73 × MO17) hybrid corn. The regression equations used for the predicted means were, for FR23 × FR140, $y = 1.36 - 0.00162x + 0.00001x^2$; for MBS73 × MBS847, $y = 1.35 - 0.00198x + 0.00001x^2$; and for FRB73 × MO17, $y = 1.33 - 0.00240x + 0.00001x^2$, where y is the transformed kernel density and x is the drying air temperature.

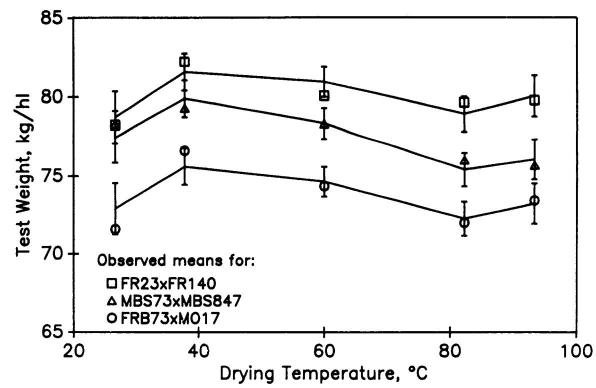

Fig. 2. The observed and predicted transformed means (—) for test weight with the least significant interval for artificially dried hard (FR23 × FR140), intermediate (MBS73 × MBS847), and soft (FRB73 × MO17) hybrid corn. The regression equations used for the predicted means were, for FR23 × FR140, $y = 55.25 + 1.449x - 0.025x^2 + 0.0001x^3$; for MBS73 × MBS847, $y = 55.13 + 1.408x - 0.025x^2 + 0.0001x^3$; and for FRB73 × MO17, $y = 49.85 + 1.433x - 0.025x^2 + 0.0001x^3$, where y is the transformed test weight and x is the drying air temperature.

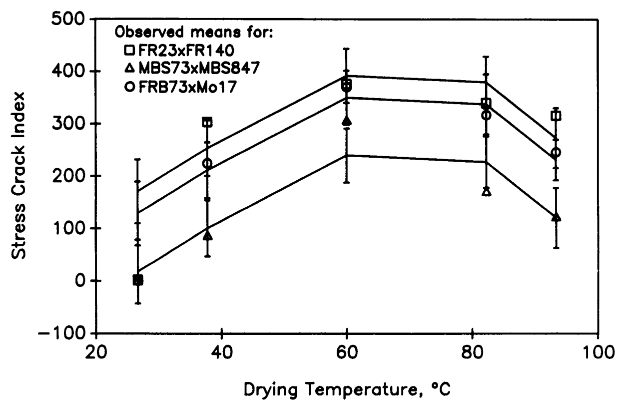

Fig. 3. The observed and predicted transformed means (—) for stress crack index with the least significant interval for artificially dried hard (FR23 × FR140), intermediate (MBS73 × MBS847), and soft (FRB73 × MO17) hybrid corn. The regression equations used for the predicted means were, for FR23 × FR140, $y = 64.79 - 0.62x + 0.23x^2 - 0.002x^3$; for MBS73 × MBS847, $y = -87.57 - 0.62x + 0.23x^2 - 0.002x^3$; and for FRB73 × MO17, $y = 22.78 - 0.62x + 0.23x^2 - 0.002x^3$, where y is the transformed stress crack index and x is the drying air temperature. Stress crack index is defined in the text.

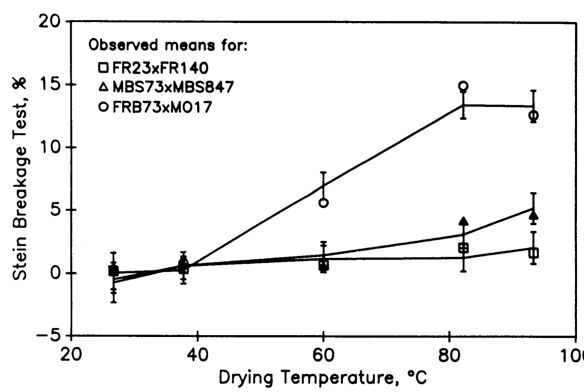

Fig. 4. The observed and predicted transformed means (—) for Stein breakage with the least significant interval for artificially dried hard (FR23 × FR140), intermediate (MBS73 × MBS847), and soft (FRB73 × MO17) hybrid corn. The regression equations used for the predicted means were, for FR23 × FR140, $y = -9.70 + 0.53x - 0.008x^2 + 0.00001x^3$; for MBS73 × MBS847, $y = -8.15 + 0.47x - 0.008x^2 + 0.00005x^3$; and for FRB73 × MO17, $y = 17.85 - 1.30x + 0.028x^2 - 0.00012x^3$, where y is the transformed Stein breakage and x is the drying air temperature.

hybrid (FRB73 × MO17) showed a greater decrease in density than the intermediate (MBS73 × MBS847) and hard (FR23 × FR140) hybrids. Densities of the hard and intermediate hybrids dried at 27 and 38°C were not statistically different, but at higher drying temperatures the densities were significantly different. Density changes in the 1986 corn dried at a lower airflow (data not shown) were similar to those observed for the 1985 crop (Fig. 1). Our findings are in agreement with density decreases reported by Gunasekaran and Paulsen (1985) for corn dried at temperatures between 20 and 65°C.

Test Weight

Test weight varied in an erratic manner for all three hybrids as drying temperature was increased from 27 to 93°C (Fig. 2). Except for the intermediate hybrid (MBS73 × MBS847), test weights of corn dried at 27°C were slightly lower than for corn dried at 93°C. However, test weight changes within each hybrid over the entire range of drying temperatures were not significantly different. The test weight of the hard (FR23 × FR140) and intermediate (MBS73 × MBS847) hybrids were not significantly different when the corn was dried at 27 and 37°C. At all other drying temperatures, test weight was significantly different among the three hybrids and decreased in the following order: hard (FR23 × FR140) > intermediate (MBS73 × MBS847) > soft (FRB73 × MO17).

Other workers have found that test weight of corn generally decreases with increasing drying temperatures (Hall 1972, Gunasekaran and Paulsen 1985). The two factors that affect test weight are kernel density and the way the kernels pack in a container. Because true density of the hybrids decreased as drying temperature increased (Fig. 1), the observed erratic pattern of test weight (Fig. 2) over the range of drying temperatures was probably caused by changes in the packing characteristics of the kernels.

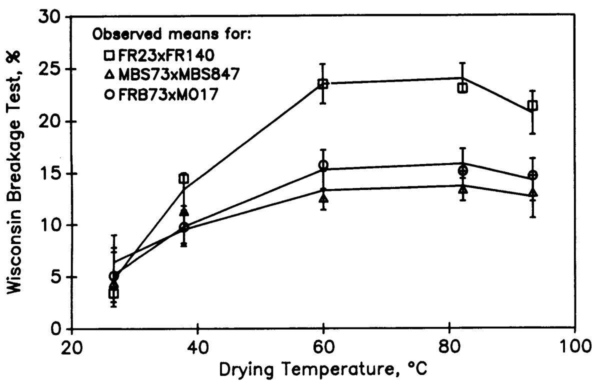

Fig. 5. The observed and predicted transformed means (—) for Wisconsin breakage with the least significant interval for artificially dried hard (FR23 × FR140), intermediate (MBS73 × MBS847), and soft (FRB73 × MO17) hybrid corn. The regression equations used for the predicted means were, for FR23 × FR140, $y = -25.78 + 1.40x - 0.009x^2$; for MBS73 × MBS847, $y = -4.52 + 0.50x - 0.003x^2$; and for FRB73 × MO17, $y = -10.92 + 0.74x - 0.005x^2$, where y is the transformed Wisconsin breakage and x is the drying air temperature.

Stress Cracking

Stress cracks are generally associated with rapid drying of corn with high-temperature air followed by rapid cooling with ambient temperature air. When handled and transported, kernels with stress cracks break more easily than sound kernels, and this may generate considerable amounts of broken corn and fines. The drying technique used in our tests eliminated the effects of rapid cooling. The severity of stress cracking in the artificially dried corn was assessed using a stress crack index (SCI). The SCI is a weighted index of corn quality based on the number of kernels with single, multiple, and checked stress cracking patterns. All hybrids followed a similar pattern; SCI increased to maximum values as the drying temperature went from 27 to 60°C, remained about the same at 60 and 82°C, and then decreased at 93°C (Fig. 3). Note that SCI values for individual hybrids dried at 38 and 93°C are similar using the equation given above. At drying temperatures >38°C, the SCIs for the hybrids increased in the following order: intermediate (MBS73 × MBS847) < soft (FRB73 × MO17) = hard (FR23 × FR140).

When the drying tests were repeated in 1986 at a lower drying air velocity, the hard (FR23 × FR140) and soft (FRB73 × MO17) hybrids followed the same SCI pattern shown in Figure 3; SCI values increased from 27 to 60°C, reached a maximum at 60°C, and decreased from 60 to 93°C (data not shown). However, in 1986 the SCI values for corn dried at 93°C were higher than for 38°C dried corn but still lower than corn dried at 60°C. These SCI results were unexpected because decreases in stress cracking at elevated drying temperatures had not been previously reported. In previous work, however, comparisons were reported on the basis of only one type of stress cracking or on the basis of the total number of stress-cracked kernels (Brown et al 1979, Gunasekaran and Paulsen 1985, Paulsen and Hill 1985, Jackson et al 1988, Peplinski et al 1989). The SCI value, which combines all three types of stress cracking and weights them according to severity, is an overall more useful index for assessing corn stress cracks and allows comparisons to be made over a wide range of drying temperatures.

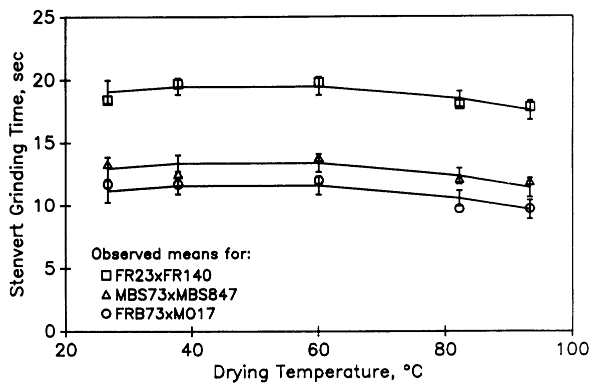

Fig. 6. The observed and predicted transformed means (—) for Stenvert grinding time with the least significant interval for artificially dried hard (FR23 × FR140), intermediate (MBS73 × MBS847), and soft (FRB73 × MO17) hybrid corn. The regression equations used for the predicted means were, for FR23 × FR140, $y = 17.02 + 0.106x - 0.001x^2$; for MBS73 × MBS847, $y = 10.89 + 0.106x - 0.001x^2$; and for FRB73 × MO17, $y = 9.11 + 0.106x - 0.001x^2$, where y is the transformed Stenvert grinding time and x is the drying air temperature.

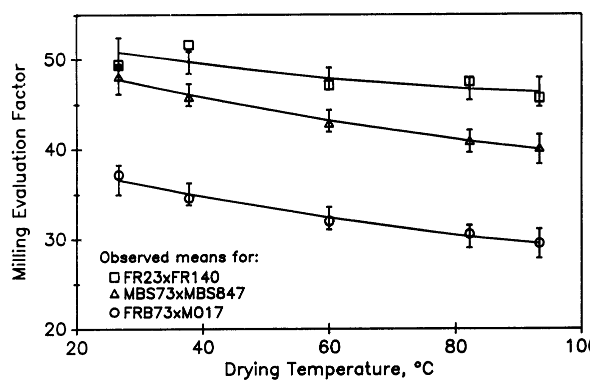

Fig. 7. The observed and predicted transformed means (—) for milling evaluation factor with the least significant interval for artificially dried hard (FR23 × FR140), intermediate (MBS73 × MBS847), and soft (FRB73 × MO17) hybrid corn. The regression equations used for the predicted means were, for FR23 × FR140, $y = 54.29 - 0.15x + 0.0007x^2$; for MBS73 × MBS847, $y = 52.60 - 0.20x + 0.0007x^2$; and for FRB73 × MO17, $y = 41.13 - 0.19x + 0.0007x^2$, where y is the transformed milling evaluation factor and x is the drying air temperature.

One possible explanation of the decrease in SCI involves the procedure used to cool the dried corn. The corn samples were placed in plastic bags immediately after drying; therefore, the rate of moisture loss was reduced. This slow cooling by conduction would tend to reduce stress cracking as does the delayed cooling used in dryeration (Thompson and Foster 1967, Brown et al 1979). In our tests, samples remained warm for several hours. The endosperm of the corn dried at 93°C may have been more pliable than the endosperm of corn dried at 60°C. This would allow for relaxation of internal stresses with less cracking in the corn.

Breakage Susceptibility

Breakage susceptibility is defined as the potential for kernel fragmentation or breakage when subjected to impact force during handling and transport (AACC 1983). Several factors such as percentage of stress-cracked kernels, thickness of corneous endosperm, and temperature of drying are known to affect breakage susceptibility. The breakage susceptibility values for the hybrids determined by the Stein (SBT) and Wisconsin (WBT) breakage testers are shown in Figures 4 and 5, respectively. For each hybrid, the SBT produced lower breakage susceptibility values at all drying temperatures than the WBT. The SBT and WBT breakage susceptibility patterns for the artificially dried hybrids were unrelated. SBT breakage susceptibility of corn dried at temperatures >60°C generally increased in the following order: hard (FR23 × FR140) < intermediate (MBS73 × MBS847) << soft (FRB73 × MO17) hybrid (Fig. 4). However, breakage susceptibility measured on the WBT increased in the following order for corn dried at temperatures >38°C: intermediate (MBS73 × MBS847) = soft (FRB73 × MO17) < hard (FR23 × FR140) hybrid (Fig. 5). The WBT values for the hybrids followed a pattern similar to SCI values at all drying temperatures (Figs. 3 and 5). This relationship suggests that the WBT provides a better measure of stress cracking in corn than the SBT.

Hardness

Hardness is an important intrinsic property of corn because it is closely related to the ratio of corneous to floury endosperm that affects dry-milling flaking grit yields. For corn dried at 27 and 38°C, SHT values decreased in the following order: hard (FR23 × FR140) > intermediate (MBS73 × MBS847) = soft (FRB73 × MO17) hybrid (Fig. 6). At drying temperatures >60°C, small but significant hardness differences were found between the intermediate (MBS73 × MBS847) and soft (FRB73 × MO17) hybrids. For each hybrid, SHT values remained relatively constant for corn dried at temperatures up to 60°C and then declined only slightly, but not significantly, at the higher drying temperatures.

Results of hardness tests, using particle size to determine corn hardness, can be affected by increased susceptibility of corn to breakage due to drying at elevated temperatures. Such drying as shown above causes the formation of stress cracks, lowers kernel density and increases breakage. This, in turn, likely affects the particle size of ground material. Since drying air temperature had little influence on SHT grinding time, this index may provide a better measure of corn hardness than methods based on particle size.

Milling Quality

The primary products derived from the corn dry-milling process are corn grits, meal, and flour. A short flow milling procedure was used to evaluate the effects of drying temperature on corn dry-milling quality. Product yields were used to calculate an MEF that is weighted to reflect grit yields.

The overall milling quality (MEF) of the hybrids decreased in the following order: hard (FR23 × FR140) > intermediate (MBS73 × MBS847) >> soft (FRB73 × MO17) hybrid (Fig. 7). The MEF of all hybrids decreased as drying temperature increased. However, as drying temperature increased from 27 to 93°C, the MEF of the hard (FR23 × FR140) hybrid decreased by only 4.5 units, whereas the intermediate (MBS73 × MBS847) and soft (FRB73 × MO17) hybrids decreased by 7.9 and 7.1 units, respectively. This suggests that harder corn has more tolerance to high-temperature drying than softer types.

Relationships Among Quality Parameters

Linear correlation coefficients between the measured quality parameters and physical properties are given in Table III. Test weight, kernel density, and SHT were all positively and highly significantly correlated with MEF. Of the two breakage susceptibility measurements, only SBT was significantly correlated with MEF. The SBT also had a significant negative correlation with the other measures of grain hardness (test weight, kernel density, and SHT) but was not significantly correlated with SCI. Martin et al (1987) also reported a correlation between SBT and hardness. By contrast the WBT was significantly correlated only with SCI. This indicates that SBT values are primarily influenced by corn hardness and to a lesser degree by stress cracking. The WBT appears to be a good measure of stress cracking. Jackson et al (1988) reported a high correlation between WBT and percent kernels with multiple stress cracks. Herum and Hamdy (1981) reported that the particle size distribution produced by the SBT was similar to that found in fine material produced during actual handling, whereas the particle size distribution from a single impact tester was not.

Models for Predicting Milling Quality

Quality measures selected by the maximum R^2 improvement technique to provide the best one-variable model, the best two-variable model, and so forth, for predicting MEF are shown in Table IV. The best one-variable model used kernel density and the best two-variable model used kernel density and test weight for predicting MEF. The three-, four-, and five-variable models added SHT, SBT, and WBT, respectively, to the MEF prediction equation. However, the degrees of R^2 improvement (P value)

TABLE III
Correlation Coefficients Between Hardness, Breakage Susceptibility, and Milling Quality Variables for Hybrid Dent Corn Dried at Various Temperatures

Variable[a]	TW[b]	KD	SHT	SCI	WBT	SBT
MEF	0.87**	0.88**	0.83**	−0.14	0.02	−0.79**
SBT	−0.64**	−0.85**	−0.57*	0.34	0.22	
WBT	0.30	−0.33	0.36	0.88**		
SCI	0.22	−0.40	0.26			
SHT	0.83**	0.69**				
KD	0.70**					

[a] MEF = Milling evaluation factor, SBT = Stein breakage test, WBT = Wisconsin breakage test, SCI = stress crack index, SHT = Stenvert hardness test, KD = kernel density.
[b] TW = Test weight.
[c] * = Significance at the 0.05% level; ** = significance at the 0.01% level.

TABLE IV
Stepwise Regression Models for Maximum R^2 Improvement for Dependent Variable Milling Evaluation Factor (MEF)

No. of Variables	Model[a]	R^2	P Value[b]
1	MEF = 146.31 KD − 140.01	0.773	0.0001
2	MEF = 87.26 KD + 1.18 TW − 157.40	0.907	0.0013
3	MEF = 81.14 KD + 0.92 TW + 0.34 SHT − 134.91	0.915	0.3298
4	MEF = 71.10 KD + 0.88 TW + 0.37 SHT − 0.10 SBT − 119.51	0.917	0.6935
5	MEF = 74.28 KD + 0.87 TW + 0.34 SHT − 0.09 SBT + 0.02 WBT − 122.24	0.917	0.7275

[a] KD = Kernel density, TW = test weight, SBT = Stein breakage test, SHT = Stenvert hardness test, and WBT = Wisconsin breakage test.
[b] Probability of obtaining an F value greater than that observed by chance alone.

achieved by adding SHT, SBT, and WBT to the models were not significant. This suggests that dry-milling quality (flaking grit yield potential) can be predicted from kernel density, and test weight measurements without considering breakage susceptibility.

Our results showed that the addition of WBT did not significantly improve the MEF prediction equation, and that SCI and WBT were not significantly correlated with MEF. These findings were unexpected as Brekke et al (1973) reported that the content of stress-cracked kernels had a negative correlation with corn dry-milling quality. More recently, Paulsen and Hill (1985) demonstrated the usefulness of WBT in selecting commercial corn lots having low breakage susceptibility and superior dry-milling quality. In the latter two studies, corn with a narrow range of hardness was used, whereas in our work, corn hybrids that varied widely in hardness were studied. This difference probably influenced our finding regarding the effect of SCI and WBT on corn dry-milling quality. The hard corn with the highest SCI and WBT breakage had the best MEF values, and, conversely, the soft corn with the poorest MEF values had less stress cracking and WBT breakage than the hard corn (Figs. 4 and 6). Regardless of the severity of stress cracking, hard corn has better milling quality than soft corn. Accordingly, hardness is the primary factor affecting corn dry-milling quality, and stress cracking and WBT breakage would be secondary factors.

CONCLUSIONS

Results of this study suggest that both drying temperature and hardness have significant effects on milling quality with hardness having the greater effect. Milling quality, as measured by MEF, decreased linearly with drying temperature for three hybrids chosen to represent a wide range in grain hardness. These results agree with those previously reported by Peplinski et al (1989). The hard hybrid showed the least percentage decrease in milling quality as drying temperature increased from 38 to 93°C.

A defined index of stress cracking allows kernels to be compared over a wide range of drying temperatures. The index was greatest (i.e., stress cracking was most severe) for the hard hybrid. Surprisingly, stress cracking was less severe at a drying temperature of 93°C than at 60°C. It is hypothesized that this is primarily the result of the procedure used to handle the samples immediately after drying.

Wisconsin breakage was greatest for the hard hybrid at all drying temperatures whereas Stein breakage was greatest for the soft hybrid. Correlations among physical properties and quality parameters suggested that Stein breakage is most influenced by kernel hardness whereas Wisconsin breakage is most influenced by stress cracking.

The model developed predicts dry-milling quality on the basis of physical properties and quality parameters. The single factor that best predicted milling quality was kernel density and the two factors that best predicted milling quality were kernel density and test weight. Other factors, in order of importance, were Stenvert hardness, Stein breakage, and Wisconsin breakage.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the technical assistance of Brian Hellman, Han Almekinder, Kyle Walton, Leslie Watters, and Cynthia Koh-Knox. We acknowledge the statistical consultation provided by Judy Santini and Wyman Nyquist.

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[Received March 15, 1990. Revision received June 8, 1990. Accepted June 8, 1990.]