RELATING RICE KERNEL BREAKING FORCE DISTRIBUTIONS TO MILLING QUALITY

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ABSTRACT. *Three−point bending tests were conducted to determine the mechanical strength distributions of brown rice kernels. Three long−grain rice cultivars (Cypress, Drew, and XL6) were initially studied. Breaking force (the force required to break a brown rice kernel in three−point bending) was not significantly related to kernel width or length. However, there was a significant correlation between breaking force and kernel thickness; thicker kernels tended to have higher breaking forces. For all three cultivars, kernel−to−kernel breaking force distributions tended to be bimodal: one dominant peak existed around 30 N and a smaller peak around 15 N. The data showed that rice samples could have similar average kernel breaking forces, but their breaking force distributions were quite different. In turn, head rice yield was not related to the average breaking force of rice kernels in a sample; however, head rice yield was closely related to the percentage of "strong" kernels, defined as kernels that sustained a 20 N force in bending. Based on this apparent finding, the breaking force distributions and head rice yields for seven additional rice lots were measured. A linear relationship was observed between the sample head rice yield and the percentage of strong kernels in the sample.*

Keywords. *Breaking force, Deformation, Distribution, Head rice yield, Kernel, Milling quality, Thickness, Three−point bending test.*

The quality of milled rice, the predominant edible form of rice, is largely determined by the yield of well−milled, whole kernels, referred to in the rice industry as head rice. Broken rice kernels are sold at a much lower price than head rice. Head rice yield (HRY), defined as the weight percentage of rough or unprocessed rice that remains as head rice after milling, is a critical quality parameter used to quantify rice quality, and thus the economic value of rice. HRY is sensitive to production and environmental conditions and can also be dramatically affected by post−harvest processing.

Research has been conducted to understand the formation of fissures in rice kernels under different drying conditions, since fissures weaken the structure and integrity of kernels and thus reduce HRY (Ban, 1971; Choudhury and Kunze, 1972; Kunze, 1979; Bonazzi et al., 1997; Cnossen and Siebenmorgen, 2000; Fan et al., 2000). Because fissures and subsequent breakage represent mechanical failures of rice kernels, it is important to understand the mechanical properties of rice kernels and their impact on rice quality.

As such, various mechanical properties of rice kernels have been measured. Goodman and Rao (1985) studied the effect of milled rice kernel hardness and grain type on HRY; a very low correlation (R = 0.22) between HRY and the average point load yield was reported. Kunze and Choudhury (1972) measured the tensile strength of rice kernels. Compression and bending tests to quantify mechanical properties of rice kernels have also been performed (Husain et al., 1971; Kunze and Choudhury, 1972; Prasad and Gupta, 1973; Chattopadhyay et al., 1979; Nguyen and Kunze, 1984; Bamrungwong et al., 1987, 1988; Wouters and de Baerdemaeker, 1988; Chattopadhyay and Hamann, 1994; Kamst et al., 1999). However, in these previous studies, the mechanical strengths of rice kernels were typically reported as average values, or based on limited experimental data from a few good kernels, which would hardly reflect the significant variations in physical and mechanical properties among all rice kernels. Little information was found on the mechanical strength distributions of rice kernels.

As detailed by Siebenmorgen (1998), a complete understanding of drying and milling behavior of rice lots will not occur until the individual kernel property distributions comprising a bulk are fully characterized. Unfortunately, there is limited information available on the relationship between kernel−to−kernel mechanical property distributions and bulk HRY of rice. Nguyen and Kunze (1984) found that the average breaking force was closely related to the percentage of fissured kernels in two rice varieties. Lu and Siebenmorgen (1995) found that the correlation between HRY and the average maximum compressive force to crush/break rough brown and white rice kernels was either insignificant or of a low order of magnitude. They also found that the percentage of broken kernels from milling was closely related to the percentage of kernels that did not sustain approximately a 15 N breaking force in bending. This finding is significant since it suggests that HRY is related to the distribution of kernel breaking forces in bending.

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Table 1. General information for rice samples.

Cultivar	Location (Arkansas)	Harvest Date (2001)	HMC	MC	MRY	HRY	DOM	Kernels	ABF	P of S
Cypress	Stuttgart	Aug. 24	19.0	12.0	69.4	63.0	101	435	28.5	87.4
Drew	Keiser	Oct. 1	21.4	12.3	70.0	58.7	103	422	24.7	81.5
XL6	Keiser	Sept. 25	17.4	11.5	66.5	46.0	90	462	24.7	68.4
Bengal	Stuttgart	Aug. 27	21.0	11.9	70.2	64.0	96	400	28.7	85.7
Cocodrie	Keiser	Oct. 30	15.2	11.9	70.3	63.1	92	401	28.4	87.5
Cypress	Keiser	Oct. 30	14.7	12.0	69.3	62.5	103	441	26.1	81.6
Drew	Keiser	Oct. 30	18.6	12.3	70.0	58.8	103	419	25.6	83.3
Lagru	Stuttgart,	Sept. 13	16.5	11.9	67.7	59.1	110	400	29.8	91.0
Wells	Keiser	Oct. 31	14.0	11.9	70.1	57.1	104	420	24.8	76.2
XL6	Stuttgart	Aug. 23	18.0	12.0	68.5	35.0	110	800	19.8	51.5

HMC = harvest moisture content (%, w.b.)
MC = milling moisture content (%, w.b.)
MRY = milled rice yield (%)
HRY = head rice yield (%)
DOM = degree of milling, as measured with a Satake MM−1B milling meter
Kernels = number of brown rice kernels tested in three−point bending tests
ABF = Average breaking force (N), calculated as the mean breaking force of all kernels tested
P of S = percentage of strong (>20 N) kernels (%)

In this study, the work of Lu and Siebenmorgen (1995) was extended to more fully investigate the relationship between kernel dimensions and corresponding mechanical breaking force, as measured using a three−point bending test. Further, the resulting kernel breaking force distributions were related to HRY. The overall hypothesis underlying this latter objective was that the kernels that break during milling, thus causing HRY reduction, have low breaking forces; the reasons for these low breaking forces are due to the kernels being immature and thin, fissured due to moisture adsorption by low MC kernels, or chalky. Concentrating on a percentage of forces within kernel−to−kernel breaking force distributions may yield more direct information to predict HRY than using the average breaking forces of kernels comprising a distribution.

Materials and Methods

Sample Preparation

Three long−grain rice cultivars, Cypress, Drew, and XL6, with harvest MCs (all moisture contents are expressed on a wet basis unless otherwise noted) of 19.0%, 21.4%, and 17.4%, respectively, were harvested in 2001 from the University of Arkansas Rice Research and Extension Center near Stuttgart, Arkansas (Cypress) or the Northeast Research and Extension Center near Keiser, Arkansas (Drew and XL6). After harvest, the rice was immediately transported to the University of Arkansas Rice Processing Lab and cleaned using a dockage tester (Carter−Day Co., Minneapolis, Minn.). Rough rice (2 kg) from each cultivar was slowly dried in thin layers at 21°C and 60% relative humidity to about 12% MC. The MC of each rice sample was measured using a single−kernel moisture tester (CTR 800E, Shizuoka Seiki, Shizuoka, Japan). General information for the three rice cultivars is listed as the first three entries of table 1.

Bending Tests

Bending tests were conducted using a texture analyzer (TA−XT2, Texture Technologies Corp., Scarsdale, N.Y.) with a three−point loading test device, as shown in figure 1. The distance between the two supporting points was set at 3.4 mm for all the bending tests. The deformation rate was set at 0.5 mm/s based on Han (1993), who found that deformation rate had little effect on bending test results. The loading head had a flat end with a thickness of 1.48 mm and width of 9.9 mm.

It should be noted that there is no standard to follow for conducting three−point bending tests of rice kernels; different experimental setups have been used in previous studies (Nguyen and Kunze, 1984; Lu and Siebenmorgen, 1995). One of the primary differences in these setups was the distance between the two points supporting the rice kernels. In the setup used by Nguyen and Kunze (1984), the distance between the two supporting points was 4.0 mm; however, the distance was 4.5 mm in the setup used by Lu and Siebenmorgen (1995), who conducted tests using only long−grain varieties. In preliminary observations during the current study, it was noted that some rice kernels, particularly shorter kernels, were cut at the ends during bending tests if the distance between the two supporting points was 4 mm or greater. In order to better estimate the breaking force resulting from bending rather than shearing, a distance between the two supporting points of 3.4 mm was chosen to accommodate both long− and medium−grain kernels tested in this approach. A flat versus a rounded loading head was used to provide a system that would allow a rapid kernel

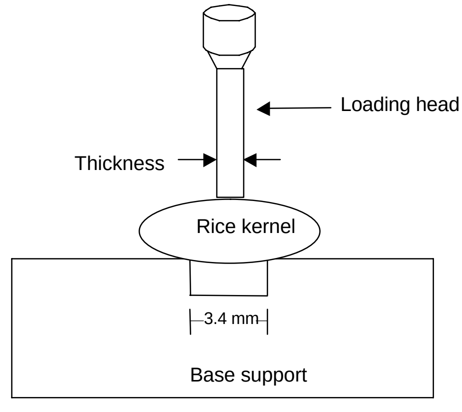

Figure 1. Schematic of the three−point bending test device. The loading head was 1.48 mm thick and 9.9 mm wide with a flat surface.

loading procedure that would minimize kernel movement during loading head contact and bending.

Before bending tests were conducted, the rice lots were equilibrated in plastic bags in a 20°C environment, and bending tests were conducted at this temperature as well. Rough rice kernels were randomly selected from each cultivar lot, and each kernel was dehulled by hand to produce brown rice kernels for the bending tests. Length, width, and thickness measurements of each brown rice kernel were made using a digital caliper. Additionally, brown rice kernels were inspected for chalkiness using a grainscope (TX−200, Kett Electric Laboratory, Tokyo, Japan). Kernels were classified as chalky if in any portion of the kernel opaque areas were detected, as described by Matsuo and Hoshikawa (1993). Totals of 435, 422, and 462 brown rice kernels of Cypress, Drew, and XL6, respectively, were tested.

Milling Tests

Two 150 g subsamples from each cultivar were milled to determine milled rice yield and HRY. The milling procedure consisted of first shelling the rough rice using a Satake huller (Satake Engineering Co., Tokyo, Japan) with a clearance of 0.48 mm between the rolls. The resulting brown rice was milled using a McGill No. 2 mill with a 1500 g weight placed on the lever arm 150 mm from the centerline of the milling chamber. Cypress and XL6 were milled for 30 s, but Drew was milled for 35 s in order to achieve similar degrees of milling (DOM). The DOM refers to the extent of bran removal during milling. Head rice was separated from brokens using a shaker table (Grainman Shaker, Grain Machinery Mfg. Corp., Miami, Fla.). The DOM was measured using a milling meter (model MM−1B, Satake Engineering Co., Tokyo, Japan) that utilizes both transmittance and reflectance measurements.

Results and Discussion

Figure 2 shows a typical brown rice kernel force−deformation curve measured during a three−point bending test. As shown in the figure, deformation was linearly related to applied load up to the break point. A significant drop in applied force indicated the break point; this force was recorded as the breaking force.

Breaking Force versus Physical Dimensions

Figure 3 shows the brown rice kernel thickness, width, and length frequency distributions for the three varieties tested.

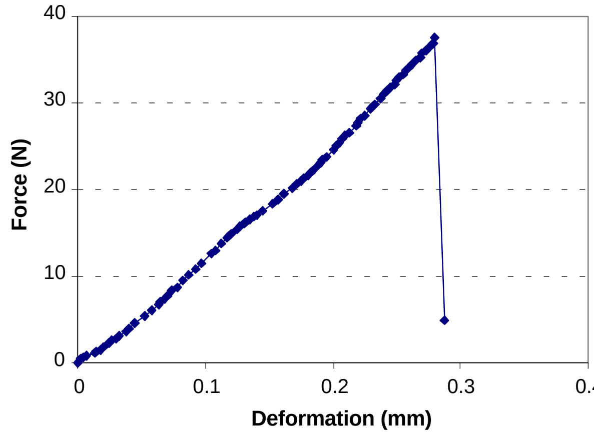

Figure 2. Typical force−deformation curve for a brown rice kernel under three−point bending.

All distributions were unimodal and normally distributed, with the exception of XL6 thickness, which showed a secondary, thin kernel mode. The relationships between breaking force and physical dimensions (length, thickness, and width) of Cypress brown rice kernels are shown in figure 4; similar relationships were found for Drew and XL6 kernels. Correlations between length or width and the breaking force of rice kernels were weak (average R^2 for the three cultivars was 0.08 for length and 0.10 for width). However, the correlation between kernel thickness and breaking force was much stronger (R^2 was 0.44 for Cypress, 0.41 for Drew, and 0.24 for XL6). It is clear that thicker kernels tended to have greater breaking forces, especially for Cypress and Drew. This is consistent with previous research (Sun and Siebenmorgen, 1993; Jindal and Siebenmorgen, 1994; Lu and Siebenmorgen, 1995).

To further elucidate the effects of kernel thickness on breaking force, graphs (fig. 5) were plotted to show the percentages of weak (breaking force <20 N) and strong (breaking force >20 N) kernels in different thickness fractions of Cypress, Drew, and XL6, respectively. It is clear that the percentage of weak and strong kernels strongly depended on kernel thickness; in turn, thickness distributions would be expected to change with harvest MC (Bautista and Siebenmorgen, 2000). Brown rice kernels in the thickness ranges of 1.3−1.4 mm and 1.4−1.5 mm were almost all weak kernels. However, the percentage of weak kernels decreased dramatically when thickness was greater than 1.6 mm. For Cypress and Drew, when kernel thickness was greater than 1.8 mm, the percentage of weak kernels was negligible.

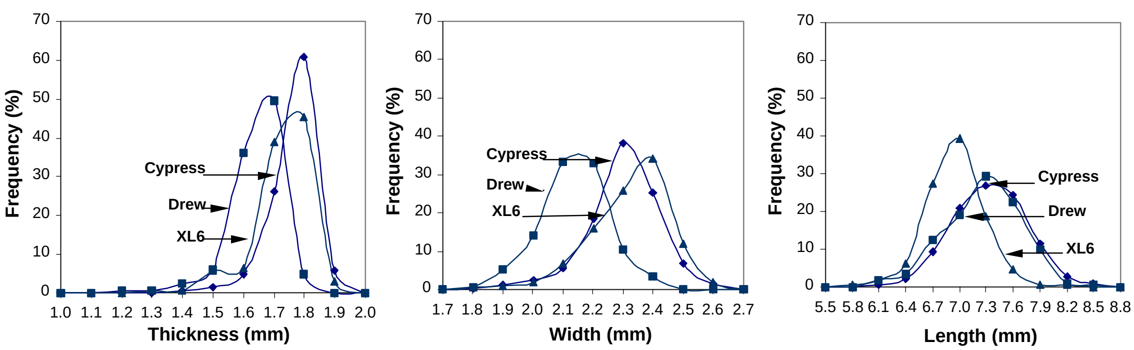

Figure 3. Brown rice kernel thickness, width, and length frequency distributions for Cypress, Drew, and XL6 varieties. Each curve represents the dimensions of 435, 422, and 462 kernels for Cypress, Drew, and XL6, respectively.

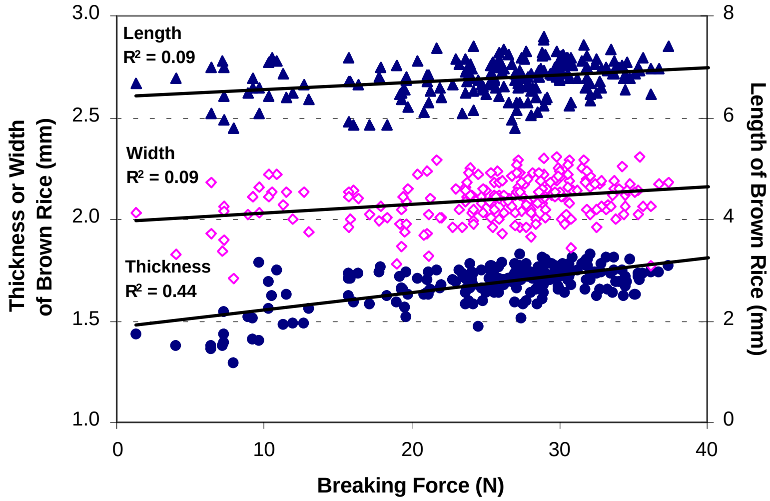

Figure 4. Physical dimensions vs. breaking force of Cypress brown rice kernels.

However, for XL6, the percentage of weak kernels was about 21% when kernel thickness was in the range of 1.8−1.9 mm. This could explain why XL6 had a weaker correlation between kernel thickness and breaking force ($R^2 = 0.24$) than Cypress and Drew.

Besides thickness, there are other factors that would be expected to affect the breaking force of rice kernels, such as the presence of fissures and chalkiness. Sharma and Kunze (1982) defined a fissure as a large internal fracture usually found to be perpendicular to the long axis of the kernel. Chalkiness in a rice kernel is an opaque section on the sides of the kernel or in the core of the kernel, and is often referred to as white belly, white core, or white back, depending upon its location on or within the endosperm (Matsuo and Hoshikawa, 1993). Both fissures and chalkiness can deteriorate the integrity of rice kernels and thus lower the fracture strength of rice kernels (Zhang, 2002). While fissure counts in the samples tested herein were not made, the number of fissured kernels in the samples would be expected to be low since the samples were harvested at high MC and dried at low temperature (Bautista and Siebenmorgen, 2000). However, chalky kernels were found in all three cultivars; the percentages of chalky kernels were 15.0%, 9.5%, and 55.0% for Cypress, Drew, and XL6, respectively. Most chalky kernels in Cypress and Drew were thin, immature kernels, but a large percentage of the chalky kernels in XL6 were found to be mature kernels. This partially explains the high occurrence of "weak" kernels in XL6, even though the thickness of these kernels was greater than 1.8 mm (fig. 5).

Breaking Force Distributions

As shown in table 1, the average brown rice kernel breaking forces were 28.5, 24.7, and 24.7 N for Cypress, Drew, and XL6, respectively. Even though Drew and XL6 had the same average breaking force, Drew had a much higher HRY than XL6 (table 1). This result indicates that the average breaking force did not accurately predict HRY. Lu and Siebenmorgen (1995) showed that the average force required to break rough rice kernels in bending was significantly correlated to HRY, but they also showed that HRY was strongly related to the percentage of rough rice kernels that failed in bending below a certain breaking force. As such, the relationship of kernel breaking force distribution (BFD) to HRY was investigated herein as a means of explaining and possibly predicting milling quality levels.

The BFDs for the three initial cultivars tested, as well as the subsequent seven samples (table 1) are shown in figure 6. Two modes were observed: one at a mean breaking force around 30 N, and another at a mean breaking force in the 10 to 15 N range, depending on the cultivar. The fundamental reason for the bimodal BFDs is not known; however, the distributions could reflect bimodal MC frequency distributions reported by Kocher et al. (1990) and Siebenmorgen et al. (1992). A hypothesis explaining these MC distributions was forwarded by Holloway et al. (1995) based on the change in MC of an individual rice kernel during its development. It is clear that Drew and XL6 had the same average breaking force (table 1); however, the BFDs were very different.

According to figure 6 and previous research (Lu and Siebenmorgen, 1995), it was justifiable to divide rice kernels into two groups: "strong" and "weak." An analysis was

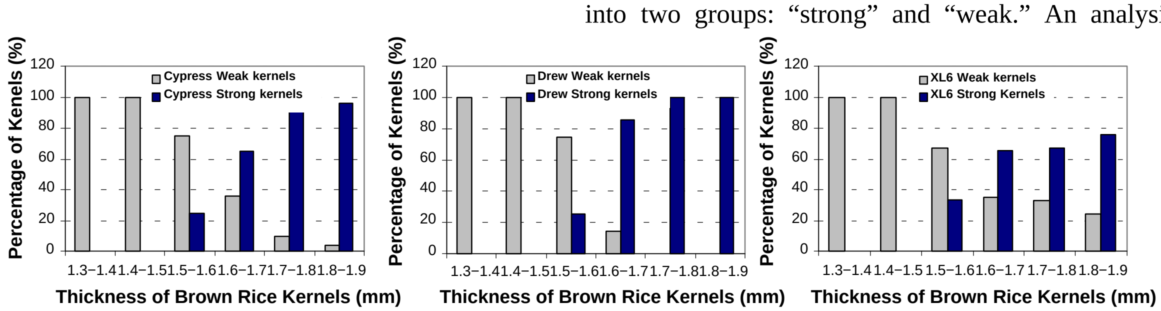

Figure 5. Percentage of "weak" and "strong" brown rice kernels in different thickness fractions of Cypress, Drew, and XL6 brown rice kernels. Strong kernels were those withstanding greater than a 20 N force in a three−point bending test.

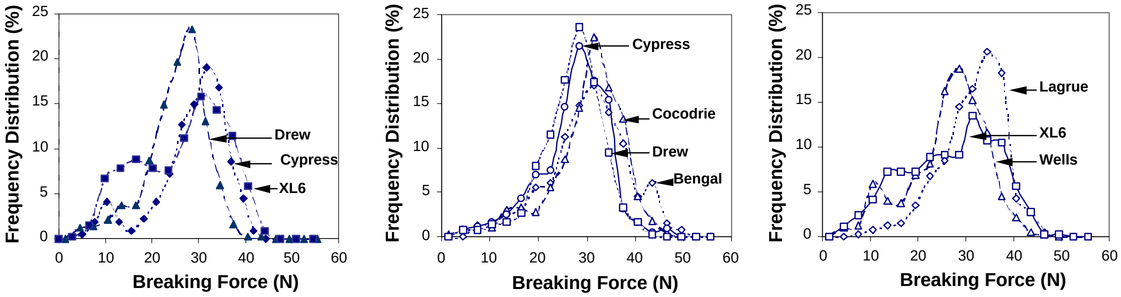

Figure 6. Breaking force distributions for the brown rice samples listed in table 1. Darkened data symbols represent the first three entries, while open symbols represent the other seven samples tested.

conducted in which HRY was correlated to the percentage of strong kernels, with the force level used to differentiate weak and strong kernels varying from 14 to 24 N. The greatest R^2 value occurred at a force level of 20 N (R^2 = 0.895). For the purposes of this study, a breaking force of 20 N was chosen as the level that separated the two groups of kernel breaking forces.

The percentages of strong kernels for the rice samples tested are listed in table 1. Although the number of strong kernels listed in table 1 is a number percentage, while HRY measures the mass percentage of head rice, the comparison still gives a clear indication as to why XL6 had the lowest HRY, since it had more than 30% weak kernels in one sample lot and more than 48% in the other.

Head Rice Yield versus Breaking Force Distribution

The percentage of strong kernels in the Cypress, Drew, and XL6 samples was closely related to HRY (darkened data symbols in fig. 7), which agrees with the postulation of Lu and Siebenmorgen (1995). HRY increased linearly with increases in the percentage of strong kernels.

In an effort to further investigate the HRY vs. percentage of strong kernel relationship described by the three darkened data symbols in figure 7, subsamples from seven additional lots harvested in 2001(table 1) were selected to conduct three−point bending and milling procedures as described above. The samples selected included both medium−grain (Bengal) and long−grain varieties obtained from various sources in Arkansas. Approximately 400 brown rice kernels of each sample lot (table 1) were exposed to three−point bending tests, and duplicate HRY measurements were made. Eight hundred kernels of a second lot of XL6 were tested to more fully investigate the properties of this cultivar. Figure 7 shows that the additional seven data points, while adding some variability, generally strengthened the linear relationship between HRY and percentage of strong kernels in a sample.

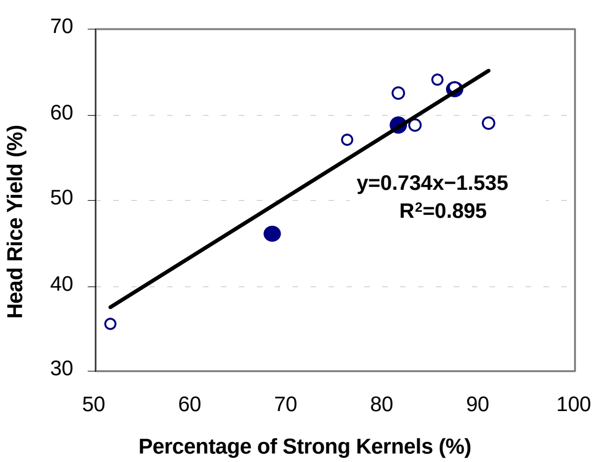

Figure 7. Percentage of "strong" kernels (kernels withstanding a 20 N force in a three−point bending test) vs. head rice yield. Darkened data symbols represent the first three entries in table 1, while open symbols represent the other seven samples tested.

It should be noted that since HRY is very sensitive to DOM (Archer and Siebenmorgen, 1995; Reid et al., 1998), rice samples should be milled to a similar DOM before relationships between the percentage of weak kernels and HRY are established. Milled rice samples can have quite different DOMs, even if they were milled under the same conditions; this is particularly true if the samples had different thickness distributions (Sun and Siebenmorgen, 1993; Chen and Siebenmorgen, 1997). In this study, the Cypress, Drew, and XL6 subsamples were milled to have similar DOMs with a range of 90 to 103 as measured with the Satake milling meter (table 1). Greater DOM values correspond to greater bran removal levels and lower HRYs. A DOM change of 10 points was shown to correspond to a HRY change of 1.0 to 1.5 percentage points (Reid et al., 1998).

Conclusions

The breaking force distributions of brown rice kernels of ten rice samples were measured using a three−point bending test. Sample HRY was linearly and directly related to the percentage of "strong" kernels within a sample. The breaking forces of brown rice kernels were not significantly related to kernel width or length, but were related to kernel thickness.

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