Influence of Drying on Rice Fissure Formation Rates and Mechanical Strength Distributions

T. J. Siebenmorgen, G. Qin, C. Jia

Abstract. *Tests were conducted to determine the effects of drying conditions on the rate of fissure formation after drying and the resultant mechanical strength distributions of individual rice kernels. Long-grain varieties Cypress, Drew, and Wells at 21% harvest moisture content (HMC) were dried at 40°C, 45°C, 50°C, 55°C, and 60°C and constant 17% relative humidity (RH) to 12% MC. Immediately after drying, the samples were placed in sealed plastic bags at 21°C. Fissure enumeration, milling tests, and individual kernel breaking force measurements were made at 1, 24, 48, and 120 h after drying ceased. Head rice yields (HRYs) decreased as drying temperature increased. Very few fissures were visible immediately after drying. Most fissures appeared within 24 h of drying cessation and corresponded to HRY reductions. There was no difference in the kernel thickness distributions of fissured and non-fissured kernels taken from the dried samples. The drying treatments produced samples having greater variation in kernel breaking forces than that of control samples. Thus, the breaking force distributions (BFDs) were affected by drying treatment, but were also affected by post-drying durations. The percentage of strong kernels in a sample, defined as those brown rice kernels withstanding a 20 N force in a three-point bending test, was strongly correlated with HRY (R^2 = 0.804, 0.835, and 0.915 for Cypress, Drew, and Wells, respectively).*

Keywords. *Bending tests, Breaking force, Drying, Fissure, Milling quality, Rice.*

Rice is typically harvested at moisture contents (MCs) of 15% to 24% (moisture contents are expressed on a wet basis unless otherwise noted) and hence needs to be dried to safe storage MCs of 12% to 13% (Bonazzi et al., 1997; Inprasit and Noomhorm, 2001). The drying process can induce internal fissuring of the kernel endosperm. Fissures drastically reduce the mechanical strength of rice kernels and typically cause kernel breakage during milling, thereby reducing HRYs.

Researchers have investigated post-drying fissure development. Sharma and Kunze (1982) reported that most fissures appeared within 48 h after drying ceased, but some additional fissures appeared up to 120 h after drying. Li et al. (1999) showed that most fissures appeared shortly after drying; the fissured kernel percentage increased rapidly in the first 4 h of post-drying, and there was no further increase in fissures beyond 48 h.

Severe drying conditions can increase the number of fissured kernels after drying (Sharma and Kunze, 1982). Arora et al. (1973) indicated that a temperature difference greater than 43°C between the drying air and rice kernels resulted in kernel cracking and that it was better to maintain the drying air temperature below a temperature of 53°C in order to minimize kernel thermal stress. Nguyen and Kunze (1984) studied the influence of post-drying environments on fissure formation, and showed that drying air temperature had a significant effect on fissuring of rough rice and that a 10°C post-drying storage temperature produced more fissured kernels than that of 45°C.

Cnossen and Siebenmorgen (2000) proposed an explanation for the cause of fissure formation during the drying process based on hygroscopic property imbalances inside kernels resulting from state transitions. They also showed that drying air temperatures above the rice glass transition temperature (Tg) could be used without reducing HRY as long as sufficient tempering was employed. Cnossen and Siebenmorgen (2000) illustrated that when drying using 60°C air, five to six percentage points of MC could be removed in a single drying pass without reducing HRYs if Cypress, a long-grain variety, and Bengal, a medium-grain variety, were tempered at 60°C for 80 and 160 min, respectively. Cnossen et al. (2003) further indicated that the post-drying tempering duration required to completely prevent fissuring was longer than that required to minimize HRY reduction. Bonazzi et al. (1997) noted that drying air temperature alone could not entirely explain the quality degradation of rice during drying, but drying rate and the drying duration were also factors. Li et al. (1999) reported that discontinuing the drying process with tempering could decrease the hydro stresses in the rice kernel, resulting in a reduction in fissure formation. They also showed that a lower intermittent ratio of drying to tempering or shorter drying pass durations could lower the percentage of fissured kernels. The results of Bonazzi et al. (1997) and Li et al. (1999) corroborate the hypothesis proposed by Cnossen and Siebenmorgen (2000).

Nguyen and Kunze (1984), in studying the effects of post-drying temperature and RH on fissure development, noted that average breaking strength of kernels was generally

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The authors are **Terry J. Siebenmorgen, ASABE Member Engineer,** Professor, Department of Food Science, University of Arkansas, Fayetteville, Arkansas; **Guoqing Qin,** Visiting Scientist, Northwest Sci-Tech University of Agriculture and Forestry, Yangling, China; and **Canchun Jia,** Postdoctoral Research Associate, Department of Food Science, University of Arkansas, Fayetteville, Arkansas. **Corresponding author:** Terry J. Siebenmorgen, Department of Food Science, University of Arkansas, 2650 N. Young Ave., Fayetteville, AR 72704; phone: 479-575-2841; fax: 479-575-6936; e-mail: tsiebenm@uark.edu.

negatively correlated to the percentage of fissured kernels at the end of a post-drying storage period. While not associated with drying experiments, Lu and Siebenmorgen (1995) also showed that the average force required to break rough rice kernels was significantly correlated to HRY; however, they also indicated that the whole kernel percentage, as determined from milling analyses, was closely related to the percentage of kernels that sustained approximately 15 N breaking force in bending. Siebenmorgen and Qin (2005) showed that samples with the same average breaking forces could have quite different kernel breaking force distributions. They also noted that the percentage of "strong" kernels (defined as kernels withstanding more than 20 N in a three-point bending test) was strongly correlated to HRY.

Nguyen and Kunze (1984) studied how average kernel breaking strength varied in post-drying environments. The subsequent work of Lu and Siebenmorgen (1995) and Siebenmorgen and Qin (2005) indicated the importance of breaking force distributions and kernel thickness in studying trends in milling quality. Given the importance of viewing kernel breaking strength from a kernel-to-kernel, distributional standpoint and the recent glass transition hypothesis addressing milling quality reduction during the drying and tempering processes by Cnossen and Siebenmorgen (2000), work was needed to quantify fissure formation rates and breaking force distributions resulting from drying/tempering treatments. As such, the objectives of this study were to measure the effects of various drying scenarios on: (1) the rate of post-drying fissure formation, and (2) the resultant kernel-to-kernel breaking force distributions.

MATERIALS AND METHODS

SAMPLE PROCUREMENT

Three long-grain varieties, Cypress, Drew, and Wells, were plot combine-harvested from the University of Arkansas Northeast Research and Extension Center near Keiser, Arkansas, on 1 October 2001 at MCs of 21.0%, 21.4%, and 20.4%, respectively. The rice was cleaned using a dockage tester (Carter-Day Co., Minneapolis, Minn.) to remove material other than grain and subsequently stored in a walk-in cooler at 4°C until May 2002 when drying experiments were conducted. Samples were stored in sealed plastic bags that were contained in sealed buckets.

DRYING

Approximately 24 h prior to drying, samples were removed from the cooler and allowed to equilibrate to 21°C while in the plastic bags. Samples were then dried in thin layers using a drying system in which a control unit (300 CFM Climate Lab-AA, Parameter Generation and Control, Inc., Black Mountain, N.C.) supplied air at desired temperatures and RHs. Approximately 90 g of rough rice was spread on each of the sixteen 152 × 254 mm perforated trays comprising the drying chamber. Each drying run consisted of setting the control unit air condition at one of five temperature settings, 40°C, 45°C, 50°C, 55°C, or 60°C, and a constant RH level of 17%, corresponding to rice equilibrium MCs of 6.4%, 6.2%, 5.9%, 5.7%, and 5.5%, respectively, according to the Chung equation (*ASAE Standards*, 2004). As the drying process commenced, sample MCs were monitored using an individual kernel moisture meter (CTR-800E, Shizuoka Seiki, Japan). When the rice MC reached approximately 12%, all 16 samples were removed from the drying chamber. Depending on the drying air conditions, the drying durations varied from 90 to 360 min to attain the desired 12% MC. The actual MCs after drying varied, depending on the drying air temperature, from 11.2% to 12.0% (average of 11.8%) for Cypress, 10.7% to 12.6% (average of 11.7%) for Drew, and 11.7% to 12.3% (average of 12.1%) for Wells.

Immediately after drying, the rice from randomly selected pairs of trays was combined and placed into eight sealed plastic bags, which were then allowed to equilibrate to 21°C. It is to be noted that, as explained by Cnossen and Siebenmorgen (2000), reduced HRYs are incurred when rice with sufficient internal MC gradients, as would be produced by high-temperature drying air treatments, is caused to undergo rapid cooling immediately after drying; this process is described in detail below.

After a 1 h duration at 21°C, two of the bags were randomly selected for fissure enumeration, breaking force tests, and HRY determinations. The same procedure was followed after 24, 48, and 120 h durations at 21°C. As such, there were eight samples produced from each drying run, with two replicate samples selected for each of the four post-drying storage durations.

As a control, two replicate 500 g samples of each variety were slowly dried from the harvest MC to 12% MC in thin layers in a large chamber controlled at 21°C and 60% RH. This slow drying procedure minimized fissure formation, and thus the milling quality of these samples represented the maximum attainable HRYs for each variety lot.

FISSURE ENUMERATION AND THREE-POINT BENDING TESTS

Two hundred rough rice kernels were randomly selected from each control and variety/drying air condition/post-drying storage duration/replicate treatment combination and dehulled by hand to avoid mechanical damage to the kernels. The thickness of each brown rice kernel was measured using a digital micrometer (62379-531, Control Co., Westwood, Texas). Each kernel was then inspected using a grainscope (TX-200, Kett Electric Laboratory, Tokyo, Japan) for the presence of fissures prior to bending force analysis.

To determine individual kernel breaking force, a three-point bending test was conducted on each of the 200 brown rice kernels using a texture analyzer (TA-XT2, Texture Technologies Corp., Scarsdale, N.Y., and Stable Micro Systems, Godalming, Surrey, U.K.) calibrated with a 5 kg (49 N) load cell. Software provided with the analyzer was used to record the force-deformation curve for each kernel, from which the force at failure was determined. The loading head was flat-faced, having a thickness of 1.5 mm and a width of 9.9 mm (fig. 1). The distance between the two points supporting a kernel was 3.4 mm for all tests, and the deformation rate was 0.5 mm/s. After placing a brown rice kernel across the supporting span, the bending test was initiated, and the maximum force attained before the kernel failed was recorded as the breaking force. Brown rice kernels withstanding more than 20 N force were categorized as "strong" kernels, based on findings reported by Siebenmorgen and Qin (2005).

MILLING TESTS

Milling tests were performed to determine the HRY of the remaining rough rice from each dried sample. Thus, a total of 42 HRY determinations were made for each variety

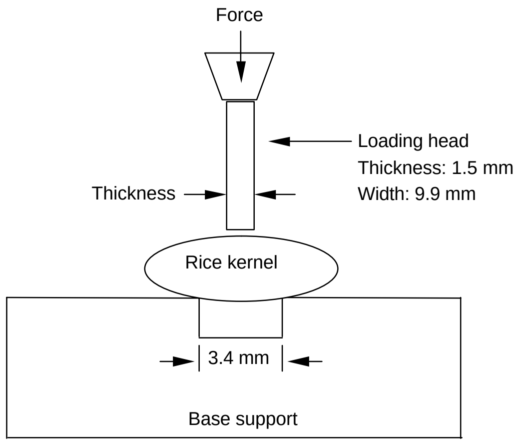

Figure 1. Schematic of the three-point bending test device.

(5 drying air temperatures × 4 post-drying durations × 2 replicates + 2 control replicates). The milling procedure consisted of first shelling 150 g of rough rice using a laboratory huller (Rice Machine THU, Satake Engineering Co., Tokyo, Japan) with a clearance of 0.48 mm between the rolls. The brown rice was milled for 35 s using a laboratory mill (McGill No. 2, Rapsco, Brookshire, Texas) with a 1500 g mass placed on the lever arm 15 cm from the milling chamber centerline. Head rice was then separated from broken rice using a shaker table (Grain Machinery Mfg. Co., Miami, Fla.). Head rice yield was calculated as the mass percentage of the original 150 g rough rice sample remaining as head rice.

Results and Discussion

Influence of Drying Temperature and Variety on Head Rice Yield

Figure 2 shows the change in HRYs for samples dried at 40°C to 60°C and placed in sealed bags at 21°C for the indicated durations. As the drying temperature increased, there was an overall corresponding decrease in HRY, although the amount of reduction in HRY varied with post-drying duration. There was essentially no HRY reduction for samples milled at the 1 h post-drying duration. However, significant HRY reductions were measured at the 24 h post-drying duration, and all of the HRY reduction that was incurred for a drying treatment occurred within 48 h after drying.

Head rice yield reduction patterns for the various drying air temperature/post-drying durations varied with variety. As most clearly indicated by the 60°C drying treatment HRY curves, Wells was the most severely impacted variety, followed by Drew and then Cypress. The Wells samples showed progressive HRY reductions as drying temperatures increased. For Cypress, there was no HRY reduction across post-drying duration for the 40°C and 45°C drying temperatures. However, higher drying temperatures produced significant ($P < 0.05$) HRY reductions for the 24 h and longer post-drying durations. For Drew, there was no significant difference in HRY response for the 40°C through 55°C drying air temperatures, but there was a significant decrease in HRY for all samples dried at these temperatures between the 1 and 24 h post-drying duration ($P < 0.05$). Additionally, the 60°C drying temperature treatment produced a dramatic decrease in HRY of Drew after 24 h of post-drying storage.

The fundamental reason for the HRY response differences among the three varieties is not apparent. Kernel thickness has been shown to be a significant factor in affecting kernel fissuring and HRY reduction (Jindal and Siebenmorgen, 1994), with the trend being that thicker kernels are generally more susceptible to fissuring than thin kernels. The average brown rice kernel thicknesses of all dried samples of Cypress, Drew, and Wells were 1.69, 1.61, and 1.69 mm, respectively. Thus, the greater HRY reductions of Wells over Drew can be at least partially attributed to the greater kernel thickness of Wells. However, this hypothesis did not hold for Cypress, which incurred the least amount of HRY reduction among the varieties for any given drying and post-drying treatment and which had an average kernel thickness equal to that of Wells. Cypress is generally known for its high and stable milling quality. Chemical compositions of the samples were not measured.

Fissure Formation

Figure 3 shows the percentage of kernels that were fissured after the various post-drying durations for each drying air temperature treatment. The percentages of fissured kernels found in the control samples were 1.0%, 1.5%, and 1.5% for Cypress, Drew, and Wells, respectively. Increasing drying temperatures resulted in progressive increases in fissured kernel percentages. The fissured kernel percentages visually correlated well with the HRY reductions shown in figure 2; this relationship is developed in subsequent sections.

An explanation of the trends in percentage of fissured kernels in figure 3 and the corresponding HRY reduction trends of figure 2 is offered by the hypothesis proposed by Cnossen and Siebenmorgen (2000). This hypothesis is based on the differences in rice kernel thermo-physical properties

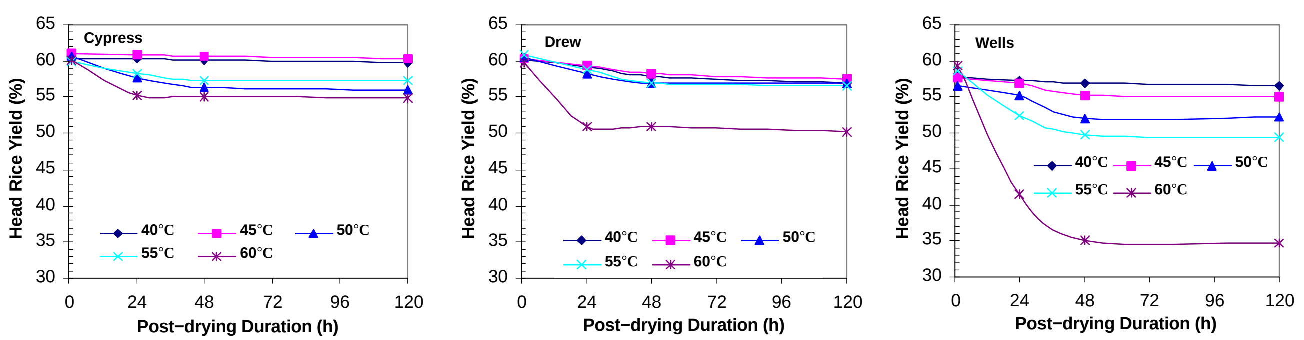

Figure 2. Head rice yields (average of two 150 g subsamples) of samples dried from approximately 21% to 12% MC using air at the indicated temperatures (constant RH of 17%) and immediately placed in sealed plastic bags at 21°C for the indicated post-drying durations. Control head rice yields for long-grain varieties Cypress, Drew, and Wells were 62.1%, 60.3%, and 59.7%, respectively.

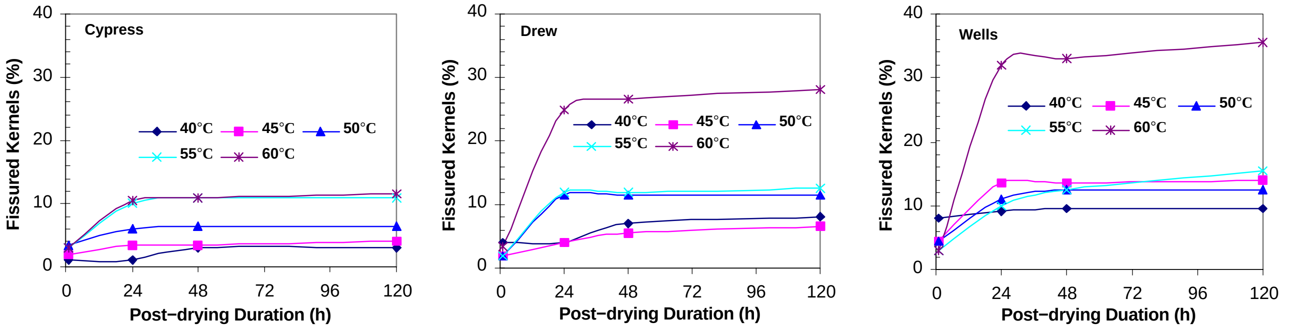

Figure 3. Fissured kernel percentage (average of two 200-kernel brown rice subsamples) of samples dried from approximately 21% to 12% MC using air at the indicated temperatures (constant RH of 17%) and immediately placed in sealed plastic bags at 21°C for the indicated post-drying durations. Fissured kernel percentages for long-grain varieties Cypress, Drew, and Wells control samples were 1.0%, 1.5%, and 1.5%, respectively.

in the glassy vs. rubbery states, corresponding to states below or above, respectively, the Tg at a given MC. For example, Perdon et al. (2000) reported dramatically greater levels of rice kernel thermal volumetric expansion coefficient above vs. below Tg. Cnossen and Siebenmorgen (2000) proposed that conditions occurring during the drying and tempering processes could lead to a significant portion of the kernel periphery transitioning into the glassy state while the center remains in the rubbery state, thus causing intrakernel material property differences. These property differences would in turn produce intrakernel differential stresses that, if severe enough, would produce material failure and fissure formation. Cnossen and Siebenmorgen (2000) demonstrated that HRY reductions from such a scenario can occur during either prolonged high-temperature drying or tempering subsequent to high-temperature drying using tempering temperatures well below Tg.

Figure 4 illustrates the hypothetical paths that kernels followed during the drying treatments at each temperature and the state point location during tempering. It is emphasized that the point locations illustrated in figure 4 correspond to the average temperature and MC of the bulk of kernels within a sample. There are large kernel-to-kernel MC differences within a sample (Bautista et al., 2005), and there are also large differences in MC from the center to surface of kernels during drying. However, figure 4 gives macroscopic indications of the kernel states during the drying and tempering process of this study.

The hypothesis proposed by Cnossen and Siebenmorgen (2000) indicates that fissures can occur if a sufficient internal kernel MC gradient is present as a significant portion of the surface of the kernel transitions from a rubbery to glassy state while the center portion of the kernel remains in the rubbery state. Figure 4 indicates that for the low-temperature drying treatments, kernels did not completely transition into the rubbery state, and thus little fissuring would be expected. Some kernels could have fissured in these low-temperature drying treatments because, while the average, bulk sample initial MC was approximately 21% for all varieties, some kernels within these samples likely would have been at a much higher MC. These kernels could have fully transitioned into the rubbery state during drying and thus could have

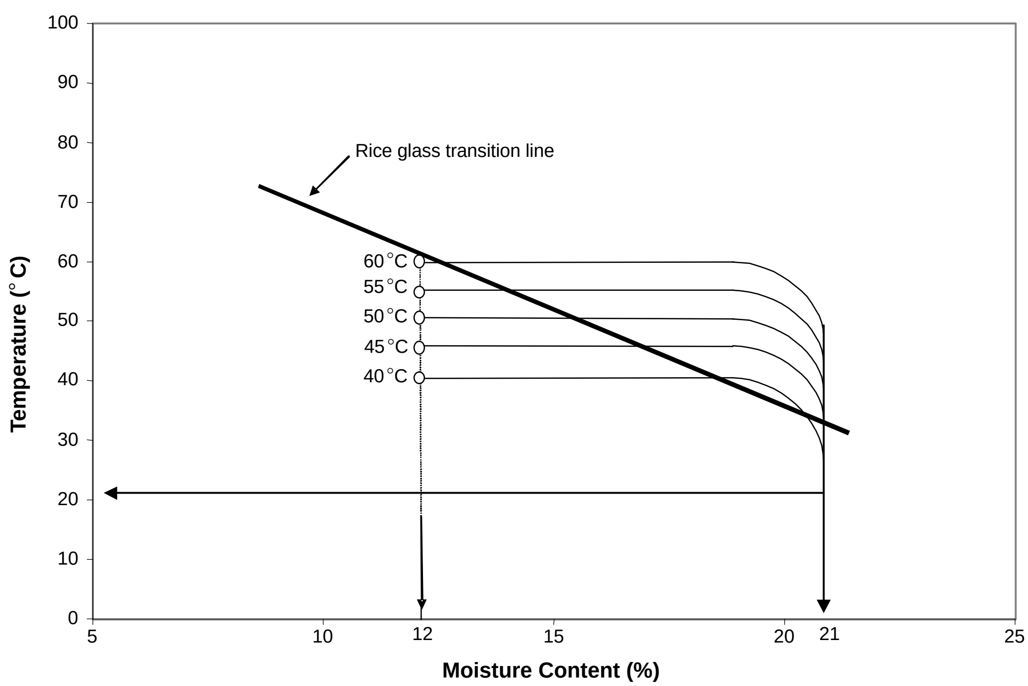

Figure 4. Drying conditions (indicated temperatures at 17% relative humidity) and tempering temperature of 21°C plotted onto a state diagram for rice.

fissured either due to extended drying or tempering at 21˚C after drying. As the drying temperatures increased, the likelihood of kernels fully transitioning into the rubbery state increased, as did the propensity for fissuring either through extended drying or tempering. The trend of progressive increases in fissuring with increasing drying temperatures is generally shown for all varieties in figure 3.

Little to no fissuring (fig. 3) and HRY reduction (fig. 2) were measured at the 1 h post-drying duration. However, practically all fissures occurred within 24 h after drying regardless of drying temperature and variety (fig. 3). This result was consistent with previous reports (Nguyen and Kunze, 1984; Li et al, 1999). The kinetics of fissure formation and propagation in rice kernels have not been fully quantified. However, the data from this study indicate that the visual appearance of fissures occurred almost entirely within 24 h of drying cessation and was completed by 48 h.

Individual Brown Rice Kernel Breaking Force Distributions

Figure 5 shows the BFDs for Cypress, Drew, and Wells samples at 1, 24, and 48 h after drying using the control, 40˚C, and 60˚C drying treatments. In all varieties, the control sample BFDs approximated a normal distribution; the mode varied with variety, ranging from approximately 24 N for Drew to 30 N for Wells to 32 N for Cypress. The cause of these varying mode levels is speculated to be due to varietal differences in kernel thickness, but also kernel width, since both determine the cross-sectional area that in large part determines the breaking force required to break a kernel. Only kernel thickness was recorded and used in this analysis due to the findings of Siebenmorgen and Qin (2005), who showed a much stronger correlation of breaking force to kernel thickness than width.

The BFDs of kernels exposed to the drying treatments exhibited a primary, yet broad peak that ranged from approximately 25 to 50 N. A secondary mode was also observed at approximately 8 N. More apparent in the Drew and Wells varieties, yet still observable in Cypress, was the trend that increasing drying treatment severity produced decreasing numbers of kernels in the high breaking force band and increasing numbers of kernels in the low breaking force band. The reason for this was the increasing number of fissured kernels, with correspondingly low breaking forces caused by more severe drying treatments (fig. 3). The mode for the weakened kernels was consistent at 8 N across varieties. Comparing the BFDs of the samples dried under control and elevated temperature treatments, it is apparent that the drying treatments caused more dispersed BFDs. As drying temperature increased, the BFD peaks of weak kernels increased in magnitude and were tightly centered at a mode of 8 N, while the peaks for strong kernels lessened in magnitude and became much more dispersed.

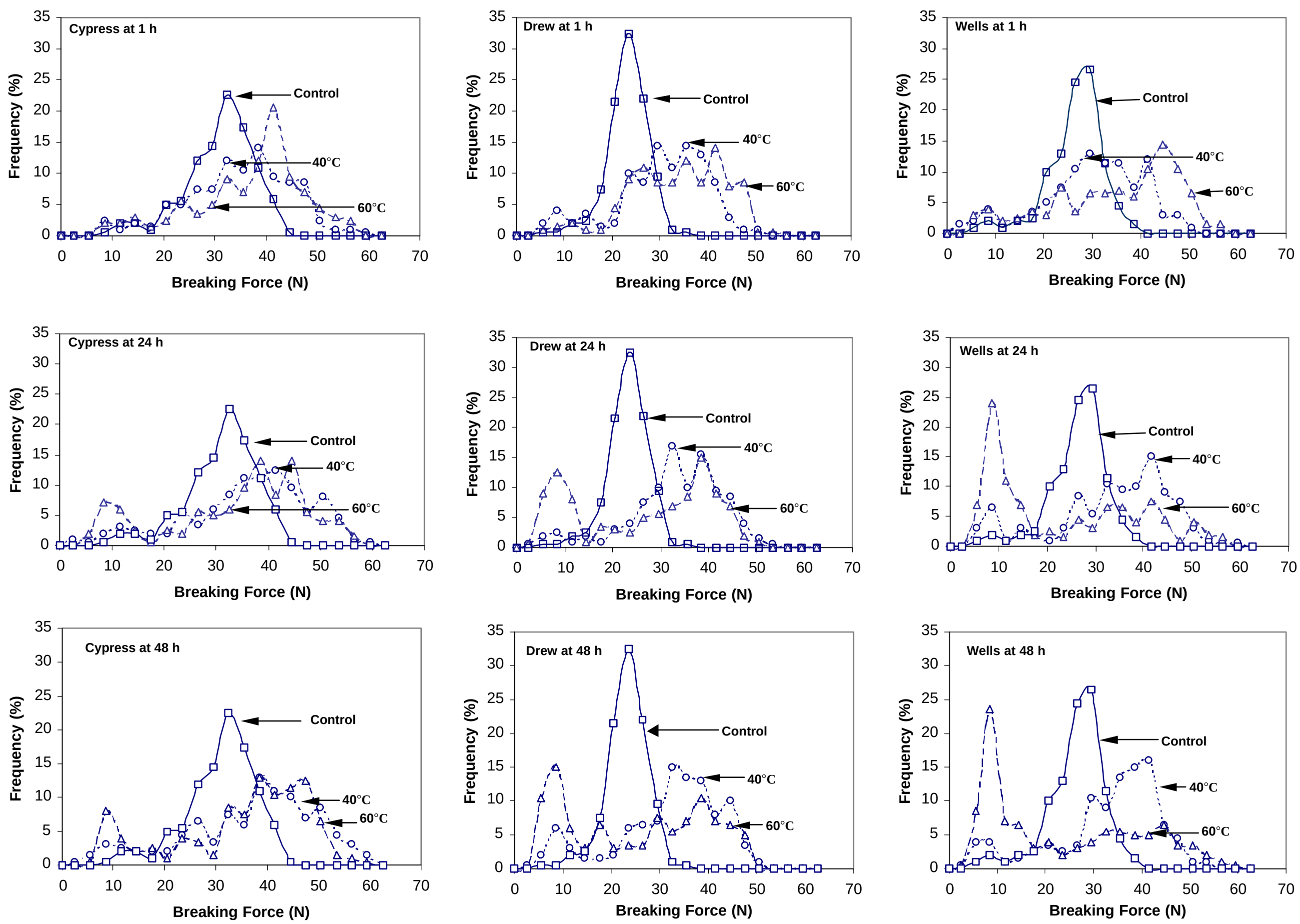

Figure 5. Breaking force distributions for Cypress, Drew, and Wells brown rice kernels. Each curve was generated using two 200-kernel brown rice subsamples selected from rough rice samples dried from approximately 21% to 12% MC using the indicated air temperatures and 17% RH and immediately placed in sealed plastic bags at 21˚C for 1, 24, or 48 h post-drying durations. The control samples were dried at 21˚C and 60% RH.

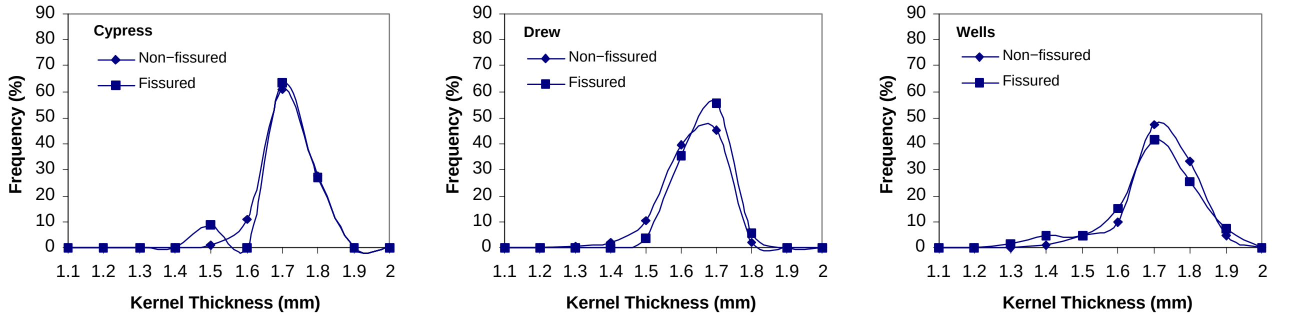

Figure 6. Thickness frequency distributions of non-fissured and fissured brown rice kernels. Data were taken from rough rice samples dried from approximately 21% to 12% MC using 60°C air and 17% RH and held in sealed plastic bags at 21°C for a post-drying duration of 48 h. The average thicknesses for long-grain varieties Cypress, Drew, and Wells samples dried under control conditions of 21°C and 60% RH were 1.67, 1.63, and 1.70 mm, respectively.

There were strong linear correlations between the percentage of fissured kernels and percentage of weak kernels (kernels with breaking forces <20 N) within each variety; the correlation coefficients (r) were 0.835, 0.712, and 0.959 for Cypress, Drew, and Wells, respectively. This indicates that the increase in weak kernels could largely be attributed to the increase in fissured kernels. Strong negative correlations at a $P < 0.01$ level were found between the percentages of fissured kernels and HRYs (−0.742 for Cypress, −0.862 for Drew, and −0.950 for Wells).

Individual Kernel Thickness Distributions

Figure 6 shows the kernel thickness distributions for fissured and non-fissured kernels dried at 60°C and 17% RH and then held in sealed plastic bags at 21°C for 48 h. The expected trend in the thickness frequency distributions within each variety was that there would be a difference in modes of fissured and non-fissured kernels. Jindal and Siebenmorgen (1994) showed that thicker kernels were more susceptible to fissuring due to moisture adsorption. Fan et al. (2000) showed that the HRY reduction of Bengal, a medium-grain and bold kernel variety, was greater under the same drying conditions as Cypress, a long-grain and more slender kernel variety. The expected trend that thicker kernels within a variety would be more prone to fissuring was not evident, as figure 6 indicates that even for the most severe drying air temperature (60°C), there were no apparent differences in fissured and non-fissured kernel thickness distributions.

Strong Kernel Percentages

The BFDs shown in figure 5 indicate that 20 N is an acceptable breaking force level to separate low and high BFD peaks. Using this criterion to differentiate “strong” from “weak” kernels, figure 7 shows the trends in strong kernel percentages vs. post-drying duration for each drying air temperature treatment for each variety. The strong kernel percentage generally decreased with increases in drying air temperature and post-drying duration, although the trends varied with variety. The trends in figure 7 closely resemble those of the HRY curves of figure 2.

Correlating Head Rice Yield to Breaking Force Distribution

Figure 8 displays a strong relationship between HRY and the percentage of strong kernels (R^2 values of 0.804, 0.835, and 0.915 for Cypress, Drew, and Wells, respectively). The R^2 values indicate that the breaking force distribution of the lots in each variety accounted for a large amount of the variation in HRY due to drying treatments. Furthermore, figure 8 shows that when all lots of the three varieties were combined into a single correlation, the R^2 value was 0.870.

Summary and Conclusions

Drying and three-point bending experiments were conducted to investigate the influence of drying air treatment and post-drying duration on individual kernel BFDs and milling quality using three long-grain varieties (Cypress, Drew, and Wells). Most fissures appeared within 24 h after drying

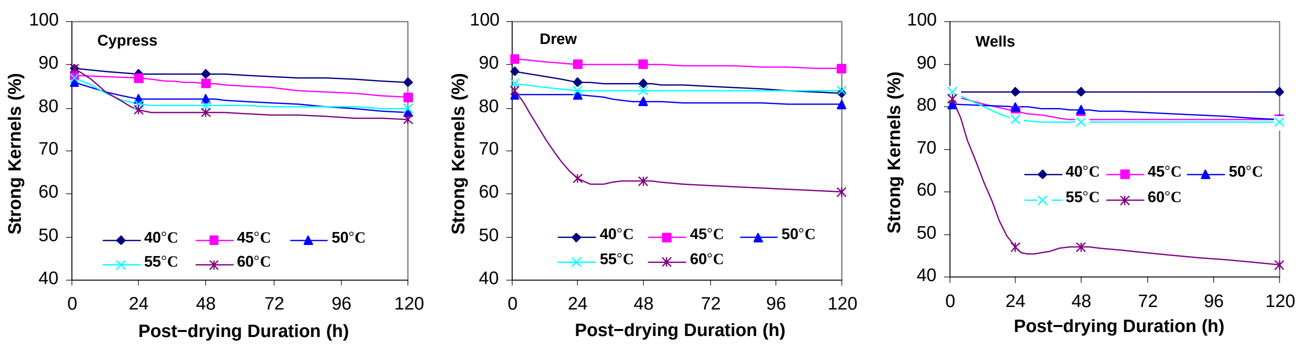

Figure 7. Strong kernel percentages (average of two 200-kernel brown rice subsamples) of samples dried from approximately 21% to 12% MC using air at the indicated temperatures (constant RH of 17%) and immediately placed in sealed plastic bags at 21°C for the indicated post-drying durations. Strong kernels were defined as those withstanding more than a 20 N force in a three-point bending test. Strong kernel percentages of long-grain varieties Cypress, Drew, and Wells control samples were 90%, 89%, and 85%, respectively.

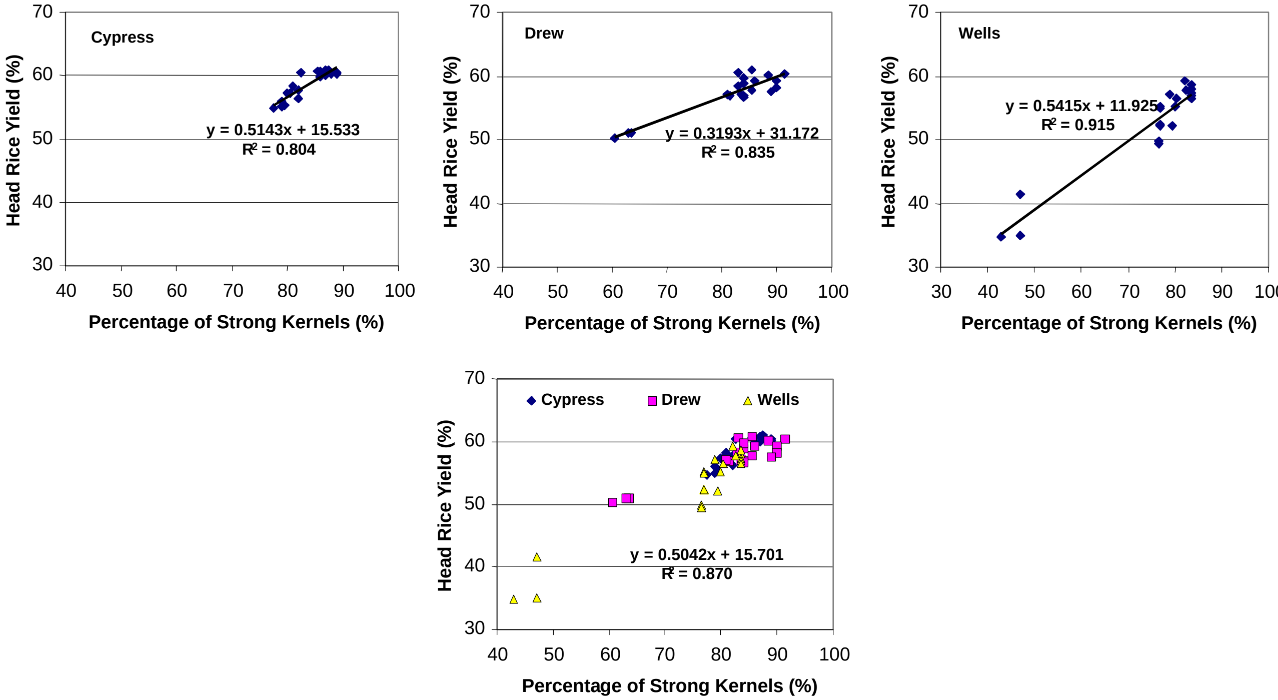

Figure 8. Correlation of head rice yield (average of two 150 g subsamples) to percentage of strong kernels for the indicated long-grain varieties. Rough rice samples were dried from approximately 21% to 12% MC using air at 40°C, 45°C, 50°C, 55°C, and 60°C (RH was held constant at 17%) and immediately placed in sealed plastic bags at 21°C air for post-drying durations of 1, 24, 48, and 120 h. Percentage of strong kernel data were generated from 200-kernel brown rice subsamples from the same samples as was used for milling analyses.

ceased, whereas few fissures were apparent immediately after drying. As drying temperature increased, the fissured kernel percentage generally increased at given post-drying durations across the three varieties.

A 20 N breaking force was used as the criterion to differentiate "strong" from "weak" kernels. The BFDs of the control-dried samples approximated a normal distribution; however, the BFDs of drying treatment samples exhibited a primary and broad peak of strong kernels and a secondary peak of weak, fissured kernels having a BF mode at approximately 8 N. Increasing the drying temperature decreased the number of kernels in the high BF peak and increased the number of kernels in the low BF peak. In relating BFD parameters to milling quality, the strong kernel percentage, using the 20 N criterion, was a good predictor of HRY with R^2 values from 0.804 to 0.915 across the three varieties.

Acknowledgements

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