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Rice fissuring response to high drying and tempering temperatures ☆

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Abstract

The objective of this study was to determine the effect of drying and tempering treatments on rice kernel fissuring at temperatures above and below the glass transition temperature (T_g). This information was correlated with head rice yield (HRY) data to determine optimum drying and tempering strategies to maximize milling quality and kernel physical integrity. Samples were dried under three different drying air conditions for various durations and then tempered for various durations at the temperature of the drying air. Results showed that the percentage of fissured kernels decreased with increasing tempering duration for typical drying durations (i.e., 3–5% points moisture content reduction in one pass). Some samples still had many fissured kernels after extended tempering, yet had a high HRY, equivalent to the control sample. This indicates that the tempering duration required for preventing kernel fissuring might be longer than the tempering duration required for maintaining a high HRY.

Keywords: Rice; Fissuring; Drying; Tempering; Glass transition; Grain quality

1. Introduction

1.1. Rice fissuring

Rice kernel fissuring is a major rice industry problem. Fissured kernels may break during the milling process and thus reduce head rice yield (HRY). HRY is the current standard to assess commercial rice milling quality, and is defined as the weight percentage of rough rice that remains as head rice (kernels that are at least 3/4 of the original kernel length) after complete milling. HRY reduction decreases the value of rice since broken kernels are typically worth half the value of head rice. Kunze and Hall (1965) stated that a rice kernel with two or three cross-sectional fissures has lost its commercial value.

Fissuring can occur in the field prior to harvest, or during harvesting, processing, and storage. Improper drying and tempering processes can be a major cause of fissuring (Ban, 1971; Kunze & Choudhury, 1972; Kunze, 1979; Sharma & Kunze, 1982; Nguyen & Kunze, 1984; Bautista, Siebenmorgen, & Cnossen, 2000; Cnossen & Siebenmorgen, 2000). Understanding the effects of drying and tempering processes on rice kernel fissuring is important to control and optimize drying and tempering conditions for maximizing milling quality.

Theories on fissure formation, as a result of drying, are based on the response of rice kernels to tensile and compressive stresses due to moisture content (MC) [1] gradients within the kernel (Kunze & Choudhury, 1972). Several researchers (Ban, 1971; Kunze, 1979; Sharma & Kunze, 1982; Nguyen & Kunze, 1984) observed that fissures did not occur until after drying had ceased. Sharma and Kunze (1982) stated that few whole rough rice kernels would fissure during the drying process itself. Severe drying conditions increased the number of kernels that fissured after drying. Since most kernels are not fissured immediately after drying, Sharma and Kunze (1982) suggested that '... some post-drying treatment or procedure can be developed that will prevent the subsequent fissures'.

1.2. Post-drying treatment

Commercial dryers use multi-pass procedures to remove moisture from freshly harvested rice. The rice is

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[1] All moisture contents are expressed on a wet basis.

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tempered by being held in bins between drying passes to reduce the MC gradients within kernels created during drying, to achieve equilibration. MC gradients cause differential stress inside the kernel, which, if sufficiently large, causes the kernel to fissure (Kunze, 1979). Proper tempering using high temperatures can minimize kernel damage, as measured by HRY, from severe drying conditions (Wasserman, Ferrel, Houston, Breitweiser, & Smith, 1964; Nguyen & Kunze, 1984; Cnossen, Siebenmorgen, Reid, & Yang, 1999; Cnossen & Siebenmorgen, 2000).

High tempering temperatures maintain high HRYs, and decrease the required tempering duration. Wasserman et al. (1964) showed increasing HRY and decreasing tempering duration with increasing tempering temperature for a short-grain rice variety dried using 43.3 °C air. HRY was 2.0% higher for rice tempered warm (40.6 °C) compared to rice tempered cold (23.8 °C). Samples tempered at 40.6 °C required 4 h of tempering while samples tempered at 23.8 °C required 6 h. Steffe and Singh (1980) found similar trends of decreasing tempering duration with increasing temperature. Nguyen and Kunze (1984) concluded that a storage temperature of 45 °C after drying reduced the number of fissured kernels by an average of 25.5% compared to a storage temperature of 10 °C, when drying variety Brazos rice at 60 °C.

1.3. Glass transition effect

Cnossen and Siebenmorgen (2000) developed a hypothesis incorporating the glass transition temperature (T_g) concept to explain rice kernel fissuring during drying and tempering. This hypothesis incorporates the transition of kernels from a "glassy" to a "rubbery" state, and vice versa, as the MC changes. The state change of kernels, as they go through a glass transition, has an important role in rice drying and tempering in terms of kernel fissuring potential (Perdon, Siebenmorgen, & Mauromoustakos, 2000). Rice kernels' thermal and material properties change depending on the temperature and MC gradients generated during processing (Slade & Levine, 1991, 1995). Perdon et al. (2000) concluded that this state transition occurs in the temperature range typically used in rice drying.

Perdon et al. (2000) showed that the physical properties of a rice kernel changed dramatically as the kernel temperature passed through T_g. At a temperature and MC below T_g, starch exists as a 'glassy' material, with low expansion coefficients, specific volume, and diffusivity. As the kernel temperature increases beyond T_g, the starch transitions from a 'glassy' to a 'rubbery' state. Above T_g, starch exists as a rubbery material with higher expansion coefficients, specific volume, and diffusivity (Slade & Levine, 1991, 1995).

During drying, the kernel temperature will increase and moisture will diffuse from the kernel. A temperature and an MC gradient will develop from the surface to the center of the kernel. The temperature gradient will disappear within 2 min and it is generally agreed upon that temperature variations in the kernel can be neglected after a few minutes of drying (Yang, Jia, Siebenmorgen, Howell, & Cnossen, 2000). The MC gradient, however, plays a much more important role during and after drying. During the tempering stage, following a drying pass, moisture will migrate from the center to the surface of the kernel and consequently the MC gradient will decrease (Kunze, 1979). If the tempering air temperature is below the T_g of the rice, the kernel will cool and go through a glass transition and become glassy as the kernel temperature decreases. It is hypothesized (Cnossen & Siebenmorgen, 2000) that if a sufficient MC gradient exists in the kernel and the tempering environment is one that produces a change of state of the starch (transitioning from the glassy to the rubbery state), the different sections of the kernel, resulting from the temperature and MC gradients, cross the T_g line at different MC values. Because of the large differences in kernel properties between the rubbery and the glassy states, specifically the thermal expansion coefficients (Perdon et al., 2000), differential stresses within the kernel could cause kernel fissuring. This is illustrated in situation 'B' in Fig. 1, which shows the path that could be followed by the surface, mid-point between the surface and the center, and the center of the kernel for a tempering temperature below T_g. The hypothesis indicates that this scenario would create kernel fissuring, with resultant HRY reduction, if there were a sufficient MC gradient inside the kernel. This hypothesis is consistent with the observations that rice kernels fissure after the drying process has ceased (Ban, 1971; Kunze, 1979; Nguyen & Kunze, 1984; Sharma & Kunze, 1982)

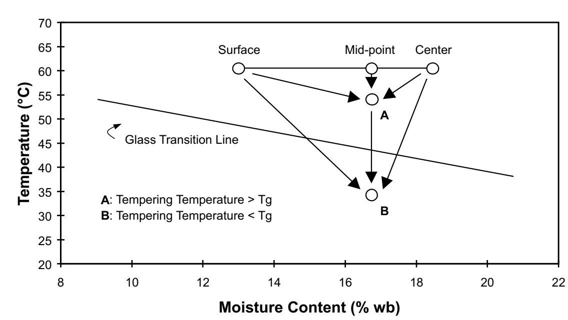

Fig. 1. Moisture content gradient inside a rice kernel at the end of drying and a hypothetical response of the various sections of a kernel during tempering for two tempering scenarios. The glass transition line represents the temperatures at which the rice transitions from a glassy (below T_g) to a rubbery state (above T_g) or vice versa. Surface, mid-point, and center refer to the surface, mid-point between the surface and the center, and the center of a rice kernel (Cnossen & Siebenmorgen, 2000).

and that fissuring levels are higher at lower tempering temperatures compared to higher tempering temperatures (Nguyen & Kunze, 1984).

Cnossen and Siebenmorgen (2000) concluded that tempering rice immediately after drying had a significant effect on HRY when, (a) the drying air conditions produced sufficient MC gradients inside the kernel, and (b) tempering conditions produced a state transition that placed the kernel, or parts of the kernel, into the glassy region. In the experiments by Cnossen and Siebenmorgen (2000), varieties Bengal (medium-grain) and Cypress (long-grain) were dried under two conditions with drying air temperatures above the T_g of the rice (60 °C, 17% relative humidity (RH)) resulting in 5.5% equilibrium moisture content (EMC) and 60 °C, 50% RH, resulting in 9.2% (EMC). For both varieties and both drying air conditions, 5.0–6.0% points MC (PPMC) could be removed in a single drying pass without reducing HRY, if the rice was tempered at 60 °C before cooling to 21 °C. For Bengal (with a harvest MC between 17% and 21%), this tempering duration ranged from 160 to 200 min and for Cypress (with a harvest MC between 17% and 22%), a tempering duration of 80–120 min was sufficient. This was based on achieving HRYs equivalent to that of gently dried control samples.

Cnossen and Siebenmorgen (2000) evaluated the effect of drying and tempering on milling quality by measuring HRY. However, Henderson (1954) and Matthews, Abadie, Deobald, and Freeman (1970) concluded that some fissured kernels would not break during the milling process and would remain as head rice. Fissured kernels may alter cooking and puffing processes and/or break during end-use processing and subsequent handling (Siebenmorgen, 1998). The breakage of kernels will reduce the quality of the final product and/or produce significant waste. HRY therefore may not be the most accurate indicator to assess the effect of drying and tempering processes on rice kernel physical integrity.

An understanding of the effect of various drying and tempering treatments on fissure occurrence, and the relation between fissure occurrence and breakage/HRY reduction will provide end-users, such as cereal and cooked-rice product manufacturers, with information to optimize their processing operations. Because of the paramount importance of milling quality and kernel physical quality, understanding this relationship would greatly improve the value, and thus the sustained profitability, of rice. Therefore, the objectives of this study were to: (a) determine the effect of various drying and tempering treatments, based on the glass transition hypothesis, on fissure occurrence, and (b) correlate fissure occurrence data and HRY data to determine optimum drying air conditions and minimum tempering durations to maximize both HRY and kernel physical integrity.

2. Procedures

2.1. Drying and tempering treatments

Rice varieties Bengal (medium-grain) and Cypress (long-grain) were harvested between 17% and 21% MC, from University of Arkansas Research and Extension Centers at Stuttgart and Keiser, Arkansas, US in 1999 and 2000. Immediately after harvest, the rice was cleaned with a Carter-Day Dockage tester (Carter-Day Co., Minneapolis, MN).

The experimental design consisted of drying experiments with the drying air and tempering temperatures above and below the T_g of the rice. The drying air conditions were those used by Cnossen and Siebenmorgen (2000): condition HI (60 °C, 17% RH), resulting in 5.5% EMC as predicted by the Chung equation (ASAE, 1999); condition HII (60 °C, 50% RH), resulting in 9.2% EMC; and condition LI (40 °C, 12% RH), resulting in 5.8% EMC. Thin-layer (3–5 mm) drying was achieved by using perforated trays, allowing the air to flow through the grains, in drying chambers in which the drying air conditions were controlled by a PG & C unit (Parameter Generation & Control Inc., Black Mountain, NC) delivering air at controlled temperature and RH. For each drying condition, samples were dried for three different durations with the intent of removing 3.0, 4.5, and 6.0 PPMC. The different magnitudes of MC gradient, created by these different drying durations, provided information on the maximum allowable MC gradient inside a rice kernel before it fissured. Fig. 2 illustrates the experimental design. Weight loss of the rice was monitored during drying to allow cessation of drying at the desired MC reduction. After each drying run, the actual MC loss of the sample was calculated by determining its MC after drying using the oven method (drying duplicate 15-g samples for 24 h in an oven set at 130 °C) described by Jindal and Siebenmorgen (1987).

Immediately after a drying run, the rice batch was split into four sub-samples. One sub-sample was immediately cooled (labeled: 0 min tempering) by placing it in a chamber set at 21 °C and 50% RH; this sub-sample was left in the chamber to gently dry to 12.5% MC. The chamber had forced air movement, allowing the samples to cool rapidly to 21 °C, while drying took between 1 and 3 days depending on the MC of the sample. Cooling the kernels to 21 °C, which is well below the T_g of the rice (as can be seen in Fig. 1), forced the kernels dried under condition HI and HII to undergo a state transition from the rubbery to the glassy state. The other sub-samples were tempered in sealed bags for either 80, 160 or 240 min at the temperature of the drying air before being taken out of the sealed bags to cool and dry in the 21 °C/50% RH chamber to 12.5% MC. The different drying durations created different magnitudes of MC gradients inside the kernel. Subsequently, the different

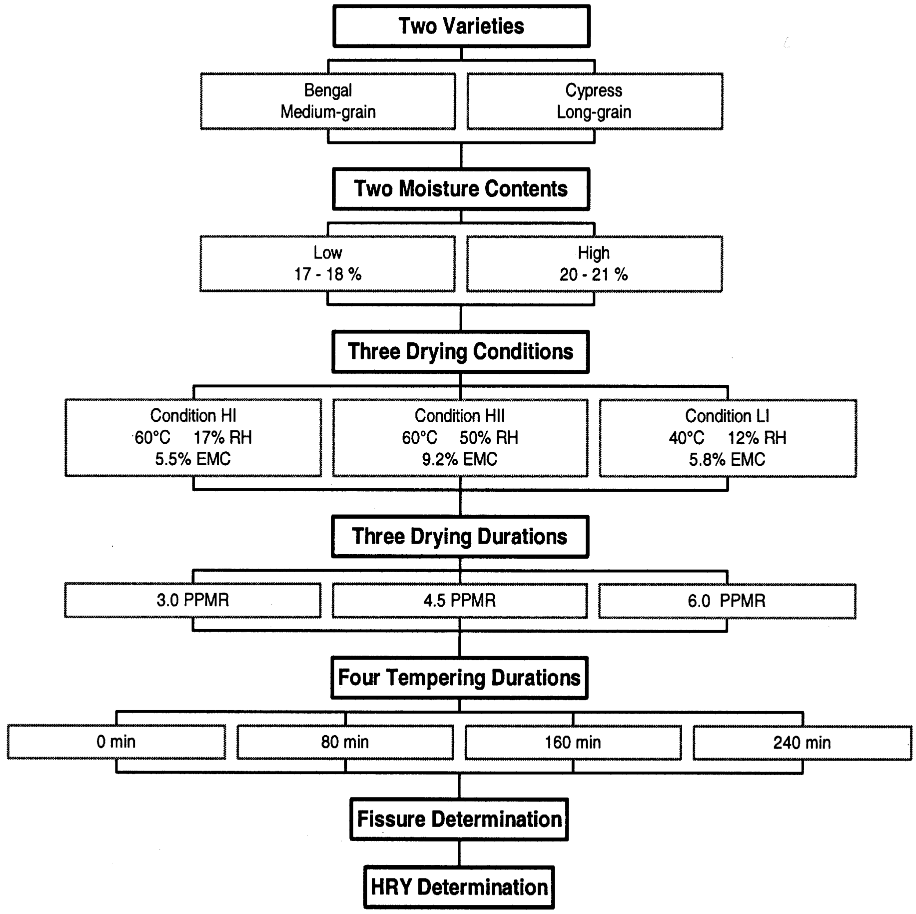

Fig. 2. Experimental design. RH is the relative humidity of the drying air, EMC is the equilibrium moisture content of the drying air, PPMR is the percentage points of moisture removed in one drying pass, and HRY is the head rice yield.

tempering durations allowed different magnitudes of MC gradient relaxation, i.e., a tempering duration of 0 min resulted in maximum MC gradient while extended tempering resulted in reduced gradients. This resulted in various levels of fissuring when the kernels were cooled and forced to undergo a state transition.

As a means of control, two samples of rice from each harvest lot were gently dried in the 21 °C/50% RH chamber from harvest MC to 12.5% MC, resulting in minimal breakage and consequently a high HRY. HRY and the percentage of fissured kernels of the samples having received different treatments were compared against the HRY and the percentage of fissured kernels of these control samples.

2.2. Fissure counting

Research (Sharma & Kunze, 1982) has shown that fissures can appear even after extended periods of time past drying. Therefore, the rice was stored at 21 °C for 2 months after the drying treatments prior to fissure counting and HRY determination. After storage, the rice was hulled with a laboratory huller (Satake, Houston, TX). The immature and chalky kernels were separated and two times 200 brown rice kernels were randomly picked from each sample for determining the percentage of fissured kernels.

Since this project aimed at characterizing the number and types of fissures, as well as correlating the percentage of fissured kernels to HRY, a non-destructive way of observing fissures had to be used. Therefore, one person using a light box visually observed the kernels. The light box was a rectangular box that had blackened walls and bottom, and had a glass top. The glass top was also blackened except for a 3.0-mm wide band across the middle, which allowed light from a light bulb inside the box to pass out of the box. Kernels were then placed on top of this band and the fissures observed by moving the kernels across this band into the shadowy region. This made the fissures appear as an obscured fraction of the kernel. The number of kernels having surface cracks was also recorded. Fig. 3 illustrates classification of the fissures.

After fissure counting, the 400 kernels were returned to the dried sample to be milled for 30 s in a McGill no. 2 laboratory mill, resulting in a degree of milling of 80–90

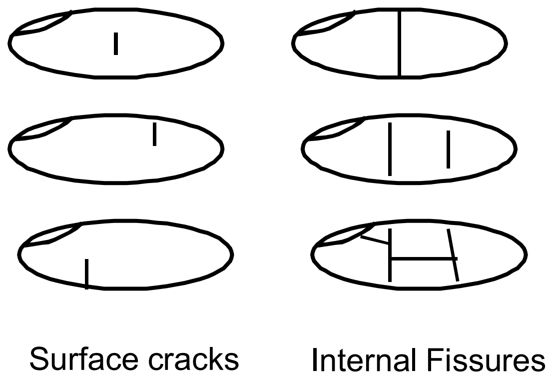

Fig. 3. Characterization of different types of fissures.

as measured with a Satake MM-1B milling meter (Satake, Houston, TX). The resulting mass of head rice in the milled sample was determined using a FOSS Graincheck 310 image analyzer (Foss North America, Minneapolis, MN) and the HRY was calculated as the mass fraction of rough rice remaining as head rice.

Statistical analyses, at a significance level of $\alpha = 0.05$, were performed using the software package JMP (SAS Institute, Inc., Cary, NC).

3. Results and discussion

Cnossen and Siebenmorgen (2000) concluded that if rice is sufficiently tempered above the T_g to reduce MC gradients, a rubbery to glassy state transition would not cause HRY reduction, if irreversible damage had not yet occurred. Insufficient MC gradient reduction before a state transition will produce fissures and consequent HRY reduction. This research confirms the conclusion by Cnossen and Siebenmorgen (2000), however, the results provide additional insight in the fissuring and breakage relationship. The most dramatic data is illustrated in Figs. 4–6, while Tables 1 and 2 show all the results for a Bengal and a Cypress lot respectively. Fig. 4 shows the percentage of fissured kernels and the HRY versus tempering duration relationships for Bengal rice (harvested in 1999) after removing 2.9 and 4.5 PPMC using 60 °C and 50% RH drying air. Removing 2.9 PPMC without tempering (0 min tempering duration) resulted in a significantly lower HRY than the HRY of the gently dried control sample. However, the sample that was tempered for 80 min at 60 °C showed no significant HRY reduction compared to the control sample, indicating that a tempering duration of 80 min was necessary to maintain a HRY equivalent to that of the control when removing 2.9 PPMC. Extended tempering (160 and 240 min) did not further improve HRY. When removing 4.5 PPMC, 160 min of tempering was necessary to maintain a HRY equivalent to that of the control sample. These results agree with the tempering dura-

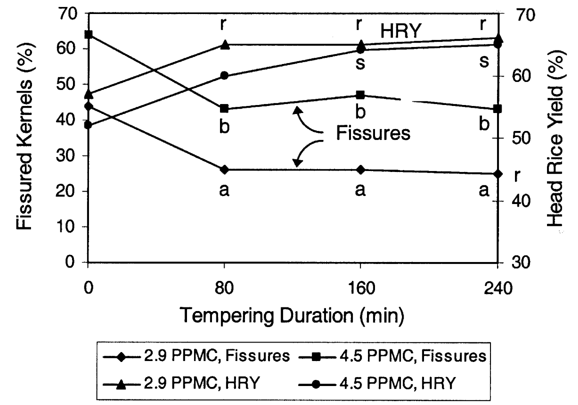

Fig. 4. Percent fissured kernels and HRY versus tempering duration for Bengal rice harvested in 1999 and dried for two different durations (PPMC is the percentage points MC removed in one drying pass) with 60 °C and 50% RH drying air. The percentage of fissured kernels and the HRY of the control sample were 24% and 65%, respectively. The harvest moisture content was 17.5%. Values with the same letter are not significantly different.

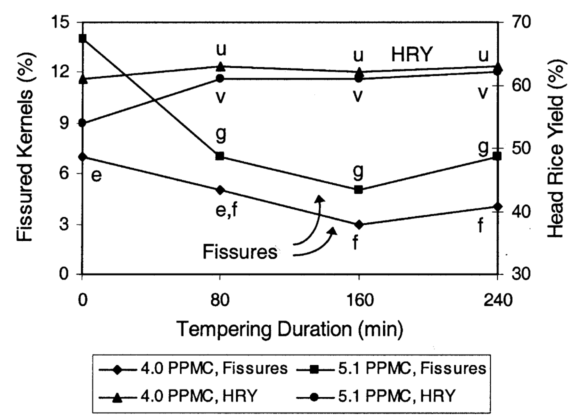

Fig. 5. Percent fissured kernels and HRY versus tempering duration for Cypress rice harvested in 1999 and dried for two different durations (PPMC is the percentage points MC removed in one drying pass) with 60 °C and 17% RH drying air. The percentage fissured kernels and the HRY of the control sample were 3% and 63%, respectively. The harvest moisture content was 18.0%. Values with the same letter are not significantly different.

tions, required to maintain high HRYs, found by Cnossen and Siebenmorgen (2000).

For the 2.9 PPMC drying duration, the percentage of fissured kernels showed a similar trend as the HRY; 80 min of tempering was sufficient to prevent no more fissured kernels than the control sample. When removing 4.5 PPMC, tempering for 80 min also significantly reduced the number of fissured kernels. However, longer tempering durations did not further reduce the number of fissured kernels. Although the samples tempered for 160 and 240 min had a HRY equal to that of the control sample, these samples still had a significantly higher number of fissured kernels (47% and 43%, respectively) than the control sample (24%). Thus, a large percentage

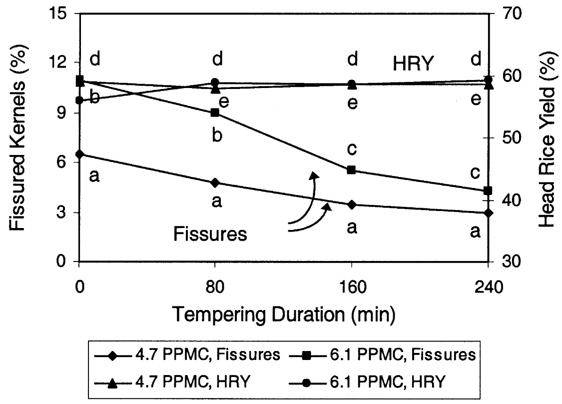

Fig. 6. Percent fissured kernels and HRY versus tempering duration for Cypress rice harvested in 2000 and dried for two different durations (PPMC is the percentage points MC removed in one drying pass) with 60 °C and 50% RH drying air. The percentage fissured kernels and the HRY of the control sample were 2% and 61%, respectively. The harvest moisture content was 20.5%. Values with the same letter are not significantly different.

of the fissured kernels did not break in the milling process but remained as head rice.

Table 1 shows the percentage of fissured kernels, the percentage of kernels having surface cracks, and the HRY results for one Bengal lot dried under all three drying air conditions for all durations. As can be seen in Table 1, both drying conditions with a drying air temperature above T_g (condition HI and HII) showed similar trends for the percentage fissured kernels and HRY. The percentage of fissured kernels increased with increasing moisture removal rates. Removing 5.3 PPMC for condition HII and 5.8 PPMC for condition HI resulted in some irreversible structural damage; even after 240 min of tempering the HRY was still 5–6% points lower than the HRY of the control sample.

The drying condition with a drying air temperature below T_g (condition LI) showed a lower number of fissured kernels but a higher number of kernels having surface cracks than the samples dried with higher temperature air conditions (Table 1). Condition LI did not cause any HRY reduction and tempering did not have any effect on the HRY. However, tempering did significantly decrease the number of fissured kernels when removing 4.4 PPMC.

For all three drying conditions, surface cracks increased with tempering duration (Table 1). Surface cracks will normally appear as a result of drying the surface too severely and the number of surface cracks would therefore be expected to increase with increasing drying duration, however, the data does not reflect this. Drying above T_g may have prevented fissuring of the surface due to the kernel being in the more flexible rubbery state. The surface cracking of the samples that were tempered for extended durations could have occurred after the tempering process, as a result of the conditions in the 21 °C/50% RH chamber, or due to some extended drying during tempering. The rice that was tempered had a higher surface MC and higher surface temperature when it was removed from the tempering environment and placed in the 21 °C/50% RH chamber, compared to those samples that were not tempered and placed in the 21 °C/50% RH chamber immediately after drying. The samples that were not tempered (0 min tempering duration) had a lower surface temperature than the samples that were tempered due to evaporative cooling during the drying process, while the tempered samples were left in the 60 °C without evaporative cooling taking place. Even though the air condition in the 21 °C/50% RH chamber was set to gently dry the samples down to 12.5% MC, relatively rapid drying of the surface could have resulted in surface cracks occurring immediately after tempering in the 21 °C/50% RH chamber. The surface MC and kernel temperature was still high and the entire kernel was in the rubbery state. Within a short period of time, the kernel cooled down and a state transition occurred. Thus, the combined effect of a surface state transition resulting in tensile stresses at the surface due to a higher kernel density and much lower thermal expansion rate in the glassy state, and additional moisture loss in the 21 °C/50% RH chamber at the surface could explain the higher number of surface cracks for the samples that were tempered.

Fig. 5 shows the percentage of fissured kernels and the HRY versus tempering duration for Cypress (harvested in 1999) when removing 4.0 and 5.1 PPMC using 60 °C and 17% RH drying air. The results show that the number of fissured kernels was lower than for Bengal. Due to a thinner kernel, which results in smaller MC gradients inside the kernel and thus in lower stress levels, Cypress was more resistant to fissuring than Bengal. Fig. 5 shows that removing 4.0 PPMC caused only a very small HRY reduction when no tempering was allowed and 80 min of tempering was sufficient to prevent HRY reduction. Removing 5.1 PPMC resulted in a larger HRY reduction when samples were not tempered before cooling; 80 min of tempering at 60 °C was required to maintain a HRY equivalent to the HRY of the control sample. For both drying durations, the percentage of fissured kernels decreased with increasing tempering; up to 160 min of tempering was necessary to minimize fissuring. The 5.1 PPMC samples did, however not significant, still show a slightly higher number of fissured kernels (5%) than the control sample (3%).

Table 2 shows the percentage of fissured kernels, the percentage of kernels having surface cracks, and the HRY results for one Cypress lot. The percentage of fissured kernels and the percentage of kernels having surface cracks showed a similar trend for both drying conditions with a drying air temperature above T_g (condition HI and HII). When removing 5.8 PPMC under the high RH drying condition (condition HII), 80

Table 1
Percent fissured kernels, percent kernels having surface cracks, and HRY for Bengal rice harvested in 1999 and dried under three drying air conditions, for three durations, and tempered for four durations

Drying duration	Tempering duration (min)	Fissured kernels (%)	Surface cracks (%)	HRY (%)
Control				
4 days		**24**	**4**	**65**
Drying air condition HII (60 °C, 50% RH)				
2.9 PPMC*	0	44	**1**	57
	80	**26**[a]	8[i]	**65**[r]
	160	**26**[a]	9[i]	**65**[r]
	240	**25**[a]	14	**66**[r]
4.5 PPMC	0	64	**6**[j]	52
	80	43[b]	**6**[j]	60
	160	47[b]	**4**[j]	**64**[s]
	240	43[b]	12	**65**[s]
5.3 PPMC	0	69	**3**[k]	32
	80	55[c]	**3**[k]	53
	160	53[c]	**6**[k]	57
	240	49[c]	**6**[k]	60
Drying air condition HI (60 °C, 17% RH)				
3.5 PPMC	0	45	7[l]	55
	80	31[d]	9[l]	**65**[t]
	160	**24**[e]	1	**65**[t]
	240	**28**[d,e]	**6**[l]	**66**[t]
4.6 PPMC	0	68	**2**[m]	37
	80	47[f]	**6**[n]	60
	160	49[f]	**2**[m]	63[u]
	240	40	**8**[n]	**64**[u]
5.8 PPMC	0	81	**2**[o]	32
	80	65	0[o]	47
	160	49[g]	**3**[o,p]	59[v]
	240	57[g]	**5**[p]	59[v]
Drying air condition LI (40 °C, 12% RH)				
3.1 PPMC	0	**21**[h]	11[q]	**65**[w]
	240	**24**[h]	13[q]	**65**[w]
4.4 PPMC	0	31	19	**65**[x]
	240	**24**	28	**65**[x]

The harvest moisture content was 17.5%. Values within one drying run with the same letter are not significantly different. Values in bold are not significantly different from the control.
* PPMC is percentage points moisture content reduction in one drying pass.

min of tempering was required to maintain a HRY equal to the control sample. Removing 5.1 PPMC under the low RH drying condition (condition HI) also required 80 min of tempering at 60 °C. However, the sample that was dried under the low RH drying condition and was not tempered, showed a much lower HRY and much higher percentage of fissured kernels compared to the sample dried under the high RH drying condition. This indicated that the low RH drying condition was much more detrimental to the rice kernel. The drying condition (condition L1), with a drying air temperature below the T_g of the rice, did not cause any HRY reduction and tempering did not have any effect on the HRY. For all three drying conditions, the number of kernels having surface cracks increased with increasing tempering duration. For Cypress, in contrast with Bengal, the number of kernels having surface cracks also increased with increasing drying duration.

For both Bengal and Cypress, the 2000 samples showed similar trends as the 1999 samples. Fig. 6 shows the percentage fissured kernels and HRY versus tempering duration for Cypress harvested in 2000. No tempering was required to maintain a high HRY when removing 4.7 PPMC and only 80 min of tempering at 60 °C was necessary to maintain a HRY equivalent to the control sample when removing 6.1 PPMC. The number of fissured kernels in the 2000 Cypress samples further decreased with increasing tempering duration after 80 min for the 6.1 PPMC drying duration. Similar to the 1999 samples, the longer drying duration also showed a slightly higher percentage of fissured kernels (4%), even after 240 min of tempering, compared to the control (2%).

The rice lots harvested in 2000 had a higher harvest MC than the rice harvested in 1999. The results showed that more moisture can be removed and shorter

Table 2
Percent fissured kernels, percent kernels having surface cracks, and HRY for Cypress rice harvested in 1999 and dried under three drying air conditions, for three durations, and tempered for four durations

Drying duration	Tempering duration (min)	Fissured kernels (%)	Surface cracks (%)	HRY (%)
Control				
4 days		**3**	**4**	**63**
Drying air condition HII (60 °C, 50% RH)				
2.8 PPMC*	0	**3**[a]	**2**	**63**[q]
	80	**4**[a]	**6**[j]	**62**[q]
	160	**3**[a]	8[j]	**63**[q]
	240	**2**[a]	**6**[j]	**63**[q]
3.9 PPMC	0	7	–**	**62**[r]
	80	**4**[b]	–	**62**[r]
	160	**3**[b]	–	61[r]
	240	**2**[b]	–	61[r]
5.8 PPMC	0	8[c]	11	60
	80	6[c]	19[k]	**62**[s]
	160	7[c]	18[k]	**62**[s]
	240	6[c]	24	61[s]
Drying air condition HI (60 °C, 17% RH)				
2.5 PPMC	0	5[d]	1	**63**[t]
	80	2[d]	**5**[l]	**63**[t]
	160	**1**	**6**[l]	**63**[t]
	240	**4**[d]	7[l]	**63**[t]
4.0 PPMC	0	7[e]	7[m]	61
	80	**5**[e,f]	9[m]	**63**[u]
	160	**3**[f]	21[n]	**62**[u]
	240	**4**[f]	23[n]	**63**[u]
5.1 PPMC	0	14	8	54
	80	7[g]	15	**61**[v]
	160	**5**[g]	28[o]	**61**[v]
	240	7[g]	31[o]	**62**[v]
Drying air condition LI (40 °C, 12% RH)				
2.6 PPMC	0	**2**[h]	**4**[p]	**62**[w]
	240	**3**[h]	**5**[p]	**62**[w]
4.5 PPMC	0	**2**[i]	23	**62**[x]
	240	**3**[i]	38	**62**[x]

The harvest moisture content was 18.0%. Values within one drying run with the same letter are not significantly different. Values in bold are not significantly different from the control.
* PPMC is percentage points moisture content reduction in one drying pass.
** Not measured.

tempering durations are required to maintain a high HRY when harvesting at a higher MC. This agrees with the findings of Cnossen and Siebenmorgen (2000). Harvest MC, however, did not have an effect on the tempering duration required to minimize fissuring levels.

4. Conclusions

The following conclusions were drawn from this study:

1. When drying rice at a 60 °C temperature (above the glass transition temperature, T_g of rice), tempering at 60 °C increased HRY and reduced the number of fissured kernels.
2. Even though some samples, after extended tempering, had a HRY equivalent to the HRY of the control sample, these samples still showed a significantly higher number of fissured kernels than the control sample.
3. The tempering duration required for maintaining kernel physical integrity (prevention of fissuring) is longer than the tempering duration required for maintaining a high HRY.
4. When drying rice at a temperature above T_g (60 °C), up to 2.9 PPMC for Bengal rice and 4.0 PPMC for Cypress rice could be removed in one drying pass without increasing fissuring levels when a tempering duration of 80 and 160 min was used, respectively.
5. When drying rice at a temperature below T_g (40 °C), tempering was not necessary to maintain a high HRY. However, tempering at 40 °C did decrease

the percentage of fissured kernels for Bengal rice when removing 4.4 PPMC.

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