

RELATING ROUGH RICE MOISTURE CONTENT REDUCTION AND TEMPERING DURATION TO HEAD RICE YIELD REDUCTION

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ABSTRACT. Previous research has indicated that kernels will fissure during the process of drying rough rice using air temperatures above the glass transition temperature (T_g) if a sufficient portion of the kernel surface transitions to a glassy state while the interior remains in the rubbery state, a condition that can result due to intrakernel moisture content (MC) gradients created by drying. State transitions can occur by such extended drying using high-temperature air or when kernels are cooled below T_g immediately after drying and before sufficient tempering has occurred. Two long-grain cultivars, Francis and Wells, at two harvest MCs (HMCs) were used to determine the maximum MC reduction that could be achieved in the initial drying pass, and the associated tempering durations required, without incurring head rice yield (HRY) reduction. Samples were dried with air at either 60°C/17% RH or 50°C/28% RH for various durations to create a range of intrakernel MC gradients and were subsequently tempered at the drying air temperature in sealed bags for durations ranging from 0 to 160 min. After tempering, samples were cooled to cause a state transition, and then slowly dried to 12.2% MC. Samples were then milled to determine HRY. Control samples were dried at 21°C/60% RH. Results showed that the amount of moisture that could be removed in the initial drying pass was directly related to the HMC and the drying air condition. The tempering duration required to prevent HRY reductions increased with the MC reduction in the initial drying pass. The HRY reduction patterns concurred with a hypothesis that explains fissure formation during the drying process based on rice kernel property changes associated with the glass transition temperature.

Keywords. Rice, Milling quality, Drying, Head rice yield, Tempering, Glass transition temperature.

In the U.S., rough rice is typically harvested at moisture contents (MCs) ranging from 14% to 24%, and subsequently dried to approximately 12% for safe long-term storage. Some rice is dried in on-farm, bin drying systems. These systems typically use ambient air or slightly heated (usually less than 11°C) ambient air to produce slow drying rates. However, the predominance of rice is dried off-farm using high-temperature, cross-flow driers. Schluterman and Siebenmorgen (2004) detail a typical cross-flow drier used in commercial rice drying. They also present spatial profiles of rice and air conditions measured inside this type of drier during drying.

High-temperature drying creates MC gradients within kernels, which induce tensile stresses at the kernel surface and compressive stresses at the kernel interior (Sharma and Kunze, 1982). Sharma and Kunze (1982) indicate that these stresses can lead to fissure formation within the kernel and subsequently reduce quality due to reduction in HRYs. In

order to reduce these stresses, tempering is typically practiced, during which kernels are held in a non-drying condition in order to allow MC gradients within kernels to subside. Intermittent drying/tempering cycles are often used to avoid fissure formation and HRY reductions.

Rice drying and tempering have been studied extensively, with the goal of drying rice more quickly while maintaining high HRYs (Ban, 1971; Kunze, 1979; Chen, 1997; Chen et al., 1997; Cnossen and Siebenmorgen, 2000, 2002). When drying rough rice, the glass transition temperature (the temperature at which a state transition occurs, causing the rice kernel to change from a “glassy” to a “rubbery” state, or vice versa) plays a significant role in determining the rate at which moisture can be removed from the kernel (Cnossen and Siebenmorgen, 2002) and the possible formation of fissures (Cnossen and Siebenmorgen, 2000). Cnossen and Siebenmorgen (2002) found that the moisture removal rate was much greater if the rice kernel temperature was above T_g .

Figure 1, from Siebenmorgen et al. (2004), shows the inverse relationship between the T_g and MC of brown rice kernels. For a given MC, if the rice kernel temperature is below T_g , the starch exists in a glassy state; if the kernel temperature is increased above T_g , the starch exists in a rubbery state with much higher diffusivity, specific heat, specific volume, and thermal expansion coefficient (Perdon et al., 2000).

Cnossen and Siebenmorgen (2000) presented a hypothesis incorporating the T_g concept to explain rice kernel fissuring during drying and tempering. To present this hypothesis, figure 2 shows hypothetical temperature and MC gradients

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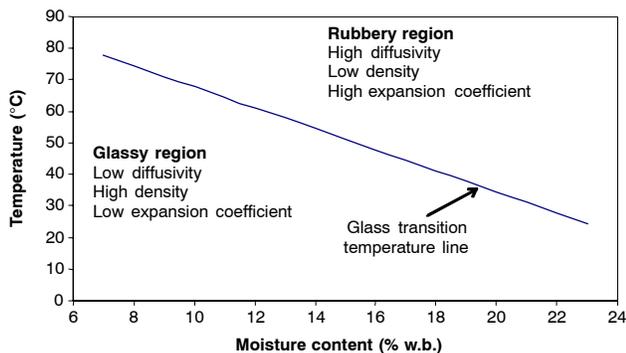


Figure 1. Glass transition temperature relationship for brown rice kernels, indicating the glassy and rubbery regions, as well as the general property trends associated with each region (Siebenmorgen et al., 2004).

created within a rice kernel during drying. When drying with air temperatures above T_g , the rice kernel transitions from a glassy to rubbery state. As indicated above, this transition dramatically changes kernel material properties, with the thermal volumetric expansion coefficient being of particular relevance (Perdon et al., 2000). In addition to thermal changes during high-temperature drying, the periphery of the kernel will dry much more quickly than the kernel center, causing an MC gradient within the kernel. Extended drying causes a sufficient volume of the kernel surface to transition to the glassy state (fig. 3). This surface volume behaves as a glassy material, with one set of property levels, while the center behaves as a rubbery material with another, very different set. The T_g hypothesis predicts that if the thermal and hygroscopic property values of the surface and center volumes are sufficiently different in magnitude, and the surface glassy region increases to a sufficient volume relative to the center rubbery region, then fissures will initiate at the interface of the two volumes.

In addition to the just-mentioned scenario caused by extended drying, the T_g hypothesis predicts that fissures can also be created during post-drying tempering and/or cooling. Depending on the temperature to which the kernel is exposed immediately after drying (fig. 4), a sufficient volume of the outer kernel may be forced to transition to the glassy state due to the rapid movement of the intrakernel cooling front, while the center remains in the rubbery state. This causes the surface and center portions of the kernel to experience

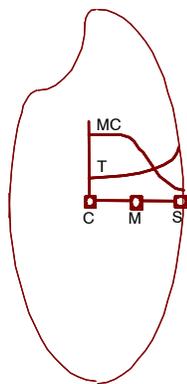


Figure 2. Hypothetical temperature (T) and moisture content (MC) distributions within a rice kernel during the drying process. Points C, M, and S correspond to the center, midpoint, and surface locations of the rice kernel, respectively (Cnossen and Siebenmorgen, 2000).

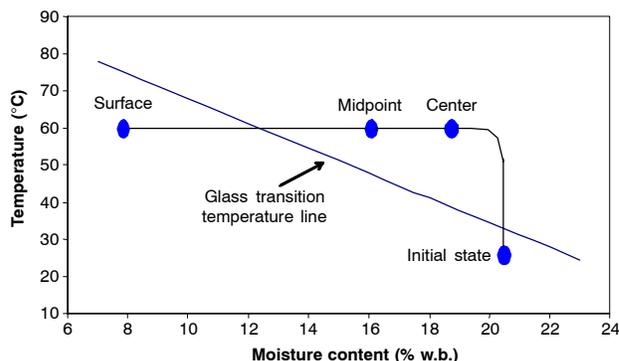


Figure 3. Hypothetical temperature and moisture content gradients within a rice kernel at the locations shown in figure 2, after extended high-temperature drying.

different magnitudes of material properties, which can cause fissure formation, as described above (Cnossen and Siebenmorgen, 2000).

During tempering, if kernels are cooled below T_g before the MC gradient is allowed to subside, fissures will occur due to the surface and center volumes conforming to different properties; this is shown with situation B in figure 4. Once the MC gradient created by drying subsides, rice kernels can be cooled to temperatures below T_g without incurring fissures.

Most commercial rice driers try to maximize MC reduction in as short a period as possible without incurring HRY reductions. Given the T_g hypothesis, the objective of this study was to determine the maximum MC reduction that could be achieved during the initial drying pass, and the associated tempering durations required, without causing HRY reduction. Drying air temperatures that produce kernel states both above and below T_g during drying were used. This information is intended to help optimize performance of commercial rice driers.

MATERIALS AND METHODS

In the fall of 2003, two long-grain rice cultivars, Francis (with harvest MCs (HMCs) of 19.5% and 17.4%) and Wells (with HMCs of 21.6% and 16.1%) were obtained from the University of Arkansas Rice Research and Extension Center near Stuttgart, Arkansas. Immediately after harvest, the rice

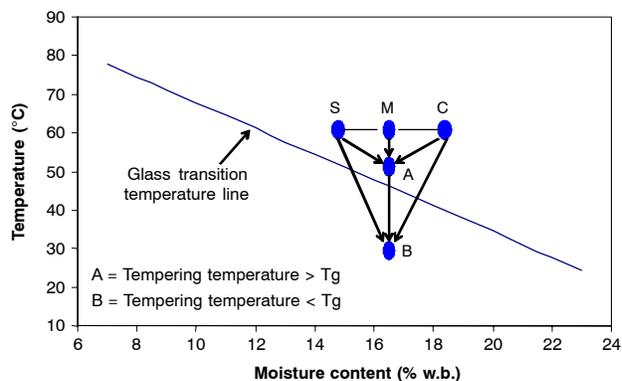


Figure 4. Hypothetical tempering situations above and below the glass transition temperature (T_g) for a rice kernel that had been dried using air temperatures above T_g . Surface (S), midpoint (M), and center (C) correspond to the kernel locations shown in figure 2.

was transported to the University of Arkansas Rice Processing Laboratories, cleaned with a dockage tester (model XT4, Carter Day Co., Minneapolis, Minn.), and stored at 4 °C for six weeks until drying tests were conducted.

Approximately 24 h prior to a drying test, rice samples were placed in plastic bags and allowed to equilibrate to 20 °C in a laboratory environment. Rough rice samples were dried using a temperature and relative humidity (RH) control unit (Climate Lab AA, 300 CFM, Parameter Generation & Control, Inc., Black Mountain, N.C.). The air conditions were monitored using a hygrometer (Hygro-M2, General Eastern, Woburn, Mass.). Air from the temperature and RH control unit was supplied to a laboratory drying chamber, which included 16 trays (25 × 14 × 6.5 cm) with perforated bottoms. The 16 trays were arranged as two 8-tray sets, which served as two repetitions. Approximately 110 g of rough rice was added to each tray to form a layer two to three kernels deep.

Rough rice was dried with air at either 60 °C/17.0% RH (5.5% EMC) or 50 °C/28% RH (7.2% EMC), where EMC is the rough rice equilibrium MC (% w.b.), as predicted by the Chung-Pfost equation (*ASAE Standards*, 2004). Samples from each cultivar/HMC lot were also dried at 21 °C/60% RH (12.2% EMC) as a control (see below). For each drying air treatment, samples were dried for various durations to produce a range of MC gradients within the kernels. After each drying duration, eight samples from each repetition were randomly paired, combined, and placed in sealed bags. The four samples from each repetition were then tempered, which consisted of placing the sealed bags in one of two ovens set at the drying air temperature, either 50 °C or 60 °C. Tempering durations ranged from 0 to 160 min in increments of 30 to 40 min; the longer durations were used for the extended drying durations. After tempering, the samples were spread onto screened trays in a conditioning chamber maintained at 21 °C/60% RH to cool and continue to dry to 12.2% MC. The purpose of tempering the samples for different increments was to determine the shortest duration needed to allow the MC gradient that was created during drying to sufficiently subside prior to cooling. If the tempering duration was too short, fissures would result according to the Tg hypothesis described above. After each drying duration, sample MC was determined in triplicate using an oven method, which comprised drying 15 g of rough rice for 24 h in a convection oven at 130 °C (Jindal and Siebenmorgen, 1987).

Each treatment and control sample was milled to determine the effect of the drying and tempering treatments on milling quality. Replicate 150 g subsamples of rough rice were dehulled using a laboratory huller (THU, Satake, Tokyo, Japan), and the resultant brown rice was milled in a laboratory mill (McGill No. 2, Rapsco, Brookshire, Texas) for 30 s with a 1.5 kg mass placed on the lever arm of the mill 15 cm from the centerline of the mill chamber. The amount of head rice, i.e., milled kernels that are at least three-fourths of the original kernel length (USDA, 1997), in each milled rice sample was determined with an image analysis system (Graincheck 2312 Analyzer, Foss Tecator, Höganäs, Sweden). Head rice yield was then calculated as the mass percentage of rough rice that remained as head rice.

For the control, five 200 g samples of rice from each of the four cultivar/HMC lots were gently dried at 21 °C/60% RH in the conditioning chamber described above from the HMC

to 12.2% MC. Extended drying using this condition has been shown to produce no reductions in HRY (Fan et al., 2000). The five HRYs from each cultivar/HMC lot were averaged to represent the control HRY of each lot. The HRYs of the different drying/tempering treatments were compared to the respective control HRYs to determine the amount of HRY reduction caused by drying and/or tempering.

RESULTS AND DISCUSSION

Figure 5 shows the HRY data for cultivar Wells (HMC of 21.6%), plotted against tempering durations, for various drying durations ranging from 10 to 55 min using drying air at 60 °C/17% RH. The HRY reduction patterns shown in figure 5 and in subsequent figures are similar to those reported by Cnossen and Siebenmorgen (2000). Samples with no tempering, in which the samples were immediately cooled upon cessation of drying, showed dramatic HRY reductions. However, when drying for 10, 20, and 31 min and tempering for at least 30 to 40 min, no HRY reductions were measured compared to the control HRY. Thus, as much as 6.4 percentage points (PP) of MC (PPMC) reduction produced no damage, given sufficient tempering before cooling. However, when drying for 43 min and reducing MC by 7.7 PP, a reduction of 4.9 percentage points of HRY (PPHRY) resulted, compared to the control HRY, even after extended tempering durations. A reduction of 18 PPHRY resulted after drying for 55 min, reducing MC by 8.8 PP, and tempering for over 2 h. Therefore, the maximum reduction in MC that could be safely achieved in a single pass with air at 60 °C/17% RH from Wells at 21.6% HMC was 6.4 PP. It is speculated that beyond this MC reduction level, intrakernel MC gradients and resultant transitioning of sufficient portions of the kernel surface to the glassy state created stresses within kernels that caused material failure and fissure initiation; for these kernels, no amount of tempering prevented breakage during milling.

Figure 6 shows the data from figure 5 plotted onto a state diagram for rice. The points in figure 6 indicate the corresponding PPMC reductions for each drying duration at the rice temperature (60 °C) and the corresponding HRY reductions (after tempering for 90 min) in relation to the Tg line. As indicated above, drying for 10, 20, and 31 min

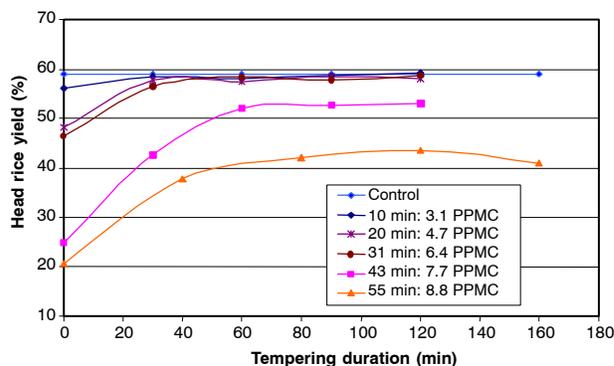


Figure 5. Head rice yield (HRY) versus tempering duration for cultivar Wells with a harvest moisture content of 21.6%. Samples were dried using 60 °C/17% RH air for 10, 20, 31, 43, and 55 min, reducing MC by 3.1, 4.7, 6.4, 7.7, and 8.8 percentage points (PPMC), respectively, tempered at 60 °C for the indicated durations, and then cooled to 21 °C. Each data point represents the average of two replicate sample HRYs.

(reducing MC by 3.1, 4.7, and 6.4 PP, respectively) and tempering for at least 90 min resulted in no HRY reductions compared to the control HRY. For these drying durations, the average sample MC after drying indicated that for the kernels within these samples, most of each kernel was in the rubbery state, which would also indicate that a significant volume of the kernel periphery had not transitioned from the rubbery to the glassy state. However, drying for 43 min and reducing MC by 7.7 PP resulted in an HRY reduction of 4.9 PP compared to the control HRY, even after extended tempering durations. For this situation, the average sample MC and temperature after drying positioned the kernel average material state near the T_g line, which would indicate that a large portion of the kernel periphery had transitioned into the glassy region while the kernel center remained in the rubbery region. Cnossen and Siebenmorgen (2000) hypothesized that this condition results in kernel fissuring and reduced HRYs. Proportionately greater HRY reductions occurred (17.1 PP) as greater proportions of kernels transitioned into the glassy region, caused by reducing MC by 8.8 PP (fig. 6).

Figure 7 shows HRYs of cultivar Francis (HMC of 19.5%) versus tempering duration for drying durations ranging from 17 to 47 min using drying air at 60°C/17% RH. When drying for 17 or 27 min and tempering for at least 60 min, no HRY reductions were measured compared to the control HRY. Thus, as much as 4.8 PPMC were reduced without appreciable damage, given sufficient tempering before cooling. However, when drying for 37 min and reducing MC by 6.2 PP, a reduction of 9.6 PPHRY resulted compared to the control HRY, even after extended tempering. A reduction of 18.2 PPHRY resulted after drying for 47 min, reducing MC by 7.2 PP, and tempering for 2 h. Therefore, the maximum allowable MC reduction in a single pass with air at 60°C/17% RH from Francis at 19.5% HMC was 4.8 PP, provided a post-drying tempering duration of at least 60 min.

Analogous to figure 6, figure 8 displays Francis (HMC 19.5%) samples dried using air at 60°C/17% RH for the various durations indicated in figure 7. Figure 8 shows that HRY reduction was not measurable until drying for 37 min, reducing MC by 6.2 PP, which resulted in an HRY reduction of 9.6 PP, even after extended tempering durations. For this situation, the average kernel MC and temperature after

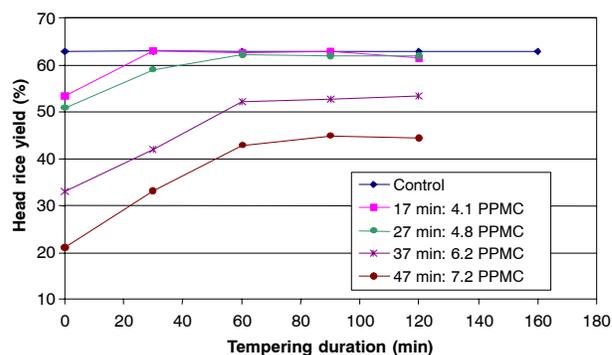


Figure 7. Head rice yield (HRY) versus tempering duration for cultivar Francis with a harvest moisture content of 19.5%. Samples were dried using 60°C/17% RH air for 17, 27, 37, and 47 min, reducing MC by 4.1, 4.8, 6.2, and 7.2 percentage points (PPMC), respectively, tempered at 60°C for the indicated durations, and then cooled to 21°C. Each data point represents the average of two replicate sample HRYs.

drying positioned the average kernel material state near the T_g line, which would indicate that a large portion of the kernel periphery had transitioned into the glassy region while the kernel center remained in the rubbery region. Greater HRY reductions occurred (18.2 PP) when MC was reduced by 7.2 PP, which caused proportionately more of the peripheries of kernels to transition into the glassy state (fig. 8).

Figure 9 displays HRY data for Francis (HMC of 17.4%) at various tempering durations and drying durations ranging from 23 to 88 min using drying air at 50°C/28% RH. Reducing MC by up to 4.5 PP and tempering for at least 90 min resulted in no HRY reductions compared to the control HRY. After drying for 88 min and reducing MC by 5.6 PP, slight HRY reductions were measured after tempering for 90 min. However, for samples in which MC was reduced by 4.5 PP, a single pass removed sufficient MC to reach a safe storage level of 12.9% MC, without measurable HRY reductions.

A T_g diagram is shown in figure 10 along with the drying and tempering data of figure 9. Figure 10 indicates the MC reductions and the corresponding HRY reductions (after tempering for 90 min) in relation to the T_g line for each drying duration using the 50°C/28% RH air condition. The

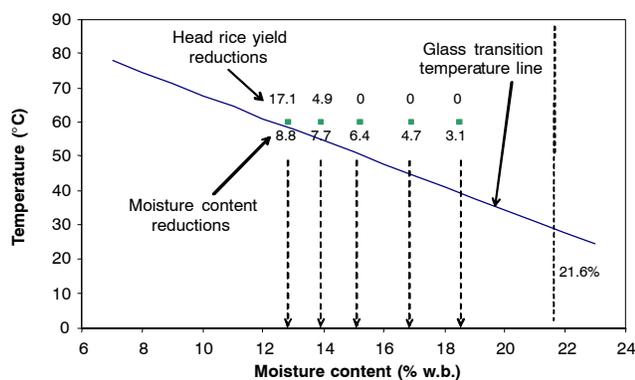


Figure 6. Head rice yield (HRY) reductions (percentage points) of cultivar Wells corresponding to the indicated moisture content reductions (percentage points) plotted onto a T_g diagram. Samples with a harvest moisture content of 21.6% were dried using 60°C/17% RH air. Samples were tempered for 90 min at 60°C immediately after drying, and before cooling and subsequent gentle drying. Each data point represents the average of two replicate sample HRYs.

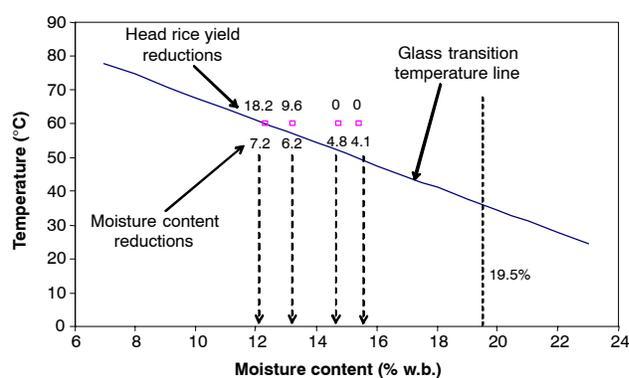


Figure 8. Head rice yield (HRY) reductions (percentage points) of cultivar Francis corresponding to the indicated moisture content reductions (percentage points) plotted onto a T_g diagram. Samples with a harvest moisture content of 19.5% were dried using 60°C/17% RH air. All samples were tempered for 90 min at 60°C immediately after drying, and before cooling and subsequent gentle drying. Each data point represents the average of two replicate sample HRYs.

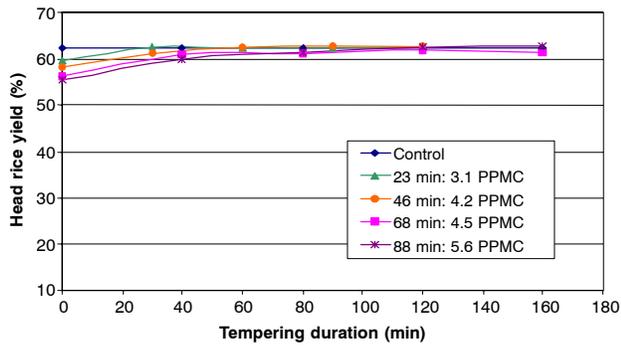


Figure 9. Head rice yield (HRY) versus tempering duration for cultivar Francis with a harvest moisture content of 17.4%. Samples were dried using 50 °C/28% RH air for 23, 46, 68, and 88 min, reducing MC by 3.1, 4.2, 4.5, and 5.6 percentage points (PPMC), respectively, tempered at 50 °C for the indicated durations, and then cooled to 21 °C. Each data point represents the average of two replicate sample HRYs.

low HMC and the mild drying condition placed the average kernel material state near or below the T_g line at the start of drying. As such, most kernels did not transition into the rubbery state during drying, and the fissuring process described above did not occur in these kernels. As such, the amount of MC reduction had little effect on fissuring in these kernels. However, it is known that some kernels within these samples had HMCs greater than the 17.4% average at the start of drying (Bautista and Siebenmorgen, 2005). For these kernels, it is reasoned that a state transition into the rubbery region did occur during drying, and thus a tempering duration of 90 min was required to prevent HRY reduction. Drying for up to 68 min, reducing MC by 4.5 PP, resulted in no HRY reductions. Less than 1 PPHRY reduction was measured after 88 min of drying followed by 90 min of tempering. Thus, drying low-HMC rice with air conditions that place the average material state near or under the T_g line resulted in little to no HRY reduction.

Figures 5 through 10 illustrate that the HMC plays a large role in affecting fissure formation according to the T_g hypothesis. To summarize this role, HRY reductions for the cultivar/HMC lots dried using 60 °C/17% RH air are plotted versus MC reductions in figure 11. These data represent samples that were tempered for 90 min at 60 °C immediately

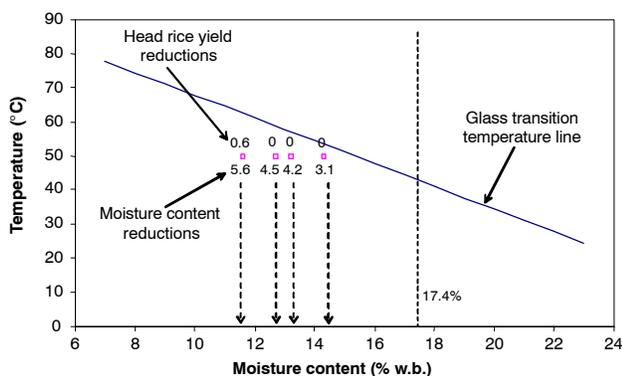


Figure 10. Head rice yield (HRY) reductions (percentage points) of cultivar Francis corresponding to the indicated moisture content reductions (percentage point) plotted onto a T_g diagram. Samples with a harvest moisture content of 17.4% were dried using 50 °C/28% RH air. All samples were tempered for 90 min at 50 °C immediately after drying, and before cooling and subsequent gentle drying. Each data point represents the average of two replicate sample HRYs.

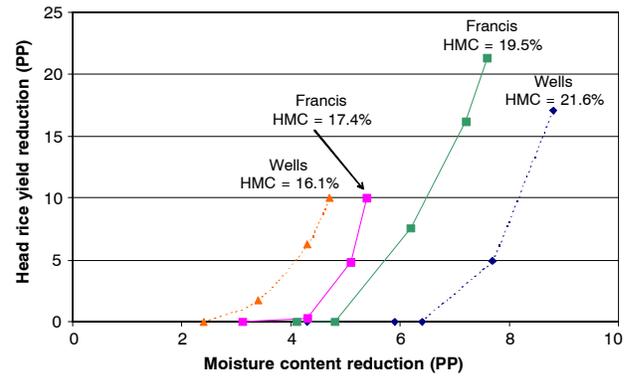


Figure 11. Head rice yield (HRY) reduction versus moisture content reduction for Wells and Francis at the indicated harvest moisture contents (HMCs) using drying air at 60 °C/17% RH. All samples were tempered for 90 min at 60 °C immediately after drying, and before subsequent cooling and gentle drying. Each data point represents the average of two replicate sample HRYs.

after drying, and before subsequent cooling and gentle drying to 12.2% MC. Moreover, the HRY and MC reduction data for Wells (HMC 21.6%) were obtained from figure 6 and for Francis (HMC 19.5%) from figure 8; the corresponding data for Wells (HMC 16.1%) and Francis (HMC 17.4%) dried at 60 °C/17% RH are not shown in previous figures. Figure 11 shows that HRY reduction began after reducing MC by 2.3, 4.2, 4.8, and 6.4 PP for Wells (16.1% HMC), Francis (17.4% HMC), Francis (19.5% HMC), and Wells (21.6% HMC), respectively, after tempering for 90 min. As the MC at which drying began increased, more moisture could be removed per drying pass without incurring HRY reductions, provided that sufficient tempering occurred immediately after drying. During drying with high HMC rice, even though a severe MC gradient formed within the kernels, fissuring did not occur until a sufficient amount of kernel peripheries transitioned into the glassy state. Thus, figure 11 shows that for the 60 °C/17% RH drying air condition, the amount of moisture that could be removed without HRY reduction was directly related to the HMC of the rice.

Analogous to figure 11, figure 12 displays data for the cultivar/HMC lots dried using 50 °C/28% RH air. The

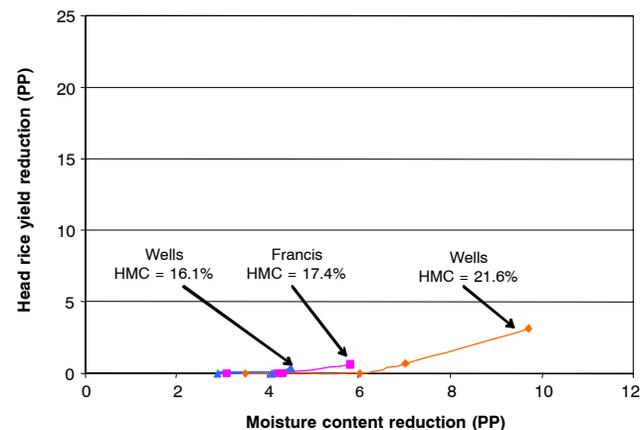


Figure 12. Head rice yield (HRY) reduction versus moisture content reduction for Wells and Francis at the indicated harvest moisture contents (HMCs) using drying air at 50 °C/28% RH. All samples were tempered for 90 min at 50 °C immediately after drying, and before subsequent cooling and gentle drying. Each data point represents the average of two replicate sample HRYs.

figure 12 trends are similar to those of figure 11 in that the MC reduction that could be achieved in a single pass without incurring HRY reduction using the 50°C drying air condition was directly proportional to the HMC.

CONCLUSIONS

For the drying conditions tested, tempering rice for at least 60 min at the drying air temperature immediately after drying was sufficient to allow intrakernel MC gradients to subside and thus prevent HRY reduction upon subsequent cooling.

Plotting the average state points of kernels before and after drying onto a Tg diagram explained whether HRY reductions would occur due to a drying/tempering treatment. Drying air and rough rice HMC conditions that placed the average kernel state initially in the glassy region allowed drying rice to a safe storage MC in one pass. However, even for this scenario, some tempering was required to prevent slight HRY reductions; this was presumably due to those high MC kernels within samples that transitioned into a rubbery state during drying. For drying air/rough rice HMC conditions that caused a state transition into the rubbery region, the amount of moisture that could be removed in a single pass without causing HRY reduction (with sufficient tempering) was directly related to the HMC. This MC reduction was dictated by the amount of the kernel peripheries that transitioned into the glassy state during drying and was correlated to the position of the average kernel state point relative to the Tg line. These observations concur with the Tg hypothesis developed by Cnossen and Siebenmorgen (2000).

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