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AN APPLICATION OF GLASS TRANSITION TEMPERATURE TO EXPLAIN RICE KERNEL FISSURE OCCURRENCE DURING THE DRYING PROCESS*

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ABSTRACT

Fissure formation during rice drying is a major cause of rice milling quality reduction. This work has applied principles of polymer science in studying thermal and hygroscopic properties of rice kernels, particularly the glass transition temperature (T_g). This data was used to develop a hypothesis that explains the occurrence of rice kernel fissuring as a result of drying. The drying process was mapped onto a state diagram to illustrate the changes in state that a kernel could

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incur through drying and tempering operations. An experiment was designed to validate the hypothesis in which the effect of the T_g on rice drying and tempering in terms of milling quality was determined. Results showed that drying air temperatures up to 60°C and high moisture removal rates could be used without reducing the milling quality, as long as sufficient tempering was allowed at a temperature above the T_g of the rice.

Key Words: Drying; Fissuring; Glass transition temperature; Rice; Tempering

INTRODUCTION

Drying and Tempering Research

In the US, rice is typically harvested at a moisture content* (MC) too high to be safely stored and therefore needs to be dried. The goal in rice drying is to lower the MC as quickly as possible to prevent spoilage. Drying processes can affect the rice kernel structure, particularly if fissures are formed. Understanding these effects is important in controlling and optimizing drying conditions. Severe drying conditions and/or exposure of the dried rice kernels to air at high relative humidity (RH) can result in kernel fissuring (Kunze and Prasad 1978, Kunze 1979, Sharma and Kunze 1982, Fan et al. 2000). Fissure formation is a major concern during rice drying because fissured kernels are not only more susceptible to breakage in the milling process, but also affect the functional properties of milled rice.

The subject of rough rice drying has been studied extensively with the goal of drying rice more quickly while maintaining a high head rice yield (HRY). HRY is defined as the weight percentage of rough rice that remains as head rice (kernels that are at least three-fourths of the original kernel length) after complete milling. Proposed theories on fissure formation are based on the response of rice when subjected to tensile and compressive stresses due to the existence of an MC gradient within the kernel (Kunze and Choudhury 1972, Kobayashi et al., 1976, Yamaguchi et al., 1980).

Fissuring or cracking resulting from hygroscopic stresses can occur in a kernel during drying and will reduce HRY (Kunze 1979, Sharma and Kunze

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*All moisture contents are expressed on a wet basis.

1982, Fan et al., 2000). However, several researchers (Ban 1971, Kunze 1979, Sharma and Kunze 1982, Nguyen and Kunze 1984) observed that fissures did not occur until after drying had ceased. Since most kernels are not fissured immediately after drying, Sharma and Kunze (1982) suggested that there is a possibility that 'some post-drying treatment or procedure can be developed that will prevent the subsequent fissures'.

In commercial rice drying, multi-pass procedures are used to remove moisture from freshly harvested rice. Between drying passes, the rice is held in bins for a certain period of time to allow MC gradients within kernels, created during drying, to subside; this holding process is referred to as tempering. Tempering decreases MC gradients by allowing moisture to migrate from the core to the outer layers of the kernel. MC gradients cause differential stress inside the kernel, which, if sufficiently large, causes the kernel to fissure (Kunze 1979). Tempering practices vary widely in commercial rice drying. Tempering durations between 6 and 24 h are used in the U.S. (Mossman 1986, Steffe and Singh 1980b).

The effect of the tempering process on drying performance (i.e. drying rate and energy utilization) has been studied extensively. Relatively few researchers (Beeny and Chin 1970, Cnossen et al., 1998, Steffe et al., 1979, Wasserman et al., 1964), however, have studied the effect of tempering on kernel quality.

Steffe and Singh (1980b) developed a theoretical model based on initial MC and drying parameters to predict tempering time for rough rice. According to their model, tempering, which was based on the RH response of the inter-kernel air, was 95 percent complete in less than 2 h and fully complete in less than 5 h, when using a 35°C drying air temperature. This work was conducted using a short-grain rice variety. Steffe et al. (1979) concluded that a 35 min tempering duration was sufficient to equalize the MC gradient in the rice kernel, after drying high MC medium-grain rice for 20 min using 38°C air. A 3 h tempering time was sufficient after drying for 35 min using 38°C air, or after drying for 20 min using 50°C air. Tempering did improve HRY, but HRYs were equal for any length of tempering considered.

High tempering temperatures have shown to be effective in maintaining high HRYs and decreasing tempering duration. Beeny and Chin (1970) dried rice with an initial MC of 24% using 54.4°C drying air and found an increasing HRY with increasing tempering duration up to 5 h. Cnossen et al. (1998) showed increasing HRYs for tempering durations up to 150 min when drying medium-grain rice with 60°C air, and tempering at this drying temperature. Wasserman et al. (1964) showedincreasing HRY and decreasing tempering duration with increasing tempering temperature for a short-grain rice variety dried using 43.3°C air. HRY was two percent 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 (1980b) found similar trends of decreasing tempering duration with increasing temperature.

Most of the previous research on rice tempering was directed to short-grain varieties, using gentle drying conditions. Limited research has addressed the influence of high tempering temperatures on rice quality. Steffe and Singh (1980b) and Wasserman et al. (1964) concluded that higher tempering temperatures would decrease the required tempering duration. Consequently, further research is needed on the influence of high drying and tempering temperatures on the quality of medium- and long-grain rice varieties.

Material Property Considerations

Siebenmorgen and Perdon (1999) and Siebenmorgen (1998) suggested that a complete and fundamental understanding of the response of kernels to various drying and tempering environments must include considerations of material properties at the temperature and MC of various sections of the kernel.

The effect of water on rice thermal and physical properties is a key in understanding the drying process. Wratten et al. (1969) showed that the physical (length, width, thickness, volume, density, and specific gravity) and thermal (specific heat and thermal conductivity) properties of medium- and long-grain rice were linear functions of MC. Morita and Singh (1979) also found that short-grain rough rice kernel dimensions at 26°C, bulk density, and specific gravity varied linearly with MC. Short-grain rice was also found to shrink by an average of 12.3% when dried from 30 to 15% MC (Steffe and Singh, 1980a). These findings account only for the effects of MC on material properties at constant temperature.

Kernel temperature is another important factor affecting rice properties. Arora et al. (1973) found an increase in milled rice thermal expansion above 53°C and showed that more rice kernels fissured when the rice was subjected to temperatures above this transition temperature. Muthukumarappan et al. (1992) found a uniform rate of thermal expansion of rice up to 58°C when measuring volumetric changes in long-grain rice during desorption and adsorption. The authors considered that thermal expansion above 60°C was not important and used a single, temperature independent rate in their model for rice drying.

Integrating the effects of water and temperature on material property changes is important in understanding fissure formation during grain drying. Polymer science has been applied in studying the effects of temperature and MC changes during processing of food components, such as starch and protein (Slade and Levine 1991, 1995). Starch, the primary component of rice kernels, is considered a partially crystalline, partially amorphous polymer whose thermal and material properties change depending on the temperature and MC gradients generated during processing (Slade and Levine 1991, 1995). At temperatures (up to 60°C) and MCs applicable during rice drying, most of the changes during processing occur in the amorphous region (White and Cakebread 1966). Physical and thermal properties of amorphous materials, such as specific heat, specific volume, expansion coefficients, and elastic modulus, change as they go through a glass transition temperature, or T_g (White and Cakebread 1966). At temperatures below T_g, amorphous materials are glassy with high viscosity and density but low expansion coefficient. At temperatures above T_g, they are rubbery with a much higher expansion coefficient and lower density.

The T_g is inversely related to MC; as MC increases, T_g decreases. Plotting T_g against its corresponding MC generates a state diagram that can be used to predict the mechanical properties of kernels at a particular temperature and MC. At a given MC, the temperature of the material relative to its T_g will determine whether the material will be in the glassy or the rubbery state. Researchers have used state diagrams and the concept of glass transition to predict changes in food properties and reaction kinetics below and above T_g (Peleg 1996).

The reaction kinetics of the rice kernel to various processing conditions will depend on whether the kernel is in the glassy or in the rubbery state. The different kinetics below and above T_g need to be taken into account when modeling the reaction of kernels to processing operations. To understand rice kernel fissuring, the material properties below and above T_g need to be investigated. Nehus (1997) measured milled rice thermal properties with a differential scanning calorimeter (DSC) and reported that rice at 16 to 18% MC had a T_g around 55°C. The increase in milled rice thermal expansion above 53°C found by Arora et al. (1973) may be the T_g identified by Nehus (1997). If so, a state transition would be expected to occur in the temperature range typically encountered during rice drying and will affect the material properties of the rice.

Objectives

The objective of this project was to relate rice kernel material property changes during the drying and tempering process to kernel fissuring. To reach this objective, T_gs were measured for Bengal, a medium-grain rice variety, and Cypress, a long-grain rice variety, dried to different MCs. From this data, a state diagram was generated and used to map a typical drying process. Material properties, specifically the volumetric expansion coefficients below T_g (glassy region) and above T_g (rubbery region), were also measured. The state diagram was the basis for formulating a hypothesis explaining kernel fissure occurrence during the drying process. The hypothesis was validated with laboratory drying tests to investigate the effects of glass transition and high drying and tempering temperatures on HRY reduction during tempering.

EXPERIMENTAL DESIGN

Variety Bengal (medium-grain) and Cypress (long-grain) rice samples with varying harvest MCs between 16 and 23%, were harvested in 1997, 1998, and 1999 from the University of Arkansas Rice Research and Extension Centers at Stuttgart and Keiser, AR, US. Immediately after harvest, the rough rice samples were cleaned in a Carter-Day Dockage Tester (Carter-Day Co., Minneapolis, MN).

Each rough rice lot was then dried to different MC levels in drying chambers. Thin layer (3–5 mm) drying was achieved by using perforated trays in drying chambers in which the drying air conditions were controlled by PG&C (Parameter Generation & Control Inc., Black Mountain, NC) $8.5\,m^3\,min^{-1}$ temperature and RH controllers. The drying air conditions were 60°C and 16.9% RH; 51°C and 24.9% RH; 43°C and 38.2% RH, resulting in equilibrium moisture contents (EMCs) of 5, 7 and 9%, respectively. The EMCs were calculated using Chung's equation (ASAE 1998). Rice was removed from the drying chambers at different drying durations, resulting in samples with bulk MCs ranging from 5 to 22%. These samples were placed in sealed plastic bags and stored at 4°C for at least 24 h prior to further analysis. The MC of each rough rice sample was analyzed by drying duplicate samples for 24 h in an oven set at 130°C (Jindal and Siebenmorgen, 1987).

Most researchers (Nehus 1997, Biliaderis 1991) have used a DSC to measure thermal properties of rice. Biliaderis (1991) and Perdon (1999) observed several transitions from the DSC thermogram for rice starches. These multiple transitions complicate the characterization of brown rice thermal properties using the DSC.

In this study, individual brown rice kernels, instead of rice flour, were used for determining the T_g in order to account for the natural variability in kernel size and MC distribution existing among rice kernels at particular bulk MCs. It was also reasoned that measurement of thermal and hygroscopic properties of kernels in a whole-kernel, rather than flour, state would be more representative and descriptive of kernel behavior during the drying process. Therefore a Perkin-Elmer thermal mechanical analyzer (TMA) (Perkin-Elmer, Norwalk, CT), cooled with a dry ice-ethanol mixture, was used. Besides accurately measuring the T_g of the rice, critical material property changes occurring around the T_g, such as the volumetric expansion coefficient (ß) and the specific volume, can be measured with a TMA.

Rice kernels were randomly sampled at least in duplicate from each dried rough rice sample and dehulled by hand. Before each analysis, the dimensions (length, width, and thickness) of the kernel were measured with a vernier caliper. After measuring the dimensions, a whole kernel first weighed and then placed in a quartz dilatometer (7.1 mm i.d., PE No. N519-0763). The dilatometer was filled with aluminum oxide (Al_2O_3), covered, and re-weighed. The dilatometer was placed in the sample holder of the TMA, and an expansion probe was used to record volume change in the sample during heating. The sample was held isothermally at -15°C for 5 min and then heated from -15°C to 65°C at a rate of 5°C/min. This heating rate was based on results reported by Perdon et al. (2000) in which the effect of heating rate (2, 5, and 10°C/min) on T_g of rice kernels was tested. The T_g at 10°C/min was significantly higher than the T_g found for heating rates of 2 and 5°C/min. It was reasoned that the slower heating rates were more accurate in measuring T_g; because there was no statistical difference in measured T_g between 2 and 5°C/min rates, the 5°C/min heating rate was used in these analyses to reduce the time required for testing. The temperature at which the volume drastically changed was considered the T_g. Perkin-Elmer Thermal Analysis Software Version 4.00 was used to identify the T_g and to calculate the volumetric expansion coefficients from the thermogram. The procedure to determine T_g is illustrated in Figure 1. The T_g was identified as the temperature where tangent lines drawn along the two regions with different slopes intersect. The coefficients of volumetric expansion in the glassy region ($ß_G$) and in the rubbery region ($ß_R$) were computed by multiplying the expansion coefficients calculated at each region by the cross-sectional area of the dilatometer (0.3941 mm^2). After TMA measurement, the kernel was re-weighed to calculate its moisture loss. The MC was subsequently analyzed by drying the kernel for 2 h in an oven set at 130°C.

A state diagram for each cultivar was constructed by plotting the T_gs of the individual kernels against their corresponding MCs. Statistical analysis of the correlation of kernel MC to its corresponding T_g was conducted using JMP IN and SAS Version 6.12 (SAS Institute, Cary, NC). In all analyses, p-values (P) <0.05 were considered to be significant.

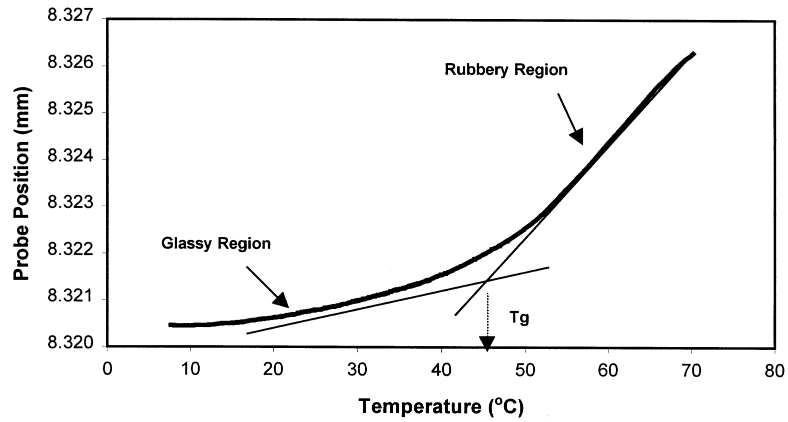

Figure 1. A typical thermal mechanical analysis thermogram indicating the assignment of the glass transition temperature (Tg) and the glassy and rubbery region.

RESULTS AND DISCUSSION

T_g and Volumetric Expansion Coefficient

As expected, the individual kernel T_gs increased with decreasing MC for both varieties. The correlations of T_g to MC were significant: −0.73 for Bengal and −0.62 for Cypress (P for both correlations were < 0.001). An overall correlation of 0.68 ($P < 0.01$) was obtained when pooling the data for both varieties. The resulting relationships represent the state diagrams for each cultivar. Figure 2 shows the combined state diagram of Bengal and Cypress.

The temperature range found for the individual brown rice kernel T_gs (17 to 58°C) corresponds to the T_g that Nehus (1997) reported for milled rice at 16 to 18% MC. In addition, this temperature range generally agrees with the transition temperatures identified by Arora et al. (1973) and Muthukumarappan et al. (1992).

Besides determining the T_g of Bengal and Cypress rice, the TMA was used to quantify the ß above and below glass transition. The mean ß for individual kernels from both cultivars above and below T_g are shown in Table 1. The mean ß in the rubbery state was 4.6×10^{-4} °C, which corresponds to the range of the brown rice thermal expansion coefficients reported by Arora et al. (1973) and Muthukumarappan et al. (1992). The relative magnitude in change in the ßs below and above glass transition was expressed as the ratio of ß in the rubbery state over the corresponding ß in

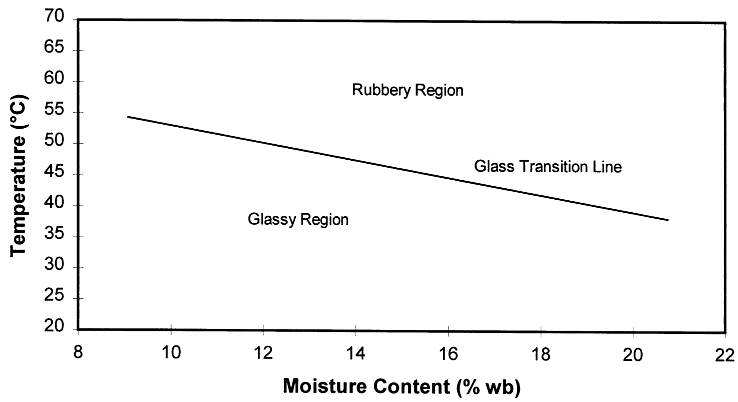

Figure 2. Combined state diagram for Bengal and Cypress indicating the glassy and the rubbery region.

Table 1. Mean Thermal Volumetric Expansion Coefficients (ß)[1] for Individual Brown Rice Kernels from Bengal ($n = 120$) and Cypress ($n = 100$) in the Glassy Region ($ß_G$) and in the Rubbery Region ($ß_R$)

Variety	$ß_G$ $\times 10^{-4}\,^{\circ}C^{1}$	$ß_R$ $\times C10^{-4}\,^{\circ}C^{1}$	$ß_R/ß_G$
Bengal	0.86^a (0.04)	4.99^a (0.17)	5.80^a
Cypress	0.89^a (0.04)	4.26^b (0.15)	4.79^b

[1]Using LSD at $\alpha = 0.05$, means within a column superscripted with the same letter are not significantly different from each other. Value in parenthesis is the standard error of the mean.

the glassy state ($ß_R/ß_G$). The $ß_R/ß_G$ was 5.80 and 4.79 for Bengal and Cypress respectively.

Rice Kernel Fissuring Hypothesis

As can be seen in Figure 2, the state transition in a rice kernel occurs in the temperature range typically encountered during rice drying and would affect the material properties in a rice kernel. The TMA experiments showed that the thermal volumetric expansion changed dramatically as the kernel temperature passed through T_g. These results may be applied in understanding the mechanism of rice kernel fissuring.

Figure 3 depicts a hypothetical kernel temperature and MC gradient created during drying. During drying, the MC of the outer layers of the kernel is lower than the MC of the center, resulting in an MC gradient throughout the kernel. Depending on the temperature, the kernel may be glassy throughout, rubbery throughout, or may have regions that are in one state while adjoining regions are in the other state. Existence of a temperature and/or MC gradient within a kernel will generate regions with different magnitudes of mechanical properties, such as different expansion coefficients or kernel densities. The difference in magnitudes of these properties may be sufficient in creating stresses that will cause the kernel to fissure. The kernel may be able to withstand some stress but when a stress limit is reached, the kernel may fissure.

A hypothetical MC gradient during the drying process is mapped onto the combined state diagram generated for Bengal and Cypress in Figure 4. The points surface, middle, and center correspond to the points 1, 2, and 3, respectively, in Figure 3. At a typical harvest MC around 16 to 22%, the kernels will be glassy at typical temperatures at harvest (around 25°C) since the mean T_g in the 16 to 22% MC range is 36°C which is above this temperature. During drying the temperature of the kernel will increase fairly rapidly to the temperature of the drying air and the material will go through a glass transition from the glassy into the rubbery region. The

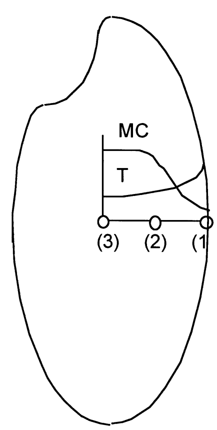

Figure 3. Hypothetical temperature (T) and moisture content (MC) gradient in a rice kernel plotted onto a rice kernel. Points 1, 2, and 3 on the x-axis of the plot correspond respectively to the surface, midpoint between the surface and the center, and center of the kernel.

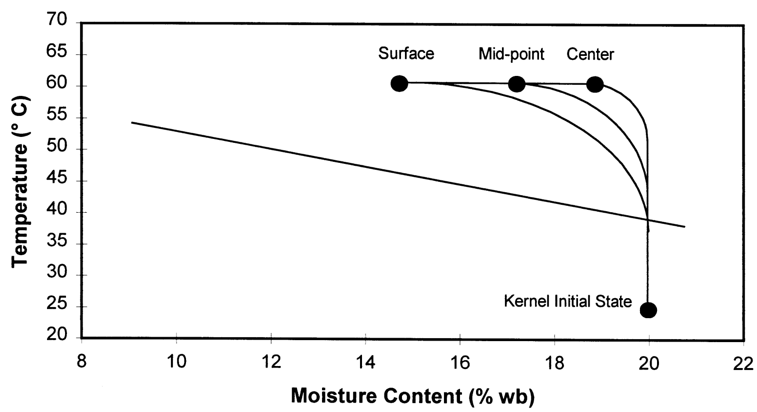

Figure 4. Hypothetical moisture content gradient in a rice kernel during drying plotted onto a state diagram.

temperature will be equal throughout the entire kernel after about 2 to 3 min (Chen et al. 1999). Depending on the drying air temperature, the kernels, or regions within the kernel, will either be glassy or rubbery as defined by their respective T_g. As drying progresses, the surface of the kernel will equilibrate to the drying air EMC.

After the drying pass, a tempering pass is typically used to allow MC gradient relaxation within the kernel. During tempering, the MC gradient from the surface to the center of the kernel will tend to equalize. After and sometimes during tempering, the rice is often cooled and the kernels will again go through a glass transition and become glassy as the kernel temperature decreases. During tempering or during cooling, depending on the temperature that the kernel is exposed to, the outer layer may reside in a glassy state, while the center is still in a rubbery state. Consequently, the different layers would be characterized by different magnitudes of material properties. Figure 5 shows alternative responses of the kernel during the tempering process.

We hypothesize that if the tempering environment is one that produces a change of state of the kernel, differential stresses within the kernel, resulting from the temperature and MC gradients, could cause kernel fissuring. This scenario is depicted by situation ‘B’ in Figure 5 in which the tempering temperature is less than the T_g of the rice and the surface, mid-point, and center of the kernel cross the T_g line at different MCs. Our hypothesis would indicate that this scenario would create kernel fissuring, with resultant HRY reduction, if there was a sufficient MC gradient inside the kernel during state transition. This hypothesis agrees with the observations of Ban (1971),

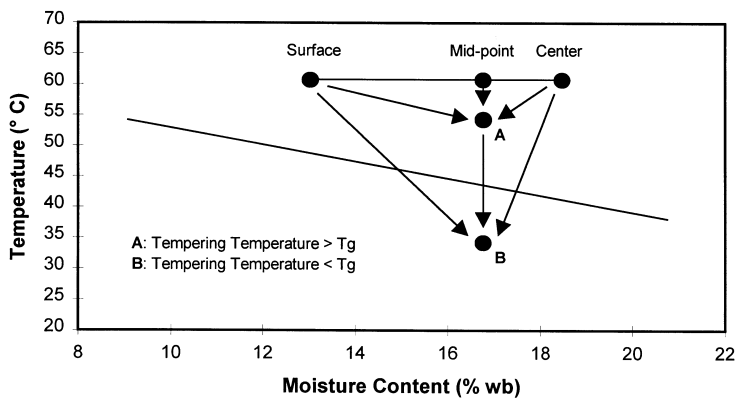

Figure 5. Alternative responses of the various sections of a rice kernel during tempering.

Kunze (1979), Sharma and Kunze (1982), and Nguyen and Kunze (1984) that rice kernels do not fissure until after the drying process has ceased.

Validation of Hypothesis

Laboratory drying tests were designed to validate this hypothesis, with the drying air and tempering temperatures above and below the T_g of the rice.

Figure 6 illustrates the experimental design. The rice lots (15 lots with harvest MCs between 17 and 23%) were dried at three air conditions: condition HI (60°C, 16.9% RH), resulting in 5.5% equilibrium moisture content (EMC) as predicted by the Chung equation (ASAE, 1998); condition HII (60°C, 50% RH), resulting in 9.2% EMC; and condition LI (40°C, 12% RH), resulting in 5.8% EMC. The thin layer drying system described in the experimental design was used for these drying experiments. For each drying condition, samples were dried for four different durations, resulting in 1.5, 3, 4.5, and 6–percentage points MC loss. 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. Two drying replications were performed for each drying condition/duration combination. Weight loss of the rice was monitored during drying to terminate drying as soon as the desired MC reduction was achieved. After each drying run, the actual MC loss of the sample was measured by drying duplicate 15 g samples for 24 h in an oven set at 130°C (Jindal and Siebenmorgen, 1987).

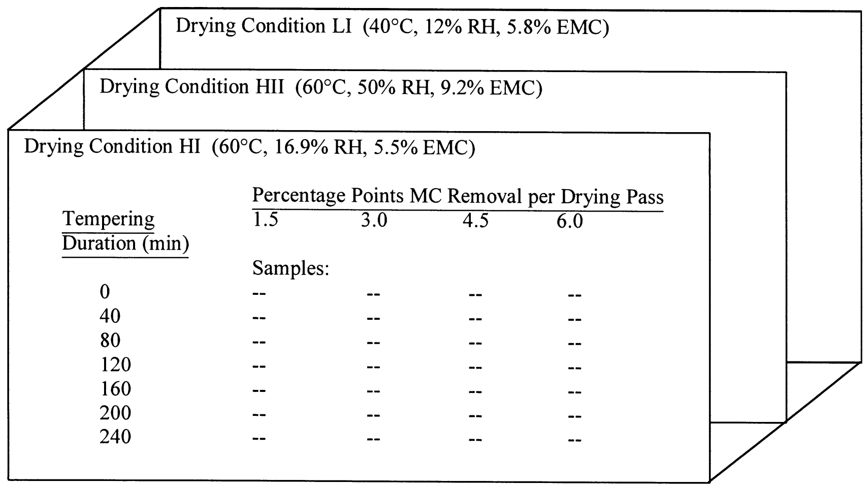

Figure 6. Experimental design for the drying and tempering experiments. Layout represents the sampling routine for each harvest location/variety/harvest moisture content lot.

Immediately after a drying run, the rice batch was split into seven sub-samples, which were tempered for varying durations ranging from 0 to 4 h in 40-min increments in an oven set at the temperature of the dryer. The varying tempering durations created varying levels of MC equilibration in the kernels, i.e., a tempering duration of 0 min resulted in maximum MC gradient while extended tempering resulted in reduced gradients. Tempering of samples was performed in sealed bags. After tempering, the samples were taken out of the sealed bags and placed into an EMC chamber maintained at 21°C and 55% RH to gently dry to 12.5% MC. This 21°C temperature is well below the T_g of the rice at typical MCs. Thus, the kernels were forced to undergo a state transition with varying levels of MC gradients due to the varying tempering durations.

Prior to milling, the samples were held in storage at 4°C for 3 months. A Satake laboratory huller was used to dehull the rice. Samples were subsequently milled for 30 sec in a McGill no.2 mill, resulting in a degree of milling of 80 to 90 as measured with a Satake MM-1B milling meter. The mass of head rice (kernels three-fourths or more of the original kernel length) was determined using a FOSS Graincheck 310 image analyzer (Foss North America, Minneapolis, MN) and the HRY calculated as the mass fraction of rough rice remaining as head rice.

As a means of control, two samples of rice from each harvest lot were gently dried in the EMC chamber from HMC to 12.5% MC, resulting in a high HRY. HRYs of the samples having received different treatments were then compared against the HRY of the control sample.

Results of the Drying and Tempering Experiments

The HMCs were measured with a Motomco 919A moisture meter (Dickey-john, Auburn, IL) after cleaning the rice. An accurate HMC, determined by the 24-hour oven procedure (Jindal and Siebenmorgen 1987), was not available when the drying runs were started. Therefore, the actual percentage points MC removed during each drying run, measured with the oven method, deviated slightly from the target MCs calculated with the initial estimation of HMC with the moisture meter.

Drying Above T_g: HRY Results

According to our hypothesis, if rice is tempered above the T_g line sufficiently long enough to reduce MC gradients, a state transition will not cause HRY reduction. Insufficient MC gradient reduction before a state transition will produce fissures and consequent HRY reduction.

Figure 7 shows the HRYs of Bengal samples for different tempering durations, after different percentage points MC were removed using the 60°C, 16.9% RH drying condition (HI). From Figure 7, removing 1.5 percentage points MC caused little damage to the rice, and tempering had no effect. This indicates that for this drying duration, sufficient MC gradients were not produced during drying to create fissures when the rice was placed in the 21°C environment and forced to undergo a state transition. However, when removing up to 4.8 percentage points MC without tempering (0 min tempering duration), a dramatically lower HRY was observed. Furthermore, the samples that were tempered for 40 min showed a significant increase in HRY relative to those receiving no tempering, and the samples tempered for 120 min did not show any HRY reduction compared to the control sample. When removing up to 5.6 percentage points MC, 160 min tempering was necessary to achieve a HRY equivalent to that of the control. This indicates that, after these tempering durations, the MC gradients were sufficiently reduced and did not lead to fissuring.

Figure 8 shows that the minimum tempering durations required to have no HRY reduction increased significantly with decreasing HMC. The HRY for the 0 min tempering durations was much lower for the

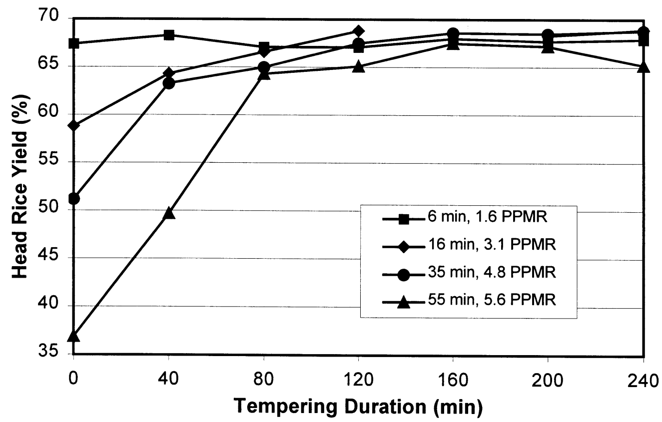

Figure 7. Head rice yield (HRY) versus tempering duration for variety Bengal rice harvested in 1998. The rice was dried for the four indicated durations (PPMR is percentage points moisture content removed in one drying pass) with 60°C and 16.9% RH drying air (condition HI). The harvest moisture content was 21.3%. The HRY of the control sample was 67.9%.

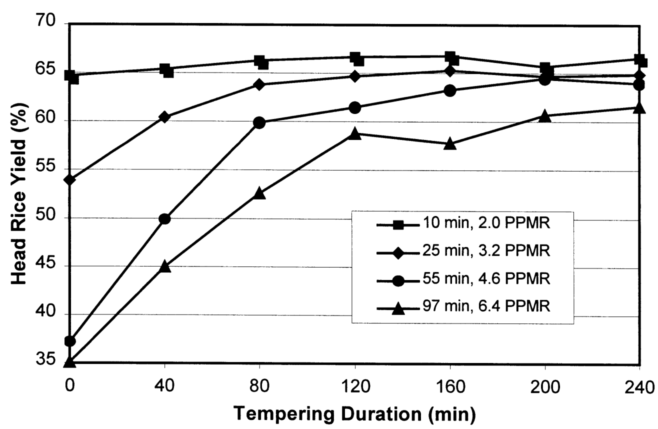

Figure 8. Head rice yield (HRY) versus tempering duration for variety Bengal rice harvested in 1999. The rice was dried for the four indicated durations (PPMR is percentage points moisture content removed in one drying pass) with 60°C and 16.9% RH drying air (condition HI). The harvest moisture content was 17.6%. The HRY of the control sample was 65.0%.

sample with a HMC of 17.6% (Figure 8) than for the sample with a HMC of 21.3% (Figure 7). As much as 200 min of tempering was necessary to remove the MC gradients in the rice kernel when removing 4.6 percentage points MC.

The maximum amount of moisture that could be removed from the rice in a single drying pass was 5 to 6 percentage points. The actual percentage points MC removed was as much as 6.4% for several harvest lots. These samples showed significant irreversible structural damage; even after 240 min tempering the HRY was lower than the HRY of the control sample (Figure 8). The maximum amount of moisture that could be removed per pass decreased slightly with decreasing HMC. This observation agrees with the findings of Fan et al. (2000). Rice dried under the 60°C and 50% RH drying condition showed slightly higher HRYs for the shorter tempering durations, indicating that these samples tempered faster.

Figure 9 represents the HRY results for variety Cypress when dried at the 60°C and 16.9% RH drying condition. Required tempering durations, to maintain a high HRY, were significantly shorter for the long-grain Cypress compared to that of the medium-grain Bengal. Tempering durations of approximately 40 min were sufficient when removing up to 4.5 percentage points MC, and only 80 min of tempering was needed to reduce the MC

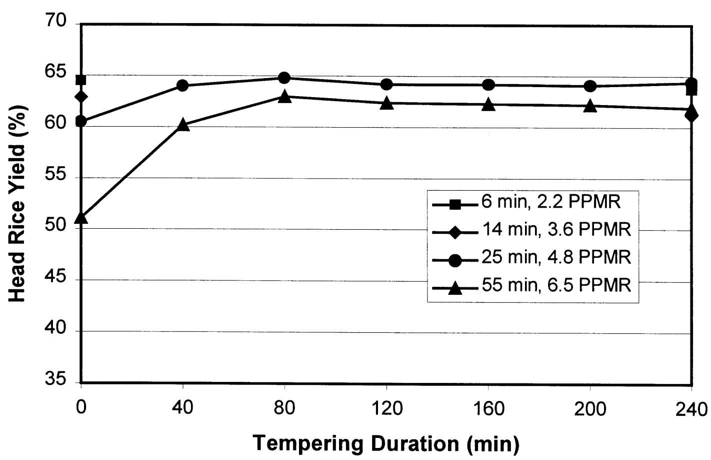

Figure 9. Head rice yield (HRY) versus tempering duration for variety Cypress rice harvested in 1998. The rice was dried for the four indicated durations (PPMR is percentage points moisture content removed in one drying pass) with 60°C and 16.9% RH drying air (condition HI). For the 2.2 and 3.6 PPMR durations only the zero and 240 min tempering durations are depicted. The harvest moisture content was 20.6%. The HRY of the control sample was 64.5%.

gradients when removing up to 6 percentage points MC. Due to a thinner kernel, the magnitude of the MC gradient in a long-grain rice kernel could be smaller compared to that of a medium-grain kernel, resulting in a faster equilibration time. Although the HRY reduction for Cypress was less dramatic compared to Bengal when the rice was not tempered, the maximum amount of moisture that could be removed in one drying pass, without experiencing irreversible structural damage, was similar to Bengal.

The shorter tempering durations for rice dried under the high RH drying condition over rice dried under the low RH drying condition that were observed with Bengal were not observed with Cypress. For Cypress as with Bengal, HMC also had a significant influence on tempering duration; the lower the HMC, the longer the required tempering duration. Cypress harvested at 23% MC required 40 min of tempering when removing 6 percentage points MC, while Cypress harvested at 20.6% MC required 80 min of tempering, when dried under the 60°C, 16.9% RH drying air condition.

Drying Below T_g: HRY Results

Due to a slower drying process, resulting in less severe MC gradients, and the fact that a state transition did not occur when cooling, tempering had little effect on the HRY for both varieties when rice was dried using a drying air temperature (40°C) below the T_g. The slower drying process did not cause a sufficient MC gradient inside the kernel to cause significant fissuring and subsequent breakage. Figure 10 shows the HRY versus tempering duration for Bengal dried with a drying air temperature below the T_g. The Bengal rice showed a small decrease in HRY with increasing amounts of MC removal. Variety Cypress showed little HRY reduction for prolonged drying durations. HMC did not have a significant effect on HRY results when using drying air temperatures less than T_g.

Future Work

Temperatures above the T_g of the rice significantly reduce the drying duration needed to remove a certain amount of moisture and reduce the tempering duration required to maintain high HRYs, since the moisture diffusivity is much higher above T_g. The HRY results of Bengal show that rice dried with the 60°C and 50% RH air tempered faster than the rice dried with the 60°C and 16.9% RH air. During the drying process, the surface of the kernel equilibrates with the EMC of the drying air. When using drying

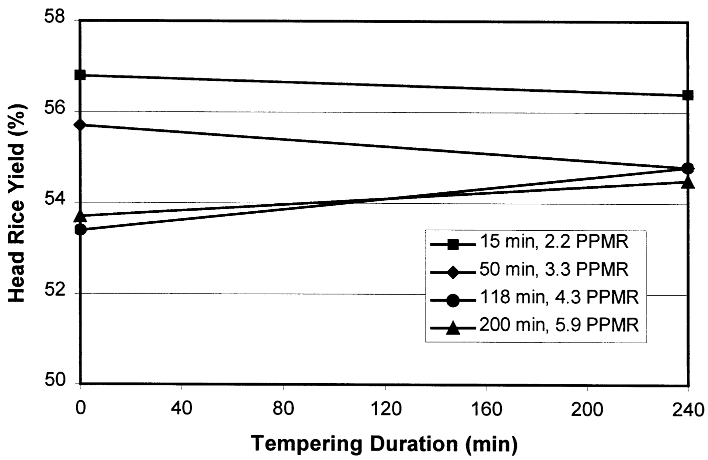

Figure 10. Head rice yield (HRY) versus tempering duration for variety Bengal rice harvested in 1998. The rice was dried for the four indicated durations (PPMR is percentage points moisture content removed in one drying pass) with 40°C and 12% RH drying air (condition LI). The harvest moisture content was 19.6%. The HRY of the control sample was 55.8%.

conditions which result in extremely low EMCs (when using high drying temperatures and low RHs), it is speculated that the surface of the rice kernel could transit from the rubbery state back into the glassy state since the T_g of the rice increases with decreasing MC. Under this scenario, the kernel would dry more slowly than if the surface were maintained above T_g. The lower diffusion, if the surface were in the glassy state, would limit diffusion from the rubbery center. With the surface in the glassy state and the center of the kernel in the rubbery state, the tempering process would also be slowed. Additional research is needed to confirm this surface phenomenon speculation and to assess whether these low EMC drying conditions change the rice kernel structure and if these changes are permanent. If structural and/or chemical changes occur in the surface layer of the kernel, these changes could affect end-use processing operations such as moisture absorption kinetics.

CONCLUSIONS

The T_gs of individual kernels of Bengal and Cypress brown rice at different MCs were measured using a thermal mechanical analyzer. The T_g

increased as MC decreased. Brown rice kernel thermal volumetric expansion coefficients were also measured and shown to be much lower in the glassy region than in the rubbery region. The measured T_gs were used to generate a state diagram. Subsequently, a hypothetical drying process was mapped onto the state diagram and a hypothesis was developed to explain kernel fissuring during the drying process.

Drying and tempering tests were conducted with medium- (Bengal) and long-grain (Cypress) rice harvested over a range of MCs to validate the rice kernel fissuring hypothesis. The results demonstrated that if a sufficient MC gradient existed in the kernel as it was cooled, forcing a transition from the rubbery to glassy state, fissures formed as indicated by reduced HRY. The results also showed that drying air temperatures as high as 60°C can be used without reducing the HRY as long as sufficient tempering, at a temperature above the T_g of the rice, is allowed. For both Bengal and Cypress and for both drying conditions with a drying air temperature above the T_g of the rice, 5 to 6 percentage points MC could be removed in a single drying pass without damaging the kernel, if the rice was tempered at 60°C before cooling to 21°C. HMC had a significant effect on the minimum tempering duration required to maintain a high HRY, the lower the HMC, the longer the required tempering duration. When drying rice with a HMC between 21 and 17% at 60°C, 160 to 240 min of tempering was sufficient for Bengal and a tempering time of 80 to 160 min was sufficient for Cypress, based on achieving HRYs equivalent to that of the control samples. Tempering had no effect on the HRY for both varieties when rice was dried using a drying air temperature below the T_g. For Bengal rice, the HRY results showed that the tempering process was faster for rice dried with high RH drying air compared to rice dried with low RH air; while this trend was consistent across HMCs, further research is needed to explain this observation.

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REFERENCES

ASAE Standards, 45th Ed. 1998. D245.5. Moisture Relationship of Plant Based Agricultural Products. St. Joseph, MI.: ASAE.

Arora, V.K., Henderson, S.M. and Burkhardt, T.H. 1973. Rice drying cracking versus thermal and mechanical properties. Transactions of the ASAE, 16(2) pp. 320–323, 327.

Ban, T. 1971. Rice cracking in high rate drying. Japanese Agricultural Research Quarterly, 6(2) pp. 113–116.

Beeny, J.M. and Chin, S.N. 1970. Multi-pass drying of paddy (rice) in the humid tropics. Journal of Agricultural Engineering Research, 15(4) pp. 364–374.

Biliaderis, C.G. 1991. The structure and interactions of starch with food constituents. Canadian Journal of Physiology and Pharmacology, 69(1) pp. 60–78.

Chen, H., Siebenmorgen, T.J. and Yang, W. 1999. Finite element simulation to relate head rice yield reduction during drying to internal kernel moisture gradient and rice state diagram. ASAE paper No. 996156, ASAE, St. Joseph, MI, USA.

Cnossen, A.G., Siebenmorgen, T.J., Reid, J.D. and Perdon, A.A. 1998. Characteristics of rough rice during tempering. ASAE Paper No. 98–6033. St. Joseph, MI.: ASAE.

Fan, J., Siebenmorgen, T.J. and W. Yang. 2000. A study of head rice yield reduction of long- and medium-grain rice varieties in relation to various harvest and drying conditions. Transactions of the ASAE. In press.

Jindal, V.K. and Siebenmorgen, T.J. 1987. Effects of oven drying temperature and drying time on rough rice moisture content determination. Transactions of the ASAE, 30(4) pp. 1185–1192.

Kobayashi, H., Miwa, Y. and Matsuda, R. 1976. Studies on the strain and the cracking of rice kernels during drying (I) – Particularly a method of calculation of cross sectional area and the modulus of elasticity of brown rice by compression test. Journal of the Japanese Society of Agricultural Machinery, 37(4) pp. 551–556.

Kunze, O.R. 1979. Fissuring of the rice grain after heated air drying. Transactions of the ASAE, 22(5) pp. 1197–1202, 1207.

Kunze, O.R. and Choudhury, M.S.U. 1972. Moisture adsorption related to the tensile strength of rice. Cereal Chemistry, 49(6) pp. 684–696.

Kunze, O.R. and Prasad, S. 1978. Grain fissuring potentials in harvesting and drying of rice. Transactions of the ASAE, 21(2) pp. 361–366.

Morita, T. and Singh, R.P. 1979. Physical and thermal properties of short-grain rough rice. Transactions of the ASAE, 22(3) pp. 630–636.

Mossman, A.P. 1986. A review of basic concepts in rice-drying research. CRC Critical Reviews in Food Science and Nutrition, 25(1) pp. 49–71.

Muthukumarappan, K., Jindal, V.K. and Gunasekaran, S. 1992. Volumetric changes in rice kernels during desorption and adsorption. Transactions of the ASAE, 35(1) pp. 235–241.

Nehus, Z.T. 1997. Milled rice breakage as influenced by environmental conditions, kernel moisture content, and starch thermal properties. MS Thesis. University of Arkansas, Fayetteville, AR.

Nguyen, C.N. and Kunze, O.R. 1984. Fissures related to post-drying treatments in rough rice. Cereal Chemistry, 61(1) pp. 63–68.

Peleg, M. 1996. On modeling changes in food and biosolids at and around their glass transition temperature range. CRC Critical Reviews in Food Science and Nutrition, 36(1) pp. 49–67.

Perdon, A.A. 1999. Amorphous state transition in rice during the drying process. Ph.D. dissertation. Department of Food Science, University of Arkansas, Fayetteville, AR.

Sharma, A.D. and Kunze, O.R. 1982. Post-drying fissure developments in rough rice. Transactions of the ASAE, 25(2) pp. 465–468, 474.

Siebenmorgen, T.J. 1998. Influence of post-harvest processing on rice quality. Cereal Foods World, 43(4) pp. 200–202.

Siebenmorgen, T.J. and Perdon, A.A. 1999. Applying glass transition principle to explain fissure formation during the drying process. Presented at the 1999 International Starch Technology Conference, June 7–9, 1999, Urbana, IL.

Slade, L. and Levine, H. 1991. A polymer science approach to structure/property relationships in aqueous food systems: Non-equilibrium behavior of carbohydrate-water systems. Pages 29–101 in Water Relationships in Foods. H. Levine and L. Slade, eds. Plenum Press: New York, NY.

Slade, L. and Levine, H. 1995. Glass transitions and water– Food structure interactions. Advanced Food Nutrition Research, 38 pp. 103–269.

Steffe, J.F. and Singh, R.P. 1980a. Liquid diffusivity of rough rice components. Transactions of the ASAE, 23(3) pp. 767–774.

Steffe, J.F. and Singh, R.P. 1980b. Theoretical and practical aspects of rough rice tempering. Transactions of the ASAE, 23(3) pp. 775–784.

Steffe, J.F., Singh, R.P. and Bakshi, A.S. 1979. Influence of tempering time and cooling on rice milling yields and moisture removal. Transactions of the ASAE, 22(5) pp. 1214–1218, 1224.

Wasserman, T., Ferrel, R.E., Houston, D.F., Breitweiser, E. and Smith, G.S. 1964. Tempering western rice. Rice Journal, 67(2) pp. 16, 17, 20–22.

White, G.W. and Cakebread, S.H. 1966. The glassy state in certain sugar-containing food products. Journal of Food Technology, 1 pp. 73–82.

Wratten, F.T., Poole, W.D., Chesness, J.L., Bal, S. and Ramarao, V. 1969. Physical and thermal properties of rough rice. Transactions of the ASAE. 12(6) pp. 801–803.

Yamaguchi, S., Yamazawa, S., Wakabayashi, K. and Hosona, H. 1980. Experimental study on the internal stress cracking of rice kernel (Part 2). A comparison between thermal and moisture stress and an arrangement of rice cracking data on the Weibull Probability Paper. Journal of the Japanese Society of Agricultural Machinery, 42(2) pp. 251–257.