Relating Rice Milling Quality Changes During Adsorption to Individual Kernel Moisture Content Distribution[1]

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ABSTRACT

Several varieties of rough rice that were either stored for an extended period of time or freshly harvested were conditioned to initial moisture contents ranging from 10 to 17%. After the individual kernel moisture content distributions were measured, the samples were soaked in water at temperatures ranging from 10 to 40°C. The samples were then dried and milled. The bulk critical moisture content, at which head rice yield began to decline due to moisture adsorption, ranged from 12.5 to 14.9%, depending on the variety, harvest moisture content, and storage conditions. The kernel critical moisture content, determined from each sample from the cumulative kernel moisture content frequency distribution, increased with increasing sample initial moisture content.

Rice quality is determined by several grading factors including head rice yield (HRY). Head rice is defined as milled rice including kernels three-fourths or more of the original kernel length (USDA 1979). The HRY is the mass fraction of rough rice that remains as head rice after complete milling. Because broken kernels have a considerably lower commercial value than that of head rice, a primary goal of the rice industry is to maximize HRY.

A primary cause of HRY reduction is the development of kernel fissures resulting from stresses induced by moisture sorption. Kernels with fissures will generally break apart during milling, causing reductions in HRY. Past research has addressed this overall issue by investigating fissure formation in individual kernels, as well as by directly measuring the effects of moisture adsorption on HRY reduction.

Fissuring Caused by Moisture Adsorption

Previous research has shown that rapid moisture adsorption leads to kernel fissuring and subsequent breakage during milling. Kunze and Choudhary (1972) showed that when kernels are suddenly exposed to a step increase in relative humidity (RH), moisture is adsorbed at their surface. This results in a swelling of the cells in the surface layers, producing compressive stresses that are balanced by tensile stresses in the inner portion of the kernel. If the compressive stresses in the surface layers develop to the extent that the resulting tensile stresses exceed the tensile strength of the central portion of the kernel, fissuring occurs. Kunze (1977) concluded that when low moisture content (MC) rice kernels in preharvest and postharvest conditions are subjected to environments causing moisture adsorption, the kernels develop internal fissures perpendicular to their long axis.

Kondo and Okamura (1930) found that field rewetting increased the number of cracked kernels, and that the percentage of cracks increased with the duration of exposure to moisture. Stahel (1935) showed that the percentage of whole grains in field rice begin to decline at an average field MC of 17–20% (all moisture contents, unless otherwise stated, are expressed on a wet weight basis) and that moisture adsorption produces fissures below the critical point of 14%. Breese (1955) reiterated Stahel's statements in his study of hysteresis in hygroscopic equilibria of rough rice.

Srinivas et al (1978) reported that fissuring of long-grain rough rice during soaking was related to the initial moisture contents (IMC) and soaking water temperatures and durations in four long-grain rice varieties: Halubbulu, Kaddi Bhatha, IR 20, and Madhu. The water temperatures in the study ranged from 5 to 85°C. An increase in the soaking water temperature generally produced higher fissuring rates and greater numbers of fissures, although sufficiently high temperatures induced gelatinization and apparent fissure healing. At 5°C, fissuring occurred after 45 min, while at 80°C, maximum fissuring occurred within 15 min.

Effects of Moisture Adsorption on HRY

Siebenmorgen and Jindal (1986) quantified the effects of moisture adsorption directly on head rice yield reductions (HRYR) for long-grain rough rice. All adsorptive conditions, including high RH air, soaking, and mixing with high MC rice, resulted in significant HRYR when the IMC was <13%. Remoistening of rice at MC >16% had no discernible effect on HRY. Chen and Kunze (1983) exposed rough rice samples at MC levels of 8.6 and 10.7% to RH environments of 64, 72, 82, and 92%, and temperatures of 20 and 30°C. Exposure duration, IMC, and RH were significant in reducing HRY. Banaszek and Siebenmorgen (1990) developed an equation to predict HRYR for rough rice exposed to moisture adsorptive conditions. They found that RH and IMC are significantly related to the HRYR caused by moisture adsorption. Temperature was of minimal importance under the adsorptive conditions used.

Variation of Individual Kernel MC

Chau and Kunze (1982) found significant variability in individual kernel MC levels in the field. They concluded that the longer rice is left in the field, the greater the probability that the kernels with lower MC will fissure before harvest. Kocher et al (1990) observed that individual kernel MC distributions showed two to three modes on early harvest dates, but that the high MC modes gradually diminished as time progressed. They concluded that this field variability was the primary reason that individual rice kernels respond differently to both field and postharvest operations.

Kunze and Prasad (1978) showed that there was a wide span of individual kernel MC levels within a mass of freshly harvested rice. Wadsworth et al (1982) found that the MC levels of thicker-kernel fractions, which included 90% of the weight of their samples, were not significantly different, but the MC levels of the remaining thinner kernel fractions were significantly higher than the bulk rice and increased with decreasing thickness. Siebenmorgen et al (1990) showed that there was considerable variation in kernel MC levels within a bulk, even after three months of equilibration. They also reported greater kernel MC variability at higher average MC levels.

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Critical Moisture Content and HRY

Siebenmorgen et al (1992) defined the critical moisture content (CMC) as the MC below which a kernel will fissure when rewetted. They found that CMC levels range from 12 to 15%, depending on varieties and environmental conditions. Kamau and Kunze (1986, *unpublished data*) determined that the MC levels at which 99% of the rough rice kernels would not fissure from moisture adsorption were 16.3 and 16.1% for Labelle and Skybonnet, respectively. Siebenmorgen et al (1992) correlated HRYR in the field to the percentage of long-grain kernels with MC levels below a critical level before rain. HRY values obtained from the harvest dates after rain were significantly correlated with the percentage of kernels >10.5% MC for Newbonnet, 12.5% MC for Tebonnet, and 13.5% MC for Lemont, as measured on the harvest dates immediately before a rain.

Juliano and Perez (1993) determined the CMC in selected varieties of rough rice after harvest in both dry and wet seasons. In their research, rice was dried to MC 10–20%, stressed by soaking in water for 2 hr, and redried before milling. The variety IR42 had a CMC of 16% in both crops, whereas the variety IR60 had a CMC of 14% in the dry season and 12% in the wet season.

In summary, the inherent variation in kernel MC in rice both before and after harvest and the existence of varying moisture adsorption behaviors and CMC levels among varieties have been addressed. Only limited research, however, has related kernel MC distributions to HRYR values due to moisture adsorption, particularly in terms of the role MC distribution plays in affecting the CMC. The objectives of this study were to: 1) quantify the overall CMC due to moisture adsorption for different rice varieties harvested and stored under varying conditions; 2) test whether the CMC due to moisture adsorption could be determined by relating the HRYR due to soaking to the percentage of kernels within a bulk having an IMC below certain levels.

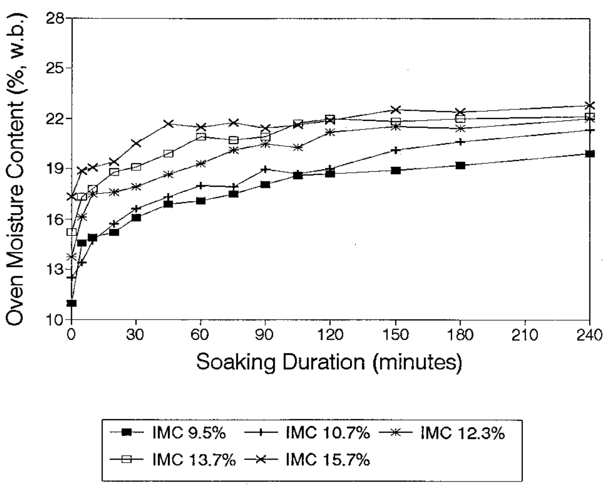

Fig. 1. Moisture adsorption curves resulting from soaking (at 20°C) Newbonnet rice stored at 13.5% moisture content with different initial moisture contents (IMC) levels.

MATERIALS AND METHODS

Sample Preparation

Five long-grain varieties, Newbonnet, Lemont, Millie, Lacassine, and Alan, were included in the study. Lemont was harvested at the Rice Research and Extension Center at Stuttgart, AR, in September 1991. Some of the Newbonnet was harvested at the Northeast Research and Extension Center at Keiser, AR, in September 1992. The convention used for variety and storage condition identification is to list the variety abbreviation subscripted by the term stored and the MC at which the rice was stored, if stored for an extended period of time, or the term fresh and the harvest MC, if soaking tests were conducted shortly after harvest. Lemont was stored at 3°C with MC 14.5% ($LM_{Stored-14.5}$) for about two years, while Newbonnet was stored at 3°C with MC 13.5% ($NB_{Stored-13.5}$) for one year before testing. The remaining varieties and two other lots of Newbonnet were harvested at the Rice Research and Extension Center in September 1993, just before the soaking tests. The harvest MC levels for the 1993 samples were 17.5% ($NB_{Fresh-17.5}$) and 24.0% ($NB_{Fresh-24.0}$) for Newbonnet, 18.5% ($AL_{Fresh-18.5}$) and 23.0% ($AL_{Fresh-23.0}$) for Alan, 20.5% ($LC_{Fresh-20.5}$) for Lacassine, and 21.5% ($ML_{Fresh-21.5}$) for Millie.

Approximately 120 kg of stored Newbonnet and Lemont were removed from cold storage and cleaned with a Carter-Day dockage tester (Carter-Day, Co., Minneapolis, MN) with No. 28, 25, and 22 sieves. The freshly harvested varieties were similarly cleaned immediately after harvest. The cleaned rice was double-bagged using plastic bags and stored at 1°C for about two months before soaking.

Cleaned rough rice was removed from cold storage 24 hr before conditioning to allow equilibration to room temperature. Each variety was divided into six lots using a Boerner divider. Each lot was conditioned to one of six target IMC levels by loading 16 450-g subsamples into perforated metal trays (254 × 152 × 150

TABLE I
Initial Moisture Content (IMC) Values Attained at Each Target Moisture Content (MC) Level

Sample	Storage or Harvest MC (%)	Procedure	Target IMC (% wb)					
			9.5	11.5	12.5	14	15.5	17
Stored at 3°C								
Newbonnet	13.5	Oven[a]	10.9	12.5	13.7	15.2	17.3	. . .
		Meter[b]	9.5	10.7	12.3	13.7	15.7	. . .
Lemont	14.5	Oven	11.2	12.2	13.8	15.6	16.9	19.1
		Meter	10.0	11.3	12.3	13.8	15.4	17.2
Freshly harvested								
Newbonnet	24.0	Oven	11.4	12.0	12.8	14.6	15.3	17.3
		Meter	10.5	11.3	12.3	13.9	14.5	16.5
Newbonnet	17.5	Oven	11.3	12.0	12.9	14.4	15.0	16.9
		Meter	10.3	11.3	12.7	13.6	14.1	16.8
Alan	23.0	Oven	11.3	12.1	13.3	13.8	14.2	18.0
		Meter	10.6	11.6	12.5	14.3	14.7	16.7
Alan	18.5	Oven	11.3	12.1	12.6	13.9	15.0	17.0
		Meter	10.5	11.6	12.4	14.1	14.8	16.2
Millie	21.5	Oven	11.3	12.1	13.0	14.3	15.0	17.0
		Meter	11.0	11.6	12.6	14.5	15.0	16.7
Lacassine	20.5	Oven	11.0	12.1	12.9	13.7	15.4	. . .
		Meter	10.1	11.6	12.5	14.9	15.2	. . .

[a] Average of three determinations.
[b] Average for 4,000 kernels.

mm) and placing them parallel above an air plenum inside a conditioning chamber. Air was supplied to the conditioning chamber by an RH and temperature control unit (PG&C Climate-Lab-AA 300 CFM, Parameter Generation and Control, Black Mountain, NC). The conditioning unit air temperature was set at 25°C and the RH was set at 37, 50, 62, 74, 83, or 90% to attain target IMC levels of 9.5, 11.0, 12.5, 14.0, 15.5, and 17.0%, respectively, based on the Modified Henderson Equation (ASAE 1994).

All freshly harvested varieties >18% MC were first dried to 18% MC using air at 25°C and 94% RH before conditioning to the target IMC levels. To prevent possible damage due to conditioning, the samples were dried gradually, at ≈2.0–2.5 percentage points per 24 hr. After conditioning, all of the samples were placed in double plastic bags and stored at 1°C for at least one week to allow for the equilibration of moisture within the kernels.

Bulk and Individual Kernel MC Measurement

The bulk sample and individual kernel MC levels of each variety-IMC sample were measured immediately before the soaking tests (described below). The bulk sample MC was determined by oven drying three replicates of 20 g, whole kernel subsamples at 130°C for 24 hr in a convection oven. Individual kernel MC levels were measured using a single kernel moisture tester (model CTR-800A, Shizouka Seiki, Shizouka, Japan). Five 800-kernel MC measurements (4,000 kernels total) were recorded for each variety-IMC level.

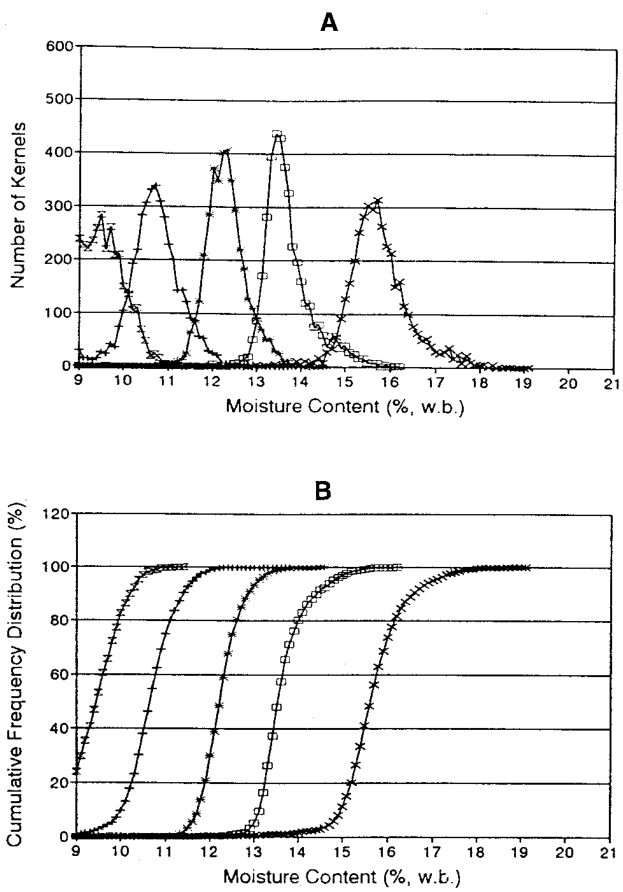

Fig. 2. Kernel moisture content frequency distributions (**A**) and cumulative frequency distributions (**B**) for 4,000-kernel samples of Newbonnet rice stored at 13.5% moisture content at five initial moisture content (IMC) levels.

Soaking Tests

Soaking tests were conducted at 10, 20, 30, and 40°C water temperatures over 14 durations (0, 5, 10, 20, 30, 45, 60, 75, 90, 105, 120, 150, 180, 240 min) for the stored varieties. The results showed that the HRY values stabilized after certain soaking durations for each soaking temperature. Based on these results, 10, 20, and 30°C soaking temperatures were selected for subsequent tests on the six freshly harvested lots. Additionally, because the maximum HRYR for a variety-IMC-soaking temperature combination was of primary interest, the soaking durations chosen for the freshly harvested varieties were those in which no HRYR values had increased in the stored variety tests: 150 min at 10°C, 120 min at 20°C, and 60 min at 30°C.

Each rice lot was removed from cold storage 24 hr before soaking. Approximately 350-g samples from each variety-IMC sample were placed in perforated metal trays and submerged in water pans placed inside the conditioning chamber. The water temperature was controlled by the air temperature of the chamber. The initial water depth in the pans was 2.5 cm, which was sufficient to submerge the rice samples for the entire test period.

After the specified soaking durations, the samples were removed from the water pans and quickly blotted with paper tow-

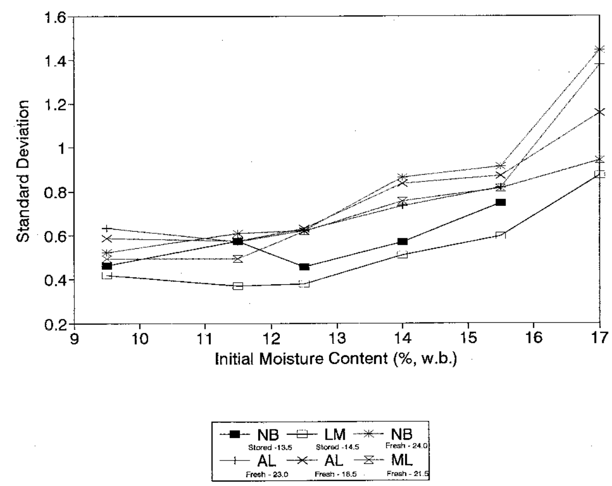

Fig. 3. Effect of initial moisture content on individual kernel moisture content standard deviations for the rice varieties Newbonnet (NB), Lemont (LM), Millie (ML), and Alan (AL), stored and fresh, at different moisture contents.

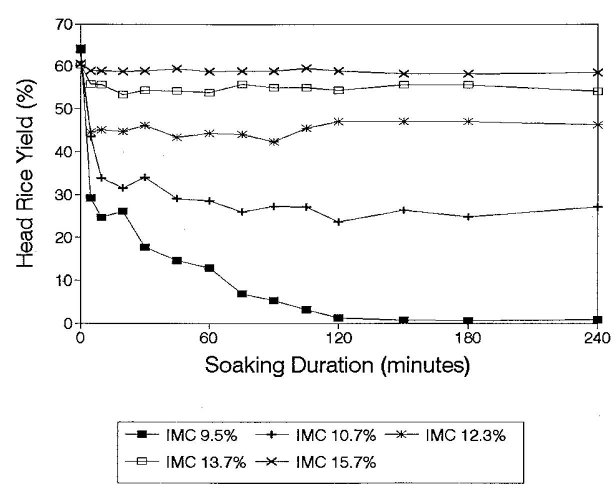

Fig. 4. Head rice yield vs. soaking duration for Newbonnet rice stored at 13.5% moisture content with the indicated initial moisture content (IMC) levels at 20°C soaking water temperature. Each data point is the average of two head rice yield determinations.

els to remove water from the kernel surfaces. Immediately after blotting, ≈20 g were taken from each of the samples for oven MC measurement. The remaining rice was placed on wire-mesh trays in a conditioning closet and exposed to air at 25°C and 62% RH until it reached the desired 12.5% MC for the milling tests. All samples with 0 soaking durations were also placed in the closet in preparation for the milling tests.

HRY Determination

All of the samples were milled at ≈12.5% MC to determine HRY. Two 150-g subsamples were milled from each sample. A McGill Sheller (Rapsco, Brookshire, TX) was first used to hull the rice using a roller clearance of 0.483 mm (0.019 in.) (USDA 1979). The resulting brown rice was milled in a McGill no. 2 laboratory mill. A 1.5-kg weight was placed on the lever arm 15 cm from the center of the mill saddle. The milling duration was 45 sec (Andrews et al 1992). A Seedburo sizing machine (Seedburo Equipment Co., Chicago, IL) was used to separate the head rice from broken kernels. The diameters of the circular indentations of the upper and lower plate of the sizing machine were 0.516 cm (13/64 in.) and 0.476 cm (12/64 in.), respectively. The HRY was calculated as: HRY (%) = (Mass of head rice immediately after milling [g]/Mass of rough rice at the milling MC [g]) ×100 (Eq. 1).

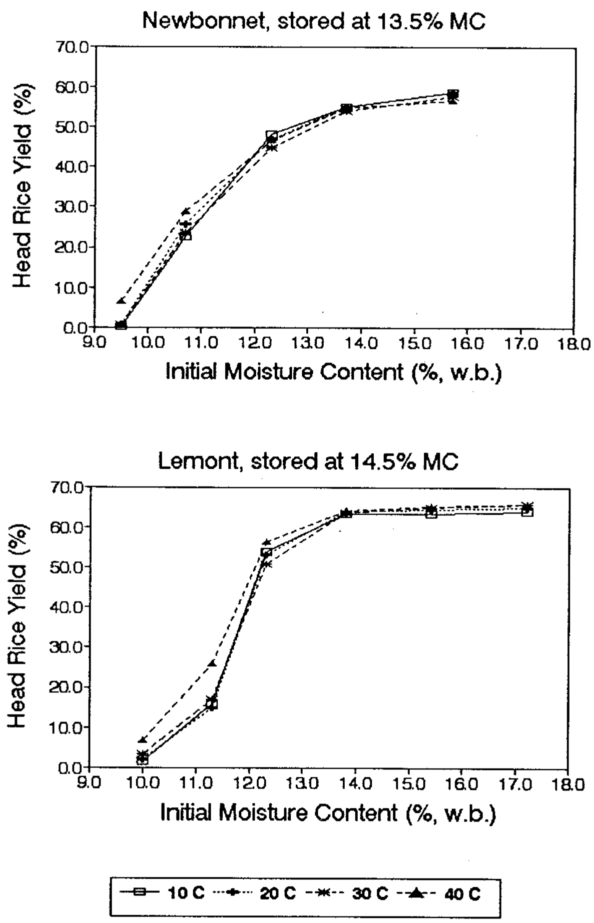

Fig. 5. Head rice yield vs. initial moisture content for the stored Newbonnet and Lemont varieties at several soaking water temperatures. Each data point is the average of head rice yields from the soaking durations in which no further head rice yield reduction occurred. Initial moisture content values are the average of 4,000 kernel moisture contents.

RESULTS AND DISCUSSION

Change in Moisture Content During Soaking

The actual IMC levels attained from the conditioning and equilibration of each of the rice samples, as determined by the oven drying procedure and the individual kernel moisture meter, are shown in Table I. The IMC values referred to herein are the actual IMC values rather than the target IMC values.

Typical moisture adsorption curves are shown in Fig. 1, which represents the MC change of $NB_{Stored\text{-}13.5}$ during soaking for the different IMC levels at the 20°C soaking temperature. The rate of water adsorption was rapid at the beginning of the soaking period (initial 15 min) and then decreased. The moisture adsorption rates generally increased with increasing soaking water temperatures for a given IMC level. The moisture adsorption rates were lower for samples with higher IMC levels. These trends were also observed for Lemont ($LM_{Stored\text{-}14.5}$) and support the findings of Lu et al (1993).

Individual Kernel MC Distributions

The kernel MC frequency distributions and associated cumulative frequency distributions of 4,000 individual kernels at each IMC for $NB_{Stored\text{-}13.5}$ are shown in Fig. 2. The frequency distributions show a considerable range in kernel MC levels at a given IMC, speculated to be due to the range in kernel maturities at harvest, as indicated by Holloway et al (1995). Also, the cumulative frequency distributions show that the slope at the midsection of each curve is steep; thus, a small MC change will affect a large number of kernels.

The standard deviations (SD) of the individual kernel MC levels at each IMC for selected varieties are shown in Fig. 3. Stored varieties generally had lower SD, indicating a more complete moisture equilibration between the kernels. The SD increased with increasing IMC, as has also been shown by Siebenmorgen et al (1990).

Reduction of HRY During Soaking

Figure 4 shows the effect of soaking duration and IMC on HRY for $NB_{Stored\text{-}13.5}$ when soaked at a 20°C temperature. The HRY generally decreased with increased soaking duration and decreased

TABLE II
Approximate Bulk Critical Moisture Content (CMC) Values and Asymptotic Head Rice Yield (HRY) Values at Several Soaking Water Temperatures

Sample	Storage or Harvest MC (%)	Bulk CMC (%)[a]	Asymptotic HRY Levels[b]		
			10°C	20°C	30°C
Stored at 3°C					
Newbonnet	13.5	13.7	58.9	58.6	57.7
Lemont	14.5	13.8	63.5	64.6	65.2
Freshly harvested					
Newbonnet	24.0	12.5	52.1	52.8	53.5
Newbonnet	17.5	13.9	56.9	57.3	59.1
Alan	23.0	14.1	49.3	48.6	51.0
Alan	18.5	14.3	50.2	50.1	51.8
Millie	21.5	14.1	59.6	58.4	61.1
Lacassine	20.5	14.9	52.5	53.6	55.1

[a] MC levels above which soaking did not produce any appreciable HRY reduction.
[b] Determined using the NLIN procedure from SAS Institute (Cary, NC).

IMC for all of the varieties tested. During the initial 30-min soaking period, a greater HRYR was observed at higher soaking temperatures than at lower temperatures (data not shown).

The effect of IMC on the HRY levels of the stored and freshly harvested varieties is shown in Figs. 5 and 6, respectively. As the IMC levels increased, the HRY levels approached asymptotic values. Table II shows these asymptotic values as determined using the NLIN procedure (SAS Institute, Cary, NC). HRY was not significantly affected at IMC levels >15.0%.

Prediction of CMC

The CMC is defined as the MC level below which kernels will fissure when rapidly rewetted. The CMC can be determined in several ways. From the standpoint of overall bulk average MC levels, the data of Figs. 5 and 6 can be used to estimate the bulk CMC by determining the MC above which no appreciable HRYR occurs. Defining the asymptotic HRY as the control HRY, the percentage of kernels that broke due to soaking was determined from the difference between the control HRY and the HRY at each

TABLE III
Head Rice Yields (HRY), Percentage of Kernels that Broke due to Soaking, and Kernel Critical Moisture Content (CMC) Data at 20°C Soaking Water Temperature

Sample	Storage or Harvest MC (%)	IMC[a] (%)	HRY[b] (%)	Asymptotic HRY[c] (%)	Brokens[d] (%)	Kernel CMC (%)
Stored at 3°C						
Newbonnet	13.5	9.5	0.8	58.6	98.6	10.7
		10.7	25.5	58.6	56.5	10.7
		12.3	46.8	58.6	20.1	11.9
		13.7	55.0	58.6	6.1	13.0
		15.7	58.6	58.6	0.0	13.0
Lemont	14.5	10.0	1.9	64.6	97.1	10.8
		11.3	14.8	64.6	77.1	11.5
		12.3	53.1	64.6	17.8	11.9
		13.8	63.9	64.6	1.1	12.7
		15.4	64.4	64.6	0.3	12.8
		17.2	65.0	64.6	–0.6	12.8
Freshly harvested						
Newbonnet	24.0	11.0	31.7	52.8	40.0	10.7
		11.6	45.2	52.8	14.4	11.0
		12.6	50.8	52.8	3.7	11.4
		14.5	51.7	52.8	2.0	11.8
		15.0	52.0	52.8	1.5	11.9
		16.7	51.9	52.8	1.6	12.0
Newbonnet	17.5	10.5	32.7	57.3	42.9	10.3
		11.3	48.7	57.3	14.9	10.8
		12.3	53.2	57.3	7.2	11.5
		13.9	56.6	57.3	1.2	12.4
		14.5	56.8	57.3	0.9	12.6
		16.5	57.0	57.3	0.5	13.1
Alan	23.0	10.3	9.7	48.6	80.0	10.8
		11.3	22.2	48.6	54.3	11.3
		12.7	37.6	48.6	22.7	12.2
		13.6	43.4	48.6	10.7	12.8
		14.1	45.3	48.6	6.8	13.0
		16.8	45.8	48.6	5.8	14.2
Alan	18.5	10.6	11.1	50.1	77.8	11.0
		11.6	32.7	50.1	34.8	11.4
		12.5	42.6	50.1	15.0	11.8
		14.3	49.0	50.1	2.1	12.6
		14.7	49.1	50.1	2.0	12.9
		16.7	48.9	50.1	2.3	13.8
Millie	21.5	10.5	36.6	58.4	37.3	10.3
		11.6	48.6	58.4	16.8	11.0
		12.4	55.9	58.4	4.2	11.3
		14.1	57.7	58.4	1.2	11.9
		14.8	57.8	58.4	1.0	12.3
		16.2	58.0	58.4	0.7	12.6
Lacassine	20.5	10.1	9.6	53.6	82.0	10.6
		11.6	30.1	53.6	43.8	11.5
		12.5	42.8	53.6	20.1	12.1
		14.9	52.9	53.6	1.3	12.9
		15.2	52.4	53.6	2.2	13.5

[a] Initial moisture content (IMC) values are average of 4,000 kernel MC values.
[b] Values are average HRY values from the soaking durations in which no further HRY reduction had occurred.
[c] Determined using the NLIN procedure from SAS Institute (Cary, NC).
[d] Percentage of kernels that broke due to soaking as calculated in Eq. 2.

variety-IMC-soaking water temperature combination, and was calculated as: % Broken kernels = ($HRY_{control}$ – HRY_{soaked}/$HRY_{control}$) × 100 [Eq. 2].

The percentage of kernels that broke due to soaking was used to estimate the kernel CMC of each sample. This percentage is shown in Table III for each variety-IMC combination at the 20°C soaking water temperature. Data for the other soaking water temperatures is given in Chen (1995). These bulk CMC data are summarized in Table II.

Another method of estimating CMC is done by relating HRYR to individual kernel MC distributions. As such, a kernel CMC for each sample was estimated from the kernel MC cumulative frequency distribution and the percentage of kernels that broke due to soaking. An assumption used in this estimation was that the percentage of kernels that broke due to soaking (Eq. 2) corresponded to the percentage of kernels below a certain MC, as determined from the cumulative kernel MC distribution for a sample. As such, the procedure used to estimate the kernel CMC overlaid the percent of broken kernels from a variety-IMC-soaking-water-temperature combination onto the vertical axis of the associated cumulative frequency distribution graph. The corresponding MC on the horizontal axis represented the kernel CMC. Figure 7 illustrates an example of estimating the kernel CMC of $NB_{Stored-13.5}$ at 12.3% IMC when soaked in water for 150 min at 20°C. Under this condition, the percentage of broken kernels was 20.1% (Table III). When overlaid on the cumulative frequency distribution, the MC to which 20.1% broken kernels corresponds was 11.9%. Thus, for IMC 12.3%, this procedure would indicate that kernels with MC <11.9% will fissure when soaked; thus, 11.9% represents the kernel CMC.

Figure 8 shows typical trends in kernel CMC levels of selected stored and freshly harvested varieties. Soaking water temperatures did not have a significant effect on kernel CMC levels. The kernel CMC increased with increasing IMC levels for each variety as typified in Fig. 8.

The trend of increasing kernel CMC with IMC is probably due to several factors, particularly the biological variation in kernel MC levels, kernel sizes, and the associated variable kernel

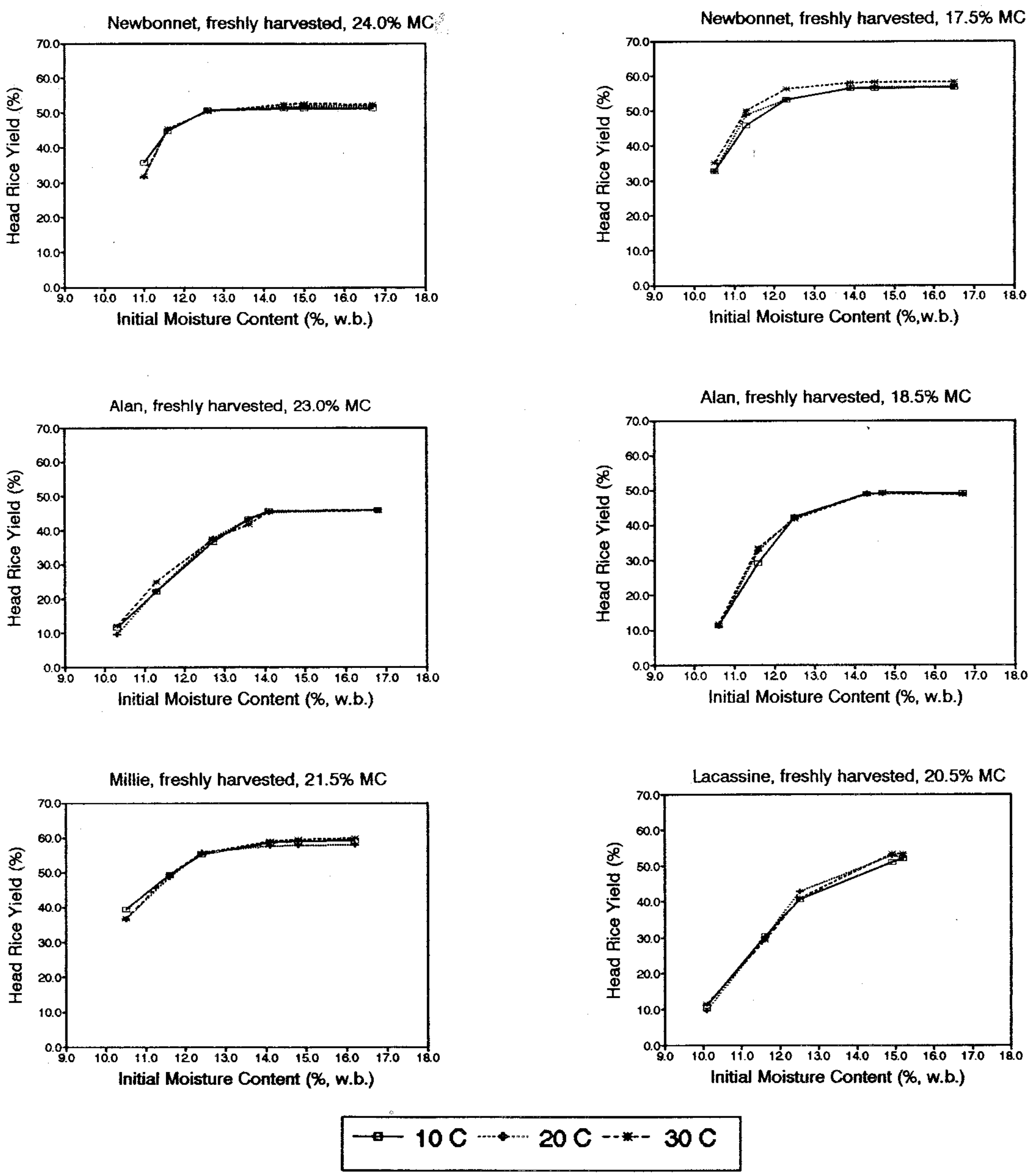

Fig. 6. Head rice yield vs. initial moisture content for the rice varieties and harvest moisture content combinations at the indicated soaking water temperatures. Each head rice yield data point is the average of two head rice yield determinations from samples that had been soaked for 150, 120, or 90 min at 10, 20, and 30°C soaking water temperatures, respectively. Initial moisture contents are the average of 4,000 kernel moisture content values.

response to a soaking environment. The kernel MC distributions indicate that there was considerable variation in kernel MC levels at a given IMC. This behavior has also been reported for rice by Siebenmorgen et al (1990) and Kocher et al (1990). Thus, for a given bulk average sample MC, the kernels in the sample exist at considerably different MC levels. These differences are due to different physical sizes and shapes, as well as different compositional makeups. Figure 3 indicates that as the IMC levels increased, the variation in kernel MC levels increased, implying that the response of individual kernels when conditioned to different environments, such as soaking, was not the same. Just as individual kernels equilibrate to different MC levels within a given sample environment, the kernel-to-kernel response to soaking, in terms of moisture adsorption rate and consequent fissuring, also varies considerably.

An illustration of this is presented using the kernel MC distributions for $NB_{Stored\text{-}13.5}$ (Fig. 2) and the resulting kernel CMC levels due to soaking (Fig. 8 and Table III). For the 20°C soaking temperature at the 12.3% IMC level, there was a 20.1% reduction in HRY due to soaking, resulting in a kernel CMC of 11.9%. At IMC 13.7%, the kernel MC profile is at a higher level and the range in kernel MC levels has widened, as indicated by the trend of increasing standard deviation with increasing IMC (Fig. 3). The 12.3% and 13.7% profiles (Fig. 2), show that there is an overlap of the profiles. Thus, kernels in both the 12.3% and the 13.7% IMC profile could be at, for example, 13.0% MC. However, the kernels from the two profiles that are at the same MC would not have the same physicochemical makeup, since they achieved this MC in different sample average MC levels. Consequently, the fissuring response of these kernels to soaking is expected to be different.

At the higher IMC levels, the moisture gradient between the kernels and the soaking water is less at the lower IMC levels, resulting in lower HRYR values (Figs. 5 and 6). However, the overall size of the kernels at the higher IMC levels is slightly larger due to hydroexpansion. Jindal and Siebenmorgen (1994) showed that larger kernels are more susceptible to fissuring than smaller ones when soaked. The combined effect of these factors was such that the kernel MC at which fissuring commenced during soaking apparently was higher at the higher IMC levels. Thus, a single MC level at or below which kernels fissured during soaking did not exist across all IMC levels. Rather, the kernel physicochemical makeup, as well as the kernel MC before soaking, dictated whether it would fissure due to rapid moisture adsorption.

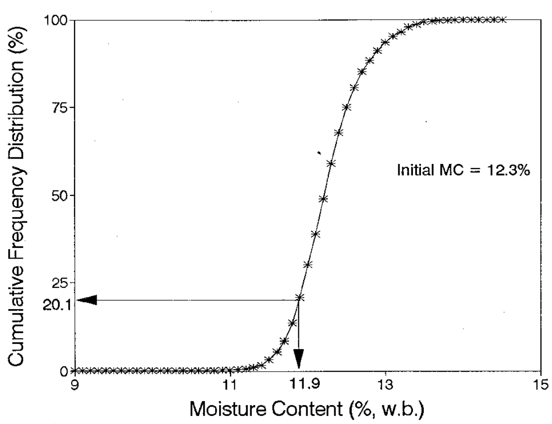

Fig. 7. Technique used to determine the kernel critical moisture content of 11.9% for a sample of Newbonnet (stored at 3°C with moisture content of 13.5%) in which 20.1% of the kernels were broken due to soaking in 20°C water temperature for 150 min.

CONCLUSION

The CMC, defined as that MC below which soaking caused HRY damage, was quantified from two standpoints. The bulk CMC varied from 12.5 to 14.9%, depending on the variety, harvest MC, and storage conditions. In general, the bulk CMC levels were similar to those in earlier studies and supports the observations of Siebenmorgen et al (1992) that rice should be harvested >15% MC to avoid the risk of HRY reduction due to rain. Soaking water temperatures of 10–30°C had little to no effect on HRY reductions or bulk CMC levels.

The second method of quantifying CMC was to predict a kernel CMC for each sample. The percentage of kernels that broke due to soaking was related to the percentage of kernels below a certain MC level, as determined from the kernel cumulative MC frequency distribution. This procedure indicated that kernel CMC varies directly with the MC of the sample before soaking. This trend is postulated to be due to several factors, primarily that kernels in a bulk have a wide range of MC levels due to their different physical and chemical properties. The response of these kernels to soaking varies and is dependent on the overall environment to which they had equilibrated, as determined by the bulk sample IMC.

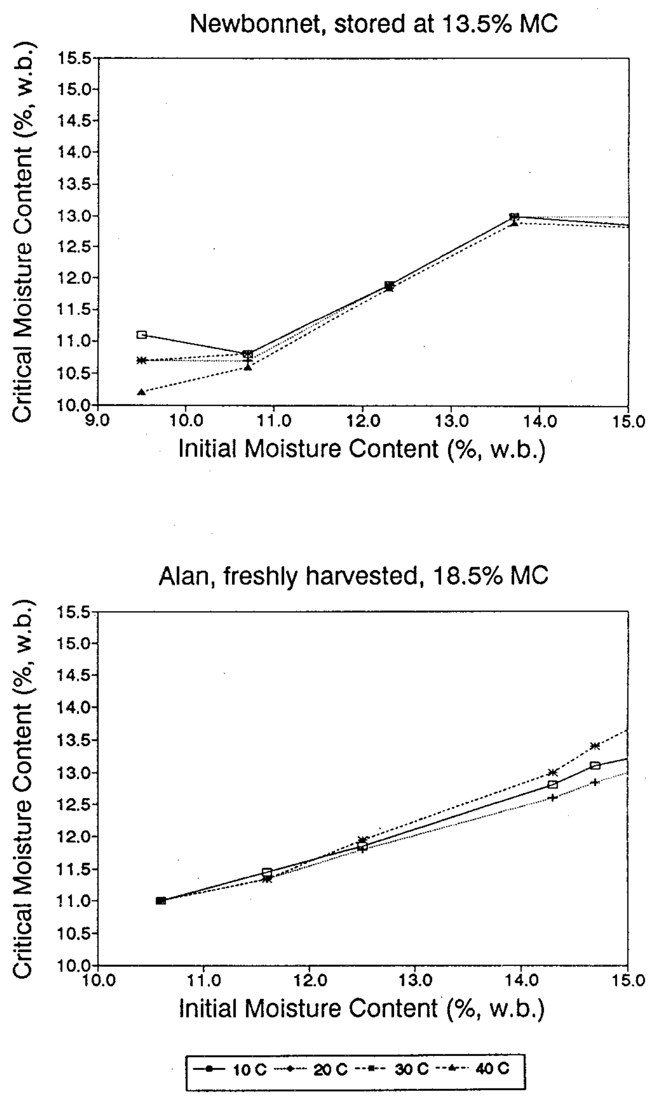

Fig. 8. Kernel critical moisture content vs. sample initial moisture content for rice and storage condition combinations at the indicated soaking water temperatures. Initial moisture content (MC) values are the average of 4,000 kernel moisture contents.

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