Predicting Rice Physicochemical Properties Using Thickness Fraction Properties

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Cereal Chem. 83(3):275–283

ABSTRACT

Long-grain rice cultivars Francis and Wells and hybrid XL8 Clearfield were harvested from two locations at three harvest moisture contents (HMC) in 2003. The rough rice was dried, fractionated into thin, medium, and thick fractions, and milled. Physicochemical properties of unfractionated and fractionated samples were determined. The effects of HMC and location on thickness distributions were investigated and the weighted-average physicochemical properties of the thickness fractions were compared with those of unfractionated rice. Generally, the growing location and HMC affected kernel thickness distributions, green kernel content, fissured kernel content, and head rice yield (HRY). As kernel thickness within samples increased, amylose content increased and the protein content and α-amylase activity decreased. Thick fractions had greater peak viscosities than medium and thin fractions. The thin, medium, and thick fraction physicochemical property weighted averages provided good predictions of most unfractionated rice sample properties. However, this approach was not entirely accurate for predicting HRY, milled rice total lipid content, and bulk density.

Rice kernels on panicles do not develop synchronously. Generally, kernels at the upper part of panicles mature first and are larger and heavier than those at the middle and bottom (Wadsworth et al 1982a; Wadsworth and Matthews 1986; Kocher et al 1990). At harvest, kernels at the lower part of a panicle can be maturing while those at the upper part are already mature (Jongkaewwattana et al 1993). The moisture content (MC) of kernels on the same panicle can thus widely vary at harvest (Chau and Kunze 1982; Kocher et al 1990; Li et al 2003). Wadsworth et al (1982b) found that rice MC decreased as the kernel thickness increased in freshly harvested rice. Kocher et al (1990) found that the MC distributions of rice kernels at harvest changed with harvest dates. At early harvest dates, the kernel MC distributions comprised two to three modes; the distributions shifted to single, lower MC modes as the rice dried.

The dimensions of rice kernels within a sample vary significantly (Wadsworth et al 1982a; Wadsworth and Matthews 1986). Additionally, the development rates of kernel dimensions have been shown to be different; Del Rosario et al (1968) found that rice kernels reached the maximum length, width, and thickness at 4, 14, and 21 days after flowering, respectively. Genetic properties, such as whether the cultivar was one to mature early or late, influenced the kernel filling rate and consequently the kernel thickness and milling performance (Jongkaewwattana et al 1993). Rice kernel filling rate was controlled by temperatures at the time of kernel filling (Yoshida and Hara 1977; Fujita et al 1984); the filling rate of rice grown at higher temperatures was greater than that at lower temperatures.

Besides dimensions and MC, other rice physicochemical properties can vary at harvest. Protein content slightly decreased, whereas amylose content, peak viscosity, and palatability slightly increased as kernel thickness increased (Wadsworth et al 1979; Matthews et al 1981a; Wadsworth and Matthews 1986; Wadsworth 1987; Matsue and Ogata 1999; Matsue 2001). Wang et al (2004) found that the peak viscosity of rice flour increased as the HMC decreased. Zhang et al (2003) revealed that the mass and amylose content of rice kernels on a panicle had ranges of 5.7–31.0 mg and 5.3–27.5%, respectively. Matsue and Ogata (1999) explained that high protein content of rice kernels on panicles was due to a deficiency of starch accumulation in the rice endosperm.

Milling properties are affected by kernel thickness. Matthews et al (1981b) noted that the thickest and thinnest rice fractions resulted in more broken kernels during polishing. Sun and Siebenmorgen (1993) found that rough rice kernel fractions thinner than 1.88 mm or thicker than 2.03 mm resulted in lower HRY than mid-thickness fractions. Wadsworth and Hayes (1991) reported that HRY were <10% for rough rice fractions thinner than 1.6 mm.

Sun and Siebenmorgen (1993) reported that both weak kernels in the thinner fractions and fissured kernels in the thicker fractions were responsible for lowering HRY. Mature kernels with low MC were more susceptible than immature kernels with high MC to field fissuring due to moisture adsorption from the environment, and those fissured kernels consequently resulted in HRY reduction. Desikachar et al (1973) found that many rice kernels at the upper part of panicles were fissured at harvest, and many at the lower part were immature.

It has often been observed that the same rice cultivar can have different bulk physicochemical properties if harvested at different MC and locations. Because of these variations, predicting bulk physicochemical properties is difficult. Rice kernel thickness distributions have played important roles in determining bulk milling and physicochemical properties. Hitherto, little was known about the effects of HMC and growing location on rice thickness distributions, and using the weighted-average properties of thickness fractions to explain variations in physicochemical properties. The overall objective of this study was to determine whether variations in bulk physicochemical properties could be explained by the weighted-average properties of constituent thickness fractions. As such, the effects of growing location, cultivar, and HMC on thickness distributions were determined and the physicochemical properties of the bulk and thickness fractions were measured.

MATERIALS AND METHODS

Materials

Two long-grain cultivars, Francis and Wells, and a long-grain hybrid, XL8 Clearfield (XL8CF), were harvested in 2003 from Lodge Corner, AR (Latitude 34° 19' 00" N; Longitude 091° 34' 00" W) at HMC of 24.3–24.9%, 18.1–18.5%, and 14.5–15.8%; and Essex, MO (Latitude 36° 48' 00" N; Longitude 089° 46' 00" W) at HMC of 21.8–25.0%, 18.6–20.0%, and 15.5–17.8%. To measure the MC of freshly harvested samples, ≈1 kg of freshly harvested rough rice from each lot was cleaned using a grain cleaner (MCI Kicker Grain Tester, Mid-Continent Industries, Newton, KS) and fractionated into thin, medium, and thick rough rice fractions using a precision sizer (ABF2, Carter-Day, Minneapolis, MN) with two cylindrical screens with 1.88- and 2.03-mm rectangular

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DOI: 10.1094/CC-83-0275

slot widths. The MC of 1,000 randomly selected kernels from each thickness fraction were measured using an individual kernel moisture meter (CTR-800E, Shizuoka Seiki Co., Shizuoka, Japan).

About 60 kg of remaining rough rice from each lot was dried inside a lab on a tarp at 24°C to a MC of 12.5% and cleaned using the grain cleaner. The rough rice was fractionated into thin, medium, and thick fractions using a commercial-scale grader (Carter-Day) with two cylindrical screens that had 1.88- and 2.03-mm rectangular slot widths, respectively. Rough rice was first placed inside the rotating 2.03-mm screen; retained rice comprised the thick fraction; rice passing through the slots was fed onto the smaller screen. The same procedure with the smaller screen produced the medium (retained kernels) and thin (through kernels) fractions. The separation procedure for each fraction was repeated to ensure a thorough separation. An unfractionated rice sample served as a reference. Thus, 72 lots (2 locations × 3 cultivars × 3 HMC × 4 thickness fractions) were produced.

Methods

Bulk densities of five replicate rough rice subsamples from the 72 lots were measured using a bulk density test apparatus (Seedburo Equipment Co., Chicago, IL) consisting of a filling funnel with a pint cup. Three replicate 1,000-kernel subsamples from each of the 72 lots were randomly selected and the mass of each was measured. An additional 200 rough rice kernels were randomly selected from each lot and hand-hulled, and the green and fissured kernels were counted using an illumination box (Grainscope TX-200, Kett Electric Laboratory, Tokyo, Japan). Kernel dimensions (length, width, and thickness) of the resulting 200 brown rice kernels were then measured using an image analyzer (Rice Image Analyzer, RIA1, Satake, Tokyo, Japan).

Replicate rough rice subsamples (150 g) from each of the 72 lots were hulled with a paddy husker (THU-35A, Satake Engineering Co., Tokyo, Japan) to produce brown rice, which was milled for 30 sec in a laboratory mill (McGill No. 2, Rapsco, Brookshire, TX). The resultant milled rice was separated into head rice and brokens using a sizing device (Grainman 61-115-60, Grain Machinery Mfg. Co., Miami, FL). HRY was calculated as the mass fraction of the 150-g rough rice sample that remained as head rice. The head rice was ground into flour using a cyclone mill (3010-030, Udy Corporation, Fort Collins, CO) equipped with a 100-mesh sieve.

Replicate rice flour moisture, crude protein, α-amylase contents, and peak viscosities were determined according to Approved Methods 44-15A (air oven method), 46-30 (combustion method), 22-02, and 61-02, respectively (AACC 2000). Replicate rice flour total lipid contents were measured by extraction with petroleum ether using a lipid extraction system (Soxtec Avanti 2055, Foss North America, Eden Prairie, MN) according to Matsler and Siebenmorgen (2005). Replicate rice flour amylose contents were measured by iodine colorimetry using potato amylose and waxy rice starch as standards (Juliano et al 1981).

Replicate onset gelatinization temperatures of rice flour samples were determined using differential scanning calorimetry (DSC) (Pyris-1, Perkin-Elmer Co., Norwalk, CT). Rice flour (≈4 mg) and 8 μL of deionic water were combined in an aluminum sample pan and sealed. The prepared samples were equilibrated overnight at room temperature and then scanned from 25 to 120°C at a rate of 10°C/min.

The firmness of cooked rice was measured using a texture analyzer (TA-XT2, Texture Technologies, Scarsdale, NY). Head rice (20 g) was added to 40 g of water and placed in a miniature rice precision cooker and cooked in a heating mantle at 98.5°C for 20 min. After the rice was cooked, the glass bowl of the cooker was transferred to another heating mantle set at 60°C and equilibrated for 5 min. Cooked rice (35 g) was transferred to a miniature extrusion cell (34.9 × 70.7 mm diameter × length) and extruded through the 33-hole (3.9 mm diameter) cell. The plunger speed and displacement were 5 mm/sec and 55 mm, respectively. The maximum force recorded during extrusion was considered the firmness of the cooked rice. Replicate measurements were performed on samples from each of the 72 lots.

Mean temperatures from June to September 2003 at Lodge Corner and Essex were obtained online at www.wunderground.com/history. Experimental data were analyzed with SAS for Windows (v. 8.1, SAS Software Institute, Cary, NC) and least significance differences were computed at $P < 0.05$.

RESULTS AND DISCUSSION

Moisture Content Distribution

Rough rice HMC of unfractionated and thickness-fractionated Francis, Wells, and XL8CF are summarized in Table I. The HMC of the unfractionated rough rice decreased from 24.9 to 14.5% at Lodge Corner and from 25.0 to 15.5% at Essex during the three harvests. The HMC of Francis and Wells from Essex decreased from 21.8 and 23.4% to 17.1 and 17.8% with harvest date, respectively, and did not decrease as low as XL8CF, which was 15.5%.

TABLE I
Moisture Content (%wb) of Thickness-Fractionated (Fig. 3) and Unfractionated Rough Rice Samples Harvested at Indicated Locations on Indicated Dates in 2003

			Thickness Fractions				
Location	Harvest Date	Cultivar	Thin	Medium	Thick	Unfractionated	Weighted Avg
Lodge Corner, AR	8/27	Francis	27.8	22.7	22.5	24.3	23.5
		Wells	30.5	24.0	22.8	24.8	23.6
		XL8CF	27.8	23.1	23.6	24.9	23.7
	9/4	Francis	18.3	17.4	17.3	18.2	17.5
		Wells	19.1	17.5	17.4	18.1	17.5
		XL8CF	17.7	17.3	17.8	18.5	17.4
	9/10	Francis	14.5	14.4	14.5	14.5	14.4
		Wells	15.7	15.3	15.4	15.8	15.4
		XL8CF	14.5	14.4	14.5	14.5	14.4
Essex, MO	9/16	Francis	23.5	19.0	17.2	21.8	19.7
		Wells	30.8	22.3	20.4	23.4	22.0
		XL8CF	27.4	21.4	22.4	25.0	22.5
	9/23	Francis	21.8	18.2	17.9	20.0	18.7
		Wells	22.0	17.6	16.6	18.8	17.4
		XL8CF	18.4	16.8	17.2	18.6	17.1
	10/2	Francis	18.7	16.1	15.9	17.1	16.5
		Wells	22.0	16.8	16.2	17.8	16.9
		XL8CF	15.6	15.0	15.3	15.5	15.1

Thin kernels usually had greater MC values than the medium and thick kernels at early harvest dates. Wadsworth et al (1982b) also reported that MC decreased as kernel thickness increased. The MC values of kernel thickness fractions were more uniform at late harvest dates as the average unfractionated bulk HMC decreased; for example, the MC of the three thickness fractions from each cultivar harvested on 9/10/2003 at Lodge Corner were approximately the same. The weighted-average MC of samples at higher HMC were at least one percentage point less than the unfractionated MC; moisture loss occurring during fractionation may have been the reason for this difference.

Individual kernel MC distributions of unfractionated samples harvested at Lodge Corner are shown in Fig. 1. At early harvests, the distributions were broader compared with the late harvests. The primary distribution peak shifted to lower MC with harvest date. The trends in HMC distributions at Essex were similar to those of Lodge Corner and all trends agree with the results of Kocher et al (1990).

The individual kernel MC distributions of Francis thickness fractions harvested from Lodge Corner and Essex are shown in Fig. 2. The MC distributions of the thin fractions, especially for the highest HMC samples, were dramatically different from those of medium and thick fractions in that the thin fractions had more high MC kernels. The distributions of the thickness fractions narrowed, that is, the kernel MC variation decreased, and shifted to lower MC with harvest date. The greater average MC of the thin fractions over the medium and thick fractions (Table I) was due to the thin fractions having more high MC kernels (Fig. 2). Similar trends were noted for the other cultivars harvested from both locations.

Thickness Distributions

The kernel thickness distributions of the three cultivars from Lodge Corner and Essex at different HMC are presented in Fig. 3. The medium thickness fraction was the dominant fraction in all Francis and XL8CF samples, comprising ≈60–80% of the total sample mass. Wells was generally a thicker kernel cultivar in that ≈45–72% of the total mass was represented in the thick fraction, compared with only 7–22% in the Francis and XL8CF cultivars. The thick fraction mass percentage of Wells from Lodge Corner increased as the HMC decreased, as was the trend for Francis at both locations. However, the thick fraction mass percentage change of Wells from Essex was not as pronounced, as was the case for XL8CF at both locations.

The thin fraction mass percentage was always <17% of the total rough rice mass and was <8% for Wells samples. The trends in thin kernel mass percentage with HMC were not consistent across location/cultivar.

Physicochemical Properties

The 1,000-kernel masses and bulk densities of the rough rice thickness fractions and the dimensions of brown rice kernels from each thickness fraction are summarized in Table II. The 1,000-kernel masses and bulk densities of the fractions from all cultivars did not vary significantly with location or HMC (data not shown). For the unfractionated samples, the 1,000-kernel mass of Wells was greater than Francis or XL8CF; however, the bulk density values of Wells and Francis were not different and were greater than that of XL8CF. The 1,000-kernel mass and bulk density were significantly different among the thin, medium, and thick fractions within each cultivar, except for the medium and thick fractions of XL8CF. The 1,000-kernel masses and bulk densities of the thin fractions were less than those of the medium and thick fractions for all cultivars. The weighted-average 1,000-kernel masses and bulk densities of the thickness fractions were similar, within 2.7 and 1.9%, respectively, of the unfractionated values. The difference in bulk densities between the unfractionated and weighted-averages may be associated with the manner in which different kernel geometries affect packing during a bulk density measurement.

Brown rice kernel dimensions, derived from rough rice that had been fractionated at ≈12.5% MC, were not affected by harvest location or MC (data not shown). Furthermore, the mean brown rice kernel length and width did not vary among thickness fractions, or between any fraction and the unfractionated sample, for each cultivar (Table II). For each cultivar, the mean brown rice kernel thickness of the thin fraction was apparently less, yet not statistically less, than the medium fraction kernel thickness. This same trend held for the medium fraction vs. the thick fraction kernel thickness. Much of the reason for the lack of statistical difference is the large amount of variability about the thickness means (data not shown). There was a definite statistical difference in kernel thickness between the thin and thick thickness fractions for all cultivars. The mean thicknesses of Francis, Wells, and XL8CF were 1.60, 1.67, and 1.62 mm, respectively. The weighted average dimensions were equal to or slightly greater (within 2.0%) than the unfractionated sample dimensions for all cultivars.

Tables III and IV show the green kernel contents in each thickness fraction of Francis, Wells, and XL8CF harvested at different HMC at Lodge Corner and Essex, respectively. The green kernel content decreased as the HMC decreased. Most of the green, immature kernels were found in the thin fractions. There were no green kernels in the thick fractions when the HMC was below ≈18% for samples harvested at Lodge Corner, yet the thick fractions from Essex still had some (1–2%) green kernels. The Wells thin fractions had greater green kernel contents than Francis and XL8CF. The thin fractions of rice samples harvested from Essex had more

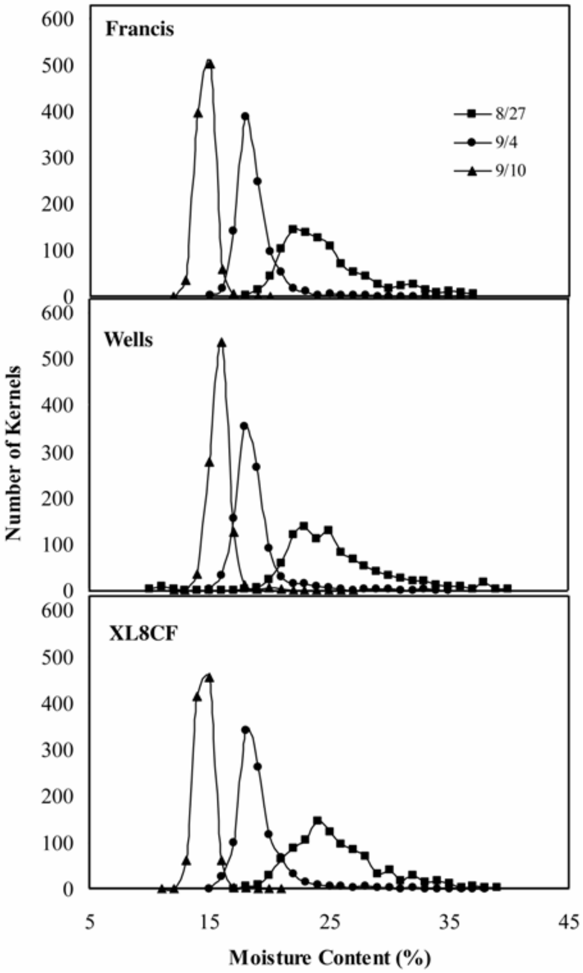

Fig. 1. Individual kernel moisture content distributions of Francis, Wells, and XL8CF unfractionated rice harvested on the indicated dates from Lodge Corner, AR, in 2003.

green kernels than those from Lodge Corner. At the last harvest, there were still 13–35% green kernels in the thin fractions from Essex, while those from Lodge Corner were 2–4%. This difference is speculated to be due to varying environmental conditions between the two locations; the average growing temperature at Essex was 3°C lower than at Lodge Corner in 2003.

The number of fissured kernels increased as the HMC decreased (Tables III and IV). At lower HMC, rice kernels are susceptible to fissuring due to high relative humidities or rainfall (Kunze and Prasad 1978; Siebenmorgen and Jindal 1986). This was especially true for the thicker fractions as thick kernels are more vulnerable to fissuring than thin (Jindal and Siebenmorgen 1994). Fissured kernels typically have a great, negative impact on HRY. The decrease in HRY of the thick fractions, often observed at the low HMC, was due to fissured kernels with a negative correlation coefficient of 0.66 ($P < 0.01\%$).

The HRY of the rice samples varied with kernel thickness and HMC (Tables III and IV). The thin fractions of the three cultivars had much lower HRY than the medium and thick fractions. Although the thin fractions had fewer fissured kernels than the medium and thick fractions, they contained more weak, immature kernels. Weak kernels are easily broken during hulling and milling, thus greatly reducing HRY. The HRY of the thin fractions of the three cultivars harvested at higher MC were ≈18–42 percentage points less than those of the medium and thick fractions, especially the thin fractions of Wells harvested at higher MC.

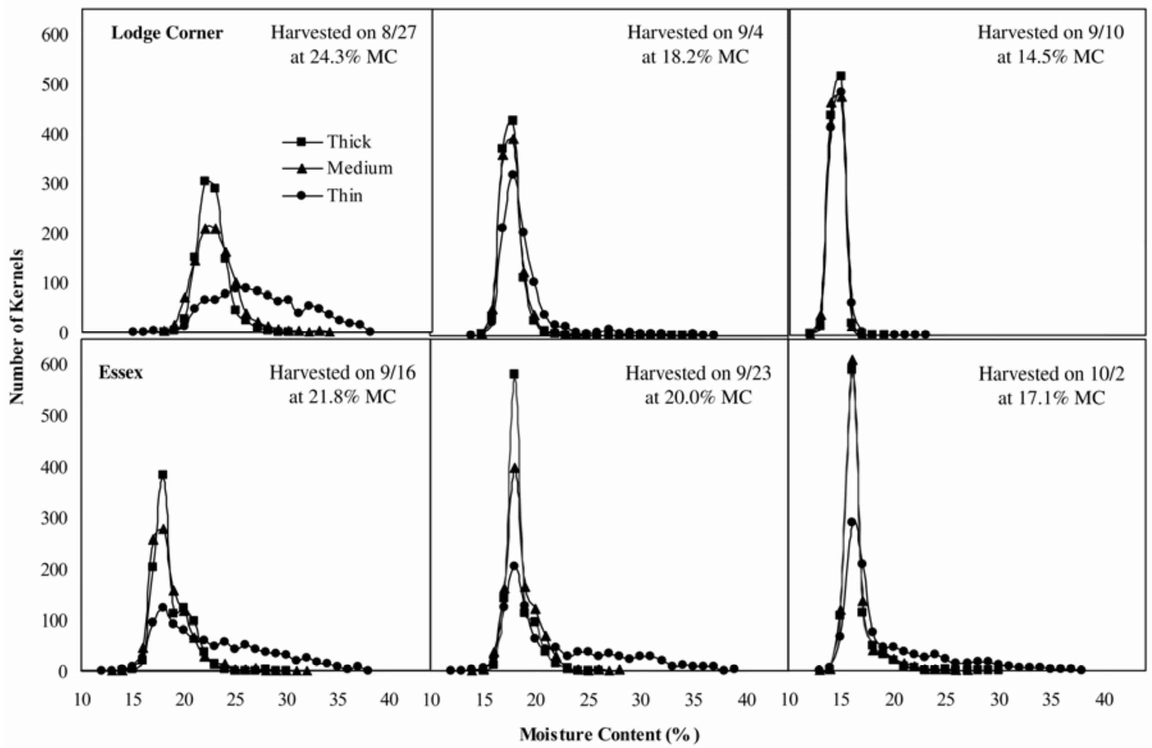

Fig. 2. Individual kernel moisture content distributions of Francis thin (<1.88 mm), medium (1.88–2.03 mm), and thick (>2.03 mm) rough rice kernels harvested on the indicated dates at the indicated unfractionated harvest moisture contents (%wb) from Lodge Corner, AR, and Essex, MO, in 2003.

TABLE II
Rough Rice Properties and Brown Rice Kernel Dimensions from Indicated Thickness Fractions (Fig. 3) from Each Cultivar[a,b]

		Rough Rice Properties		Brown Rice Kernel Dimensions[e]		
Cultivar	Thickness Fraction	1,000-Kernel Mass (g)[c]	Bulk Density (kg/m^3)[d]	Length (mm)	Width (mm)	Thickness (mm)
Francis	Thin	18.7d	535e	6.35b	2.01a	1.45b
	Medium	24.2c	599b	6.78ab	2.09a	1.62ab
	Thick	28.4ab	608a	7.13ab	2.14a	1.71a
	Unfractionated	24.0c	589bc	6.80ab	2.05a	1.60ab
	Weighted Avg	24.4	593	6.80	2.09	1.62
Wells	Thin	18.1d	521f	6.50b	1.99a	1.44b
	Medium	24.4bc	599b	6.87ab	2.09a	1.64ab
	Thick	29.6a	610a	7.37a	2.16a	1.74a
	Unfractionated	26.0b	592bc	7.10ab	2.11a	1.67ab
	Weighted Avg	26.7	599	7.10	2.12	1.68
XL8CF	Thin	19.3d	533e	6.30b	2.06a	1.44b
	Medium	24.6bc	584c	6.76ab	2.14a	1.63ab
	Thick	26.5b	582c	6.93ab	2.12a	1.71a
	Unfractionated	23.7c	568d	6.63ab	2.12a	1.62ab
	Weighted Avg	24.3	579	6.74	2.13	1.62

[a] Harvest location and moisture content did not statistically affect the indicated rough rice properties or brown rice kernel dimensions.
[b] Values in the same column with different letters are significantly different ($P < 0.05$).
[c] Mean of three 1,000-kernel mass measurements, averaged across harvest location and moisture content.
[d] Mean of five bulk density measurements, averaged across harvest location and moisture content.
[e] Mean of dimensions of 200 kernels, averaged across harvest location and moisture content.

The HRY of the medium and thick fractions of the three cultivars from both locations generally decreased as the HMC decreased, due primarily to the presence of fissured kernels. Thick fraction HRY decreased much faster with HMC decreases than medium fraction HRY. Unlike the medium and thick fractions, the HRY of the thin fractions increased as the HMC decreased, due to increasing maturation and mechanical strength of immature kernels.

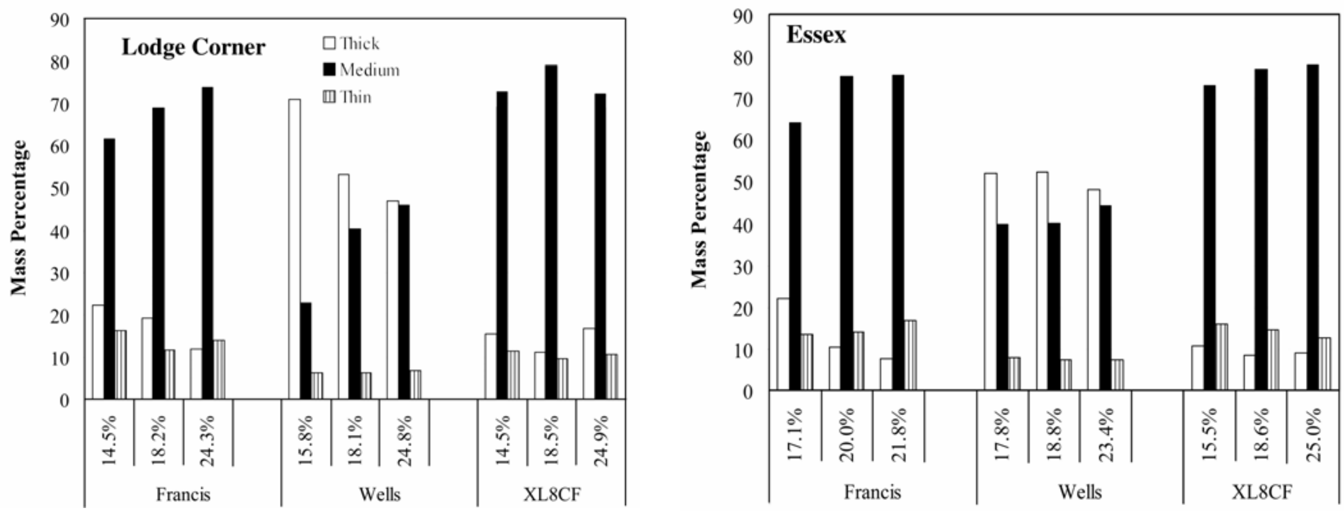

Fig. 3. Mass fractions of thin (<1.88 mm), medium (1.88–2.03 mm), and thick (>2.03 mm) rough rice kernels harvested at indicated unfractionated moisture contents (%wb) from Lodge Corner, AR, and Essex, MO, in 2003 and dried to ≈12.5% MC before thickness fractionating.

TABLE III
Green and Fissured Kernels in Brown Rice Samples (200 kernels) and Physicochemical Properties (mean of replicate measurements) of Head Rice and Flour Samples[a,b]

Sample	Thickness Fraction	Green Kernels (%)	Fissured Kernels (%)	HRY[c] (%)	α-Amylase Activity (U/100 g)	Protein Content (%)	Amylose Content (%)	Total Lipid Content (%)	Peak Visc. (RVU)
Francis-24.3	Thin	48	1	37.9ij	2.5c	8.4ab	20.3d	0.29c	243c
	Medium	5	1	69.4ab	2.0cd	8.2ab	22.7c	0.44a	242c
	Thick	4	1	70.9a	1.8cd	8.0b	23.1bc	0.38ab	263a
	Unfractionated	13	2	63.3d	1.9cd	8.0b	22.5c	0.33bc	243c
Francis-18.2	Thin	16	0	45.8h	2.6bc	8.2ab	20.5d	0.28c	243c
	Medium	1	0	67.2b	2.0cd	7.7b	22.4c	0.40ab	253b
	Thick	0	3	65.6c	1.6d	7.7b	22.6bc	0.33bc	263a
	Unfractionated	3	1	63.2d	2.1cd	8.0b	21.9c	0.33bc	250b
Francis-14.5	Thin	3	3	48.5g	4.0a	7.6b	21.5cd	0.34b	245bc
	Medium	0	5	64.9cd	2.5c	7.0c	21.9c	0.36b	254b
	Thick	0	9	61.5e	2.3c	7.5b	23.6b	0.29c	264a
	Unfractionated	1	6	61.0e	2.5c	7.7b	22.3c	0.29c	251b
Wells-24.8	Thin	67	4	28.7k	2.6bc	8.3ab	19.6d	0.20d	235d
	Medium	13	1	64.0cd	2.0cd	7.6b	22.0c	0.34b	239c
	Thick	5	1	70.6a	1.7d	7.7b	22.9bc	0.32bc	251b
	Unfractionated	8	4	64.2cd	1.8cd	7.6b	22.5c	0.27c	243c
Wells-18.1	Thin	30	2	39.5i	2.8bc	8.7a	20.1d	0.24cd	221e
	Medium	2	3	67.2b	2.4c	7.9b	22.1c	0.27c	235d
	Thick	0	3	70.0a	1.7d	7.5b	23.0bc	0.25cd	246bc
	Unfractionated	3	2	64.8cd	1.6d	7.9b	23.5b	0.31bc	253b
Wells-15.8	Thin	4	2	39.8i	3.3b	8.8a	19.8d	0.23d	233d
	Medium	1	5	63.3d	2.4c	8.5ab	22.8bc	0.30bc	247b
	Thick	0	10	64.4cd	2.2c	8.1ab	23.7b	0.28c	251b
	Unfractionated	2	8	58.4f	2.5c	8.5ab	23.3bc	0.28c	247b
XL8CF-24.9	Thin	30	2	37.0j	2.3c	9.3a	25.1ab	0.35b	204g
	Medium	7	1	65.5c	1.9cd	9.3a	25.4a	0.38ab	204g
	Thick	3	0	65.9c	1.6d	9.1a	25.9a	0.28c	206fg
	Unfractionated	8	2	60.0ef	1.6d	8.5ab	25.9a	0.39ab	201g
XL8CF-18.5	Thin	5	0	40.1i	2.2c	8.9a	23.9b	0.33bc	207fg
	Medium	1	1	64.9cd	1.7d	8.4ab	24.2b	0.28c	211f
	Thick	0	1	64.5cd	1.7d	8.3ab	25.6a	0.25cd	201g
	Unfractionated	2	1	61.1e	1.8cd	8.7a	25.0ab	0.32bc	197g
XL8CF-14.5	Thin	2	8	44.5hi	4.0a	8.9a	24.5ab	0.29c	210f
	Medium	0	2	63.0d	2.4c	8.4ab	25.2ab	0.41a	211f
	Thick	0	6	63.4d	1.8cd	8.1ab	24.9ab	0.27c	220e
	Unfractionated	1	6	60.2ef	2.5c	8.5ab	25.7a	0.28c	210f

[a] Rough rice of each cultivar was harvested from Lodge Corner, AR, at indicated unfractionated sample moisture contents (%wb) in 2003, dried to 12.5% MC, and thickness fractionated (Fig. 3).
[b] Mean values in the same column with different letters are significantly different ($P < 0.05$).
[c] Head rice yield.

The HRY of unfractionated samples were less than those of the weighted-average HRY of the thin, medium, and thick fractions (data not shown). Unfractionated sample HRY were 0.5–7.0 percentage points less than weighted-average HRY across all sample lots. Sun and Siebenmorgen (1993) reported similar trends, with differences between the unfractionated and weighted-average HRY for long-grain samples ranging from 1.1 to 3.9 percentage points. HRY is determined in part by the size and shape uniformity of kernels comprising a sample (Jongkaewwattana and Geng 2001). The unfractionated samples were a mixture of thin, medium, and thick kernels; when these bulk samples were separated into thickness fractions, the sample uniformity increased, as did the HRY. This could at least partially account for why the weighted-average HRY were greater than those of the unfractionated samples.

The α-amylase activity and protein content of the rice flour samples generally decreased as the kernel thickness increased (Tables III and IV). The thin fractions contained more green kernels than the medium and thick fractions. Normally, immature rice kernels have greater α-amylase activity compared with mature kernels (Del Rosario et al 1968). Additionally, thin kernels have

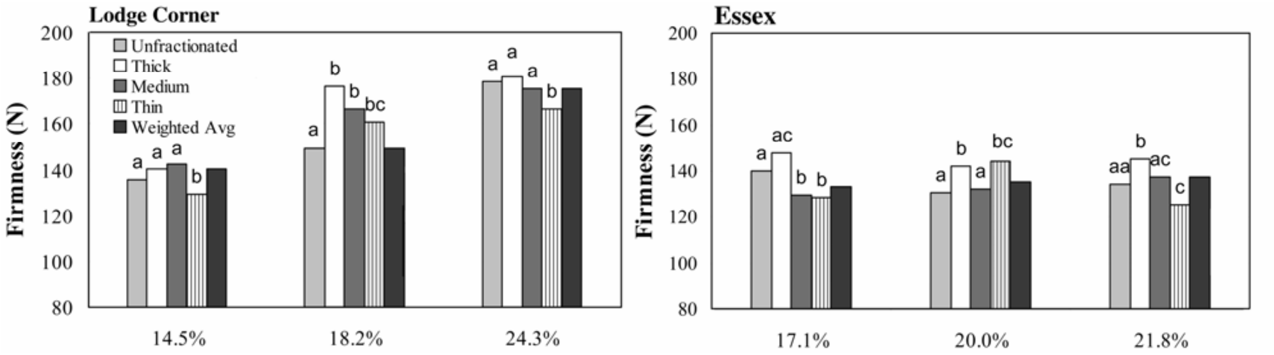

Fig. 4. Cooked rice firmness of Francis rice harvested at indicated moisture contents (MC %wb) from Lodge Corner, AR, and Essex, MO, in 2003, dried to 12.5% MC, and thickness fractionated (Fig. 3). Bars for each location with different letters are significantly different ($P < 0.05$).

TABLE IV
Green and Fissured Kernels in Brown Rice Samples (200 kernels) and Physicochemical Properties (mean of replicate measurements) of Additional Head Rice and Flour Samples[a,b]

Sample	Thickness Fraction	Green Kernels (%)	Fissured Kernels (%)	HRY[c] (%)	α-Amylase Activity (U/100 g)	Protein Content (%)	Amylose Content (%)	Total Lipid Content (%)	Peak Visc. (RVU)
Francis-24.3	Thin	52	1	41.7g	3.1b	7.8cd	21.3e	0.28c	219cd
	Medium	11	1	70.1ab	2.2c	8.1cd	22.4d	0.36b	240b
	Thick	3	3	70.4ab	1.7d	7.3d	23.5c	0.29c	246ab
	Unfractionated	18	3	62.3cd	1.9cd	7.6d	22.1de	0.31c	230bc
Francis-18.2	Thin	36	1	47.9f	2.8bc	8.3c	22.3d	0.31c	220cd
	Medium	2	2	66.1bc	2.1cd	7.9cd	22.7d	0.37b	232bc
	Thick	1	4	65.9bc	1.7d	7.1d	23.1cd	0.30c	251a
	Unfractionated	8	1	58.3d	2.2c	7.4d	22.6d	0.41a	233bc
Francis-14.5	Thin	25	2	43.1fg	2.9b	8.6bc	21.9de	0.32bc	209d
	Medium	2	4	66.1bc	2.1cd	8.1cd	22.6d	0.39ab	238b
	Thick	1	10	61.1d	1.6d	7.6d	23.1cd	0.31c	251a
	Unfractionated	8	4	59.3d	1.9cd	8.3c	22.7d	0.35b	233bc
Wells-24.8	Thin	86	0	30.7i	2.5c	7.9cd	22.5d	0.19e	211d
	Medium	18	0	67.6b	2.5c	7.8cd	23.2cd	0.29c	224cd
	Thick	5	1	72.3a	1.8cd	7.5d	23.4c	0.27c	241b
	Unfractionated	19	2	59.4d	1.9cd	7.5d	23.1cd	0.28c	230bc
Wells-18.1	Thin	57	1	41.5g	3.8a	8.4c	22.4d	0.24d	195ef
	Medium	14	2	67.8b	2.3c	8.5c	22.7d	0.37b	217cd
	Thick	2	5	67.4b	1.7d	8.1cd	23.8c	0.36b	246ab
	Unfractionated	7	3	62.4cd	1.9cd	7.6d	23.4c	0.34bc	226c
Wells-15.8	Thin	35	2	41.6g	3.1b	8.9b	22.4d	0.18e	198e
	Medium	4	6	62.4cd	2.4c	8.3c	22.7d	0.31c	221cd
	Thick	2	18	63.0c	1.4d	7.7cd	23.5c	0.30c	247ab
	Unfractionated	4	9	54.2e	1.9cd	7.9cd	23.5c	0.30c	227c
XL8CF-24.9	Thin	34	0	40.3h	2.5c	9.0b	23.3cd	0.34b	187f
	Medium	8	0	67.3b	1.9cd	8.5c	24.2c	0.45a	194ef
	Thick	10	1	68.1b	1.9cd	9.1b	25.0b	0.35b	200e
	Unfractionated	12	1	62.8c	2.3c	9.1b	23.9c	0.35b	194ef
XL8CF-18.5	Thin	34	1	39.2h	2.5c	9.6a	24.2c	0.39ab	192ef
	Medium	6	1	64.8c	1.8cd	8.9b	24.8b	0.43a	198e
	Thick	5	1	67.4b	1.9cd	9.2b	25.5ab	0.38ab	200e
	Unfractionated	8	2	62.9c	1.8cd	8.9b	25.1b	0.40a	199e
XL8CF-14.5	Thin	13	2	39.1h	2.1cd	9.7a	25.1b	0.33bc	188f
	Medium	1	2	63.3c	1.5d	8.5c	26.2a	0.42a	195ef
	Thick	1	2	63.4c	1.6d	8.8bc	26.1a	0.31c	200e
	Unfractionated	5	2	58.1d	1.7d	8.9b	26.0a	0.36b	193ef

[a] Rough rice of each cultivar was harvested from Lodge Corner, AR, at indicated unfractionated sample moisture contents (%wb) in 2003, dried to 12.5% MC, and thickness fractionated (Fig. 3).

[b] Mean values in the same column with different letters are significantly different ($P < 0.05$).

[c] Head rice yield.

greater protein content than thick kernels (Matthews et al 1981a; Wadsworth and Matthews 1986; Matsue et al 2001). The protein contents of the rice samples in this study were positively correlated with α-amylase activity ($r = 0.43$, $P < 0.01$). α-Amylase activity was not affected by location, HMC, or cultivar; the average, unfractionated sample α-amylase activity was 2.0 units/100 g. However, protein content was affected by cultivar but not location or HMC. The average protein contents of unfractionated Francis, Wells, and XL8CF were 7.8, 7.8, and 8.8%, respectively.

Rice flour amylose content increased as the kernel thickness increased, which agrees with Matthews et al (1981a) and Matsue et al (2001). Zhang et al (2003) reported that amylose content was positively correlated with intrapanicle rice kernel weight, indicating that mature kernels had greater amylose content than immature kernels. Amylose content was not affected by HMC or location but was affected by cultivar; the average, unfractionated amylose content of XL8CF (25.3%) was significantly greater than those of Francis (22.4%) and Wells (23.2%).

The total lipid content of brown rice (not listed) decreased as the kernel thickness increased. The total lipid contents of unfractionated brown rice were 2.1–2.6% and did not vary significantly with growing location, HMC, or cultivar. The total lipid content of milled rice did not follow the same trends as that of brown rice. The thin thickness fractions of the milled rice samples generally had lesser total lipid contents than the medium fractions and was similar to, or less than, that of the thick fractions.

The peak viscosity (PV) of the rice flour samples (Tables III and IV) were affected by location, HMC, cultivar, and kernel thickness. The PV values generally increased as the kernel thickness increased, which agreed with the results of Matsue et al (2001). The greater proportion of starch in thicker kernels offers an explanation for the greater PV of the thick fractions. Protein

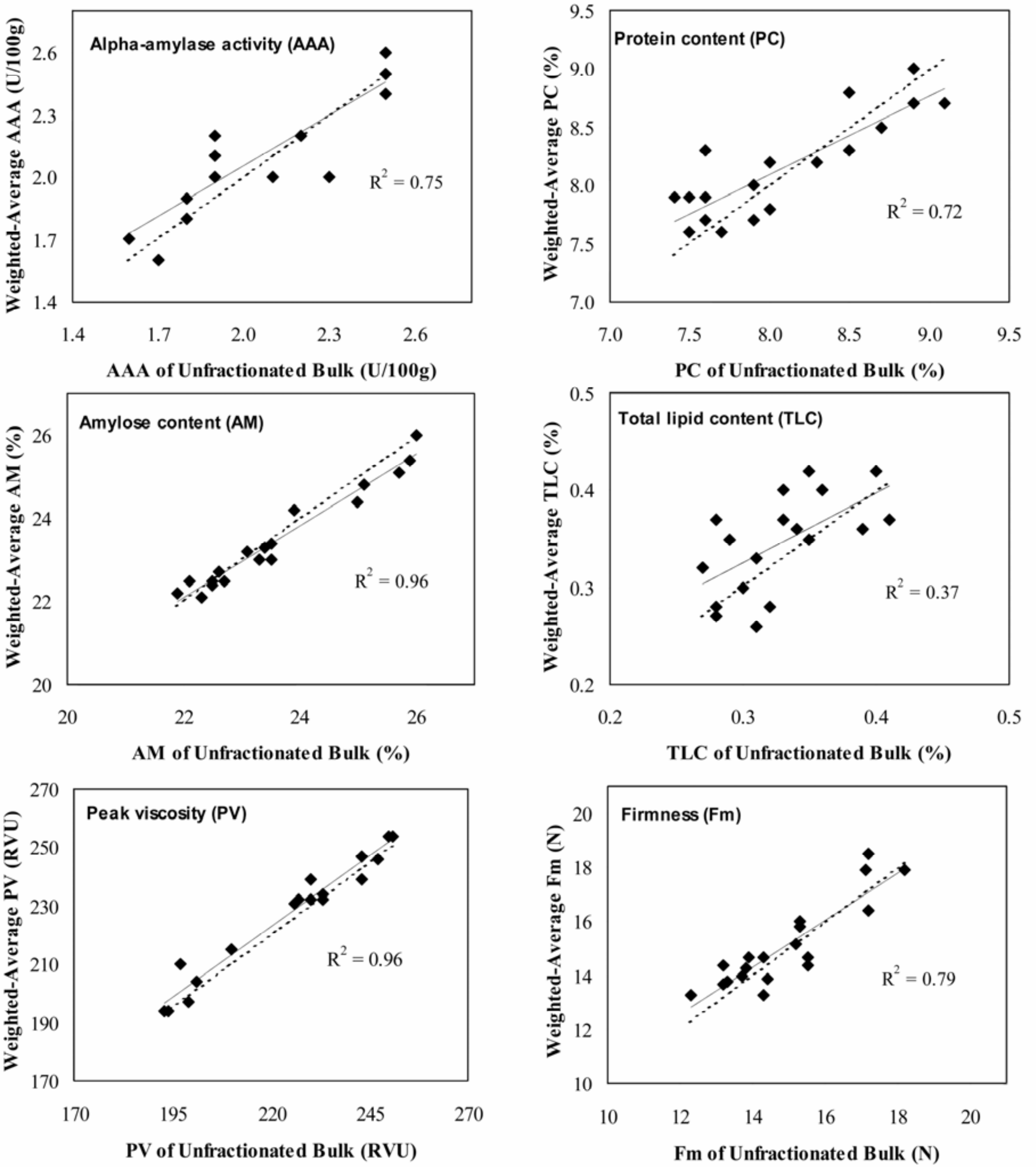

Fig. 5. Relationships between indicated weighted average properties from thickness fractions and those from unfractionated samples. Solid and dotted lines represent the weighted average prediction trend lines and the theoretically perfect prediction lines, respectively.

content was negatively correlated with the overall PV of the 72 rice sample lots ($r = –0.80$, $P < 0.001$). Generally, PV varied with cultivar and location in the order: Francis > Wells > XL8CF and Lodge Corner > Essex. The PV generally increased as the HMC decreased, which agreed with Wang et al (2004).

Cultivar and HMC did not significantly affect the onset gelatinization temperature of rice flour samples (data not shown). Growing location did affect the onset gelatinization temperatures; however, enthalpy was not affected by growing location. The rice flour onset gelatinization temperatures averaged across the three cultivars and HMC were 75.3 and 73.8°C for rice harvested from Lodge Corner and Essex, respectively. The lower rice flour gelatinization temperature at Essex vs. Lodge Corner is supported by the findings of Suzuki et al (2003, 2004), who reported that the amylopectin of rice grown at lower temperatures is more branched with shorter branch chains compared with rice grown at higher temperatures, which results in rice samples with lower gelatinization temperatures. The average growing temperature at Essex was 3°C lower than at Lodge Corner in 2003.

The firmness values of Francis cooked rice from Lodge Corner and Essex are shown in Fig. 4. Firmness values of Wells and XL8CF followed similar trends across thickness fractions as those of Francis. There were inconsistent trends in firmness among the thickness fractions. There was a general tendency for firmness to increase as kernel thickness increased, although in many instances there was no statistical difference between the medium and thick fractions. Cooked rice firmness was affected by HMC and location. For samples of the three cultivars harvested from Lodge Corner, the firmness of cooked rice was 135–193 N and decreased as the HMC decreased. However, similar trends were not found for the same cultivars harvested from Essex in that HMC did not affect firmness. The firmness values of cooked rice from Essex were 121–152 N, which was significantly less than those from Lodge Corner. The reason for the firmness variation by location is unknown, but could be due to different growing environmental conditions.

Comparison of Weighted-Average Properties to Unfractionated Property Values

Most physicochemical properties of the unfractionated samples were predicted well by the corresponding weighted-average properties of the thin, medium, and thick fractions. Figure 5 shows the correlations between unfractionated sample properties and the weighted averages of thickness fraction properties for α-amylase activity, protein content, amylose content, total lipid content, peak viscosity, and cooked rice firmness. The solid and dotted lines in Fig. 5 represent the weighted-average trend lines and the theoretically perfect prediction lines, respectively. The dotted line, with a slope of 1.0, denotes perfect agreement between weighted-average properties and those of unfractionated samples. Linear regression analysis slopes of the weighted-average property predictions were 0.81 for α-amylase activity ($R^2 = 0.75$), 0.67 for protein content ($R^2 = 0.72$), 0.87 for amylose content ($R^2 = 0.96$), 0.72 for total lipid content ($R^2 = 0.37$), 0.97 for peak viscosity ($R^2 = 0.96$), and 0.87 for cooked rice firmness ($R^2 = 0.79$). The weighted-average predictions of α-amylase activity, amylose content, peak viscosity, and firmness were fairly accurate as indicated by regression slopes ≥0.87. The predictions for protein content and total lipid content were not as accurate; these properties are closely related to the milled rice degree of milling. The degree of milling is, in turn, dependent on kernel uniformity, and thus differences in milling behavior could produce differences between the unfractionated sample properties and those predicted by thickness fraction weighted averages.

Similar correlations between unfractionated bulk properties and the weighted-average properties of thickness fractions were noted for HMC ($R^2 = 0.98$), 1,000-kernel mass ($R^2 = 0.98$), and bulk density ($R^2 = 0.41$). However, the HRY of unfractionated bulk rice samples were not well predicted by weighted-averages of thickness fractions ($R^2 = 0.18$); the reasons for this are attributed to kernel size uniformity causing differences in milling behavior, as presented above.

CONCLUSIONS

The primary emphasis of this study was to assess whether variation in rice sample properties could be accounted for by the weighted average of constituent thickness fraction properties. Most unfractionated physicochemical properties, particularly α-amylase, protein, and amylose contents, as well as MC and 1,000-kernel mass, were well predicted by the weighted average of the thickness fraction properties. Processing (peak viscosity) and sensory (firmness) properties were also well predicted. The properties that were not particularly well predicted were those of milling quality and properties associated with degree of milling (rice flour lipid content). The kernel-to-kernel dynamics involved in bran removal during milling is highly affected by kernel size uniformity. As such, the weighted-average response of milling each thickness fraction separately was different from that of milling an unfractionated sample. Bulk density, for reasons similar to those applied to milling quality but involving packing of kernels, was also not accurately predicted by the weighted average of thickness fraction bulk densities.

To produce a robust data set, rough rice of several cultivars was harvested over a range of HMC at two locations. Most of the milling and physicochemical property trends affected by HMC and kernel thickness followed trends reported previously. However, many properties were dependent on the growing location. The two locations selected for this study had different growing temperature regimes, with an average of 3°C difference in growing season temperature. It is speculated that physicochemical differences associated with location are due to different environmental temperatures during kernel development. Yoshida and Hara (1977), Suzuki et al (2003, 2004), and Counce et al (2005) document the effects that environmental temperatures during kernel development have on rice kernel properties.

ACKNOWLEDGMENTS

We thank the Arkansas Rice Research and Promotion Board and the corporate sponsors of the University of Arkansas Rice Processing Program for project financial support.

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[Received December 12, 2005. Accepted January 17, 2006.]