Physical and Functional Characteristics of Broken Rice Kernels Caused by Moisture-Adsorption Fissuring

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ABSTRACT

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Fissuring caused by rapid moisture adsorption generates broken kernels upon milling; brokens are often ground to flour. The recent increase in demand for rice flour has promoted interest in brokens. This study investigated the physical and functional characteristics of brokens resulting from milling lots with various levels of moisture adsorption-induced fissuring. Two long-grain (LG) cultivars and one medium-grain (MG) cultivar were conditioned to five initial moisture contents (IMCs), rewetted, and then reconditioned to 12% moisture content. Brown rice fissure enumeration and milling analyses as well as size distribution and functionality analyses of brokens were conducted. As IMC decreased, the percentage of fissured kernels increased and, consequently, the amount of brokens generated increased. Although the number of fissures/kernel also increased with decreasing IMC, the mass distribution of the resultant brokens was not affected by IMC. Across all IMC levels, the mass percentage of the medium-sized brokens was greatest for the LG cultivars, whereas that of the large-sized brokens was greatest for the MG cultivar. Regardless of IMC, peak, setback, and final viscosities were greatest for head rice and decreased significantly with decreasing size of brokens. Thus, brokens of different sizes have different functional properties and, hence, may be fractionated for different end-use applications.

Fissuring caused by rapid moisture adsorption is a common problem faced by rice producers, primarily due to the result of logistical harvesting considerations. Moisture adsorption-induced fissuring is generally associated with water entering a relatively dry kernel. Although rapid and substantial moisture adsorption by a rice kernel causes it to develop stresses in all three kernel dimensions, the principal stresses appear to be parallel to the kernel's long axis; the kernel fissures when these stresses exceed the tensile strength of the kernel (Kunze 1977, 1979). Hence, these fissures usually appear as "large internal fractures perpendicular to the long axis of the kernel" (Sharma and Kunze 1982). Such moisture adsorption environments are created 1) by rainfall or high-humidity conditions, as well as diurnal cycles of temperature and relative humidity (RH) in fields before harvest, 2) in bins holding freshly harvested rice, 3) in certain types of dryers ahead of the drying front, and 4) in postharvest operations as a result of inadvertent overdrying and subsequent rewetting of rice (Kunze and Prasad 1978; Calderwood 1984; Siebenmorgen and Jindal 1986).

Because rice is mostly consumed as "milled, intact kernels" (Cooper et al. 2008), the extent of fissuring in rice kernels and consequent breakage upon milling directly affect the market value of a rice lot. Milled kernels that are less than three-quarters of the "unbroken kernel length" are referred to as broken kernels (USDA 2009), whereas the remaining "whole" kernels are generally known as "head rice" or "fancy" in the rice industry. Although the relative price of brokens to head rice varies significantly over time, brokens are typically worth 60–80% of the market value of head rice. Zhang et al. (2005) and Siebenmorgen et al. (2005) showed that fissured kernels are significantly weaker than "sound" kernels (kernels without fissures). Thus, fissured kernels often break during hulling and milling. Fissured kernels are also more prone to spoilage because of their increased susceptibility to microbial and insect attack (Velupillai and Pandey 1990). Thus, fissuring in rice kernels is an economic concern for rice producers and processors.

Broken rice kernels have largely been underutilized in the rice industry (Okpala and Egwu 2015). However, the demand for brokens and rice flour has recently increased considerably. Part of this increased demand is caused by an increasing number of people being diagnosed with celiac disease, an autoimmune, genetic disorder of the small intestine (Hartmann et al. 2006; Woodward 2007). The only treatment for this disease is strict adherence to a gluten-free diet. Many gluten-free formulations use rice as a primary ingredient because it is naturally gluten-free. Rice is also increasing in popularity as an ingredient because of its hypoallergenicity (Bean et al. 1983; Gujral et al. 2003; Gujral and Rosell 2004).

In most baby foods (Hasjim et al. 2013), rice noodles (Hasjim et al. 2013; Kim and Shin 2014), puddings (Hasjim et al. 2013), rice cakes, rice breads, and fermented rice products (Kim and Shin 2014), rice is ground and used as flour. In addition to being gluten-free and hypoallergenic, other desirable characteristics of rice flour include its white color, bland taste, ease of digestion, and low levels of sodium, fat, and protein (Kim and Shin 2014). Novel uses of rice flour and rice starch also include the manufacture of biodegradable or edible films (Dias et al. 2010) and edible cutlery (www.bakeys.com). Thus, it has become more economically justifiable to grind brokens to produce flour for such applications (Qian and Zhang 2013).

In addition to these applications, brokens are also utilized by the pet-food industry. Some pet-food formulations require intact brokens, whereas most others require rice flour. The recent growth of the pet-food industry in the United States, as well as the increasing demand for rice flour for the uses described earlier, has led to a steady increase in the use of brokens.

The U.S. Department of Agriculture classifies the largest, intermediate, and smallest broken rice kernels as second heads, screenings, and brewers, respectively (USDA 2009). However, broken kernels are generally either sold as "intact brokens" or consolidated and ground into flour, regardless of the size of these kernels.

Brokens have been reported to have different functional properties from those of head rice (Proctor and Goodman 1985; Wang et al. 2002), in particular, lower peak (PV) and final (FV) viscosities compared with head rice. However, it is not known whether brokens of different sizes differ in functional characteristics. If so, it may be beneficial to fractionate brokens based upon their size and direct these size-fractionated streams toward specific end-use applications. Additionally, although several studies have addressed the impact of rapid moisture adsorption on the overall extent of fissuring and resultant milling yields, none have investigated this impact on the particle-size distribution of brokens produced during milling. It is hypothesized that kernels with multiple fissures will

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break into smaller pieces during the milling process and, thus, alter the relative distribution of brokens, with possible consequences on functional behavior. Thus, the objectives of this study were to 1) evaluate the effects of rapid moisture adsorption on the overall extent of fissuring, the number of fissures/kernel, and the particle-size distribution of brokens, and 2) quantify the functionality of brokens resulting from milling rice lots that had incurred various levels of moisture adsorption-induced fissuring.

MATERIALS AND METHODS

Sample Procurement and Preparation. Roy J (pureline, long-grain [LG]), CL XL745 (hybrid, LG), and Jupiter (pureline, medium-grain [MG]) cultivar lots were combine-harvested at Arkansas locations in fall 2014 at 17.1, 19.1, and 20.6% moisture content (MC), respectively. Unless otherwise specified, MC is reported on a wet basis. The bulk lots were cleaned with a dockage tester (XT4, Carter-Day, Minneapolis, MN, U.S.A.) to remove foreign material and unfilled kernels. The cleaned bulk lots were stored in sealed containers at 4°C for six months prior to testing.

Approximately 14 kg of rough rice from each cultivar lot was removed from cold storage and equilibrated to room temperature (22 ± 1°C) for 24 h. Each 14 kg lot was divided into six sublots: five 2 kg sublots were conditioned to 9, 11, 13, 15, or 17% initial MC (IMC) and one 4 kg sublot to 12% IMC. The conditioning was accomplished in a chamber equipped with an air-control unit (5580A, Parameter Generation and Control, Black Mountain, NC, U.S.A.). The sublots were spread in thin layers on screen-bottomed trays inside the chamber; conditioning air was maintained at 37°C and 30% RH to achieve 9 and 11% IMC, and at 26°C and 52% RH to achieve 12, 13, 15, and 17% IMCs. MC of the sublots was checked periodically with a grain moisture tester (AM 5200, Perten Instruments, Hägersten, Sweden); when the sublots reached the target IMC, the rice was transferred into air-tight bags and sealed. The actual IMC of the conditioned sublots was determined by drying duplicate 15 g subsamples in a convection oven (1370FM, Shellblue, Sheldon Mfg., Cornelius, OR, U.S.A.) maintained at 130°C for 24 h (Jindal and Siebenmorgen 1987); actual IMC of the conditioned sublots was within ±0.3 percentage points of the targeted IMC. This procedure was replicated three times for each cultivar.

Preliminary Analysis. Before any moisture-adsorption treatments were applied, an analysis was performed to determine whether the abovementioned conditioning process in itself created any measurable amount of fissuring. Samples (300 g each) were obtained from each of the 54 cultivar–IMC–replicate sublots (three cultivars × six IMCs × three replicates) and reconditioned to 12% MC, because milling analyses are typically performed at approximately 12% MC. The reconditioning was accomplished in the abovementioned chamber by using air at 26°C and 70% RH to gently remoisten the 9 and 11% IMC samples to 12% MC, and at 26°C and 52% RH to gently dry the 13, 15, and 17% IMC samples to 12% MC. When all 54 samples attained 12% MC, 300 rough rice kernels were randomly selected from each sample and manually dehulled for enumeration of fissures (described later). Additionally, the milling yield from each of these 54 samples was determined (described later).

Statistical analyses showed that there were no significant differences in the extent of fissuring or the milling yield among the samples of each cultivar that had been conditioned to 9, 11, 12, 13, 15, or 17% IMC and then reconditioned to 12% MC (results not shown). Thus, the conditioning process used to attain the various IMC levels had not induced fissuring in the kernels. Additionally, because there were no differences in fissuring levels across the cultivar–IMC–replicate sublots, the 12% IMC sublots that would not receive any moisture-adsorption treatment were deemed appropriate "controls" for estimating fissure levels for the actual experiment.

Moisture-Adsorption Treatments. To create fissures caused by rapid moisture adsorption, the remaining rice (approximately 1.5 kg) of the 45 different 2 kg sublots was wrapped in vinyl screencloth bags and soaked for 2 h in a water bath (Precision 280, Precision Scientific, Winchester, VA, U.S.A.) held at 30 ± 1°C, drained for 30 min, allowed to air dry at 22 ± 1°C on screen-bottomed trays for 1 h, and then gently redried to approximately 12% MC inside the conditioning chamber with air at 26°C and 52% RH. The control (12% IMC) sublots were not rewetted.

Brown Rice Fissure Enumeration and Determination of Milling Yield. Samples (300 kernels each) were randomly selected from each treated or dried sublot and manually dehulled. Brown rice kernels were visually examined for fissures with a fissure-inspection box (TX-200 Grainscope, Kett Electric Laboratory, Tokyo, Japan). Fissured kernels were enumerated and expressed as a number percentage of the 300 rough rice kernels. The number of fissures per kernel was also enumerated.

Milling yield was quantified by the milled rice yield (MRY) and head rice yield (HRY). MRY represented the mass of milled rice and HRY the mass of head rice, both expressed as a percentage of the original, dried rough rice (150 g). Because milling yield is affected by the degree to which rice is milled (i.e., level of bran removal from head rice), and the milling duration required to attain a certain degree of milling (DOM) differs among cultivars (Siebenmorgen et al. 2006b), a preliminary experiment was conducted to determine the milling durations necessary to attain a desired DOM for each of the three cultivars used. From each of the nine cultivar–replicate and control (12% IMC, not rewetted) sublots, four 150 g samples were dehulled with a laboratory huller with a clearance of 0.048 cm between the rollers (THU-35A, Satake Engineering, Tokyo, Japan). The brown rice samples were then milled for four durations (10, 15, 20, or 25 s for Roy J and CL XL745; 10, 20, 25, or 30 s for Jupiter) in a laboratory mill (McGill number 2, Rapsco, Brookshire, TX, U.S.A.) with a 1.5 kg mass placed on the lever arm 15 cm from the center of the milling chamber. Then, a sizing device (61, Grain Machinery Manufacturing, Miami, FL, U.S.A.) was used to separate head rice from brokens. The DOM was quantified by surface lipid content (SLC); SLC decreases as bran is removed (Cooper and Siebenmorgen 2007). SLC was determined by scanning 50 g of head rice with a near-infrared reflectance spectrophotometer (DA7200, Perten Instruments, Hägersten, Sweden) (Saleh et al. 2008) and plotted as a function of milling duration. Exponential functions were used to describe the relationships between SLC and milling duration for each cultivar sublot; from the resulting curves, the milling durations necessary to reach an SLC of 0.4% were averaged to be 19 s for Roy J, 25 s for CL XL745, and 24 s for Jupiter.

Thus, for conducting milling analyses, one 150 g sample from each of the 45 cultivar–IMC–replicate rewetted sublots was dehulled, milled for the durations established above, and separated. MRY and HRY were recorded, and the brokens were used for subsequent analyses.

Physical and Functional Characteristics of Broken Kernels. The size distributions of brokens were determined with sieve analysis per ANSI/ASAE Standard S319.6 (ANSI/ASAE 1997). According to this standard, a sieve analysis requires "at least a 100 g sample, although lower sample amounts may be used if necessary." The amounts of brokens generated during milling from samples of the 9 and 11% IMC sublots were sufficient to charge a sieve set following the standard's recommendation. However, additional batches of 150 g samples of the 13, 15, and 17% IMC sublots were processed to yield sufficient amounts of brokens to charge the sieve set. A sieve shaker (RX-29, RO-TAP, Mentor, OH, U.S.A.) with U.S. sieve numbers 10 and 12, having square openings of 2.00 and 1.68 mm, respectively, was operated for 15 min for each sample, distributing brokens into large (retained on the 2.00 mm sieve), medium (passed through the 2.00 mm sieve but retained on the 1.68 mm sieve), and small (passed through the 1.68 mm sieve) broken kernel fractions. The control (12% IMC) sublots generated negligible amounts of brokens; hence, particle-size distribution analyses were not conducted for these sublots.

Paste viscosities of flour obtained from the head rice and the small, medium, and large broken kernel fractions from each sublot were determined according to AACC International Approved Method 61-02.01. From each fraction, approximately 7 g of head rice or broken kernels was ground into flour with a cyclone sample mill (3010-30, UDY Corporation, Fort Collins, CO, U.S.A.) equipped with a 0.5 mm (100 mesh) screen. Duplicate 2 g subsamples of flour were dried in the convection oven at 130°C for 1 h to determine MC, per AACCI Approved Method 44-15.02. Adjusted for MC, viscosities were determined on a paste of 3 g of rice flour in 25 mL of distilled water with a viscometer (RVA-Super 4, Newport Scientific, Warriewood, NSW, Australia). The flour paste from each broken kernel fraction was held at 50°C for 1.5 min, heated to 95°C at 12.2°C/min, held at 95°C for 2 min, cooled to 50°C at 12.2°C/min, and held at 50°C for 1.5 min. PV, setback viscosity (SBV), and FV were reported in centipoises.

Data Analyses. Analysis of variance ($\alpha = 0.05$) was conducted and means separated according to Fisher's least significant difference procedure ($P < 0.05$) with JMP Pro software (version 12.0.1, SAS Institute, Cary, NC, U.S.A.). Statistical significance ($P < 0.05$) was determined, and significant differences were indicated by using separate-letter reporting.

RESULTS AND DISCUSSION

Brown Rice Fissure Enumeration and Milling Yield. Brown rice fissured kernel percentages (FKs), MRYs, and HRYs attained for the cultivar–IMC combinations are shown in Figure 1. Across all cultivars, IMC had a profound effect on the extent of fissuring and resultant HRY; as IMC prior to rewetting decreased, the extent of fissuring increased and HRY correspondingly decreased.

The FKs of the 15 and 17% IMC rewetted sublots were comparable with those of the control (12% IMC) sublots, particularly for the two LG cultivars. However, as IMC decreased, FKs progressively

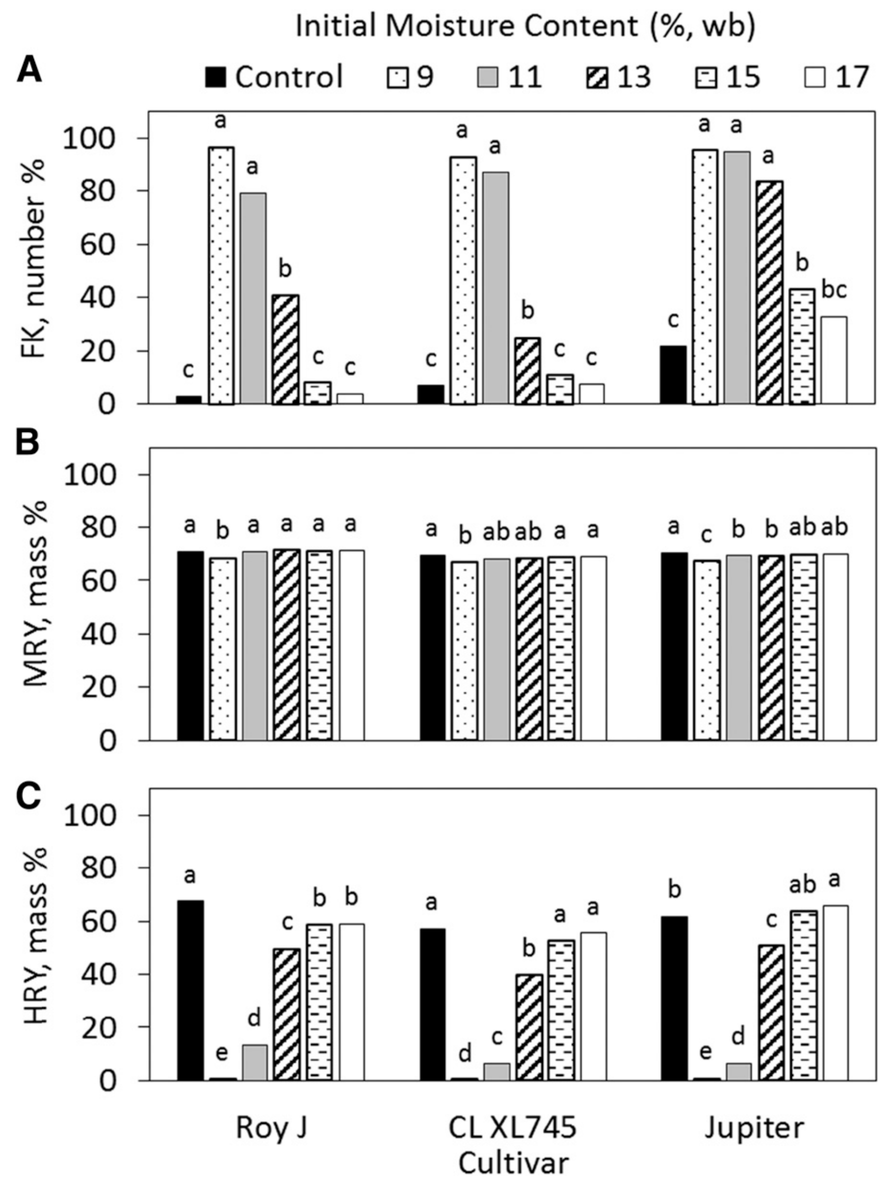

Fig. 1. A, Brown rice fissured kernel percentage (FK); **B,** milled rice yield (MRY); and **C,** head rice yield (HRY) for the indicated cultivar–initial moisture content (IMC) combinations after being conditioned to five IMC levels, rewetted, and then reconditioned to 12% moisture content (MC). The control (12% IMC) sublots were not rewetted but rather conditioned from harvest MC to 12% MC. Within each cultivar–IMC set, values followed by the same letter are not significantly different ($P > 0.05$). Bars are based on the mean values of three experimental treatment replications.

TABLE I
Brown Rice Fissured Kernel Percentage (FK) and Frequencies (%) of Brown Rice Fissures per Kernel (F/K) for the Indicated Cultivar–Initial Moisture Content (IMC) Combinations

Cultivar, IMC (% wb)[z]	FK (%)	Number of F/K								
		0	1	2	3	4	5	6	7	8
Roy J										
9	96.7	3.3	2.3	3.6	11.2	20.0	26.9	19.4	9.2	4.0
11	79.2	20.8	18.8	20.8	22.2	13.1	3.3	1.0	1.0	…
13	40.6	80.1	12.7	5.0	1.7	0.7	…	0.3	…	…
15	8.1	93.0	4.2	2.1	0.6	0.3	…	…	…	…
17	3.8	96.8	2.3	0.9	…	…	…	…	…	…
Control	3.0	97.0	1.7	1.2	0.3	…	…	…	…	…
CL XL745										
9	93	10.0	7.1	11.8	17.1	17.1	21.3	12.9	6.3	2.2
11	87	13.0	16.4	24.4	23.8	15.2	5.2	1.6	0.3	0.3
13	24.8	75.2	15.0	7.9	1.8	0.3	…	…	…	…
15	10.7	89.3	6.2	2.7	1.2	0.4	0.3	…	…	…
17	7.6	92.4	5.0	1.8	0.8	…	…	…	…	…
Control	6.8	93.2	4.4	1.7	0.6	…	0.3	…	…	…
Jupiter										
9	95.3	4.7	5.8	23.9	36.6	19.8	7.7	1.8	1.3	…
11	94.8	5.2	22.6	41.9	23.0	5.6	0.7	0.2	0.3	…
13	83.4	16.6	38.1	30.4	9.2	0.3	…	…	…	…
15	43.0	57.0	34.4	8.3	0.3	…	…	…	…	…
17	32.7	67.3	25.8	5.9	1.1	0.3	…	…	…	…
Control	21.8	78.2	19.1	2.7	…	…	…	…	…	…

[z] Abbreviation: wb = wet basis.

increased; clear statistical differences in FKs were observed as IMC decreased below 15%. In fact, across all cultivars, almost all the kernels fissured in the 9% IMC sublots, similar to results reported by Mukhopadhyay and Siebenmorgen (2012).

As the extent of fissuring increased with decreasing IMC, HRY correspondingly decreased. HRY declined sharply as rice with IMC < 15% was rewetted, as indicated by the separate-letter report in Figure 1. This confirmed the general recommendation that rice must be harvested before it dries below 15% MC in the field to avoid fissuring caused by rapid moisture adsorption. Expectedly, all the fissured kernels produced by rewetting the 9% IMC sublots broke during milling, yielding an HRY value of 0%. These FK and HRY results corroborated the findings of Srinivas et al. (1978), Siebenmorgen and Jindal (1986), and Bautista et al. (2004) in that the lower the IMC of the rice when it is rewetted, the greater the extent of fissuring and consequent breakage of kernels when milled and, hence, the more the reduction in HRY.

For all cultivar–IMC combinations, MRY also decreased with decreasing IMC, although clear statistical differences did not occur until 9% IMC rice was rewetted. This suggests that, with severe fissuring and consequent breakage during milling, some endosperm leaves with the bran stream, thus decreasing the total mass of rice produced through milling. These results corroborated the findings of Mukhopadhyay and Siebenmorgen (2012, 2014). Reduced MRY has economic implications, in that both head rice and brokens have economic value and, thus, contribute to the total value of a rice lot.

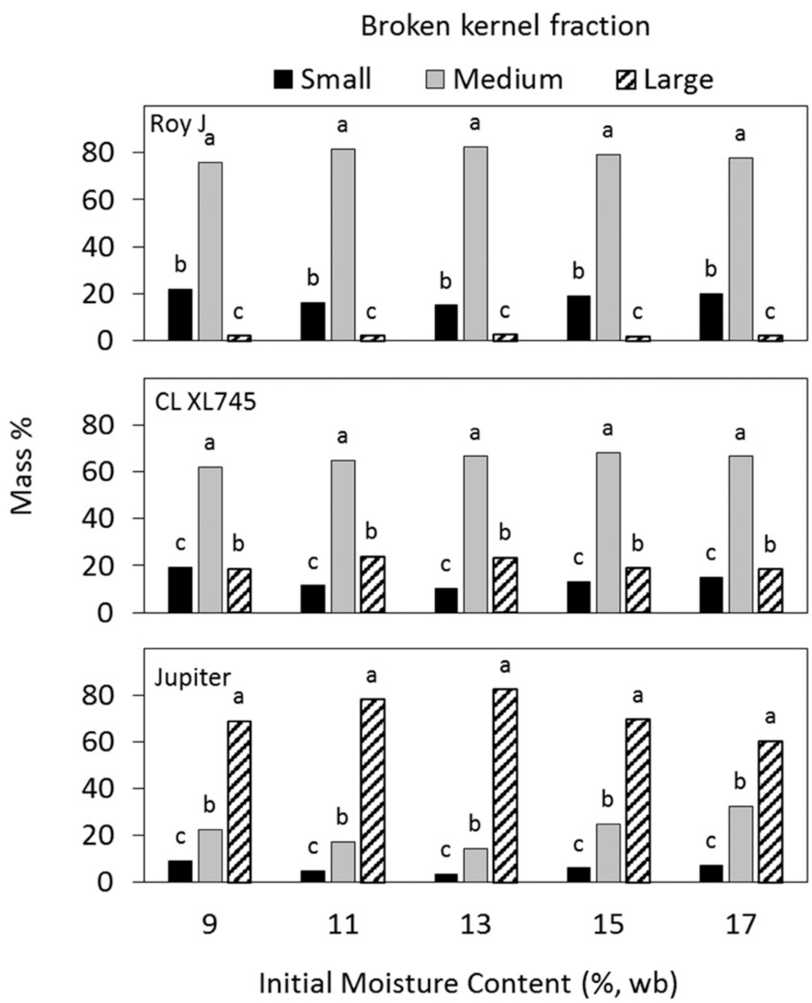

Fig. 2. Mass percentages of small (passed through the 1.68 mm sieve), medium (passed through the 2.00 mm sieve but retained on the 1.68 mm sieve), and large (retained on the 2.00 mm sieve) broken kernel fractions for the indicated cultivar–initial moisture content (IMC) combinations. Within each cultivar–IMC–broken kernel fraction set, values followed by the same letter are not significantly different ($P > 0.05$).

The control as well as the rewetted sublots of MG Jupiter generally had greater FK compared with the corresponding LG Roy J and CL XL745 (Fig. 1). The increased fissure susceptibility of Jupiter is believed to be caused by its thick and wide kernel shape (Lan and Kunze 1996) relative to the two LG cultivars.

For all cultivars, as IMC prior to rewetting decreased, not only did the percentage of fissured kernels increase but also the number of fissures per kernel (F/K) increased (Table I). The 15 and 17% IMC sublots of Roy J and CL XL745 had frequency distributions of fissures per kernel similar to that of the control. However, as IMC decreased below 15%, increasing numbers of kernels developed multiple fissures. For example, for the control sublot for Roy J, 97% of all the kernels had 0 F/K, 1.7% had 1 F/K, 1.2% had 2 F/K, and 0.3% had 3 F/K; none of the kernels had more than 3 F/K. However, with decreasing IMC, these frequency distributions continued to skew toward greater F/K; at 9% IMC, only 3.3% of the kernels had 0 F/K, whereas most of the kernels (79.5%) had 4–8 F/K.

Interestingly, not only did the rewetted sublots of MG Jupiter generally have greater FK at the corresponding IMC compared with the two LG cultivars (Fig. 1) but also all of its rewetted sublots had more F/K than its control, including the 15 and 17% IMC sublots (Table I). Additionally, Jupiter had significantly greater numbers of kernels with multiple fissures at 9, 11, and 13% IMC compared with the LG cultivars, probably because of its greater kernel thickness relative to the LG kernels, as described earlier.

Physical and Functional Characteristics of Broken Kernels. Because it was speculated that brown rice kernels with multiple fissures were more prone to breakage into smaller pieces during milling, the resultant mass distribution of the broken kernel fractions would, in turn, be expected to be affected by the extent of fissuring in the kernels. Because F/K increased with decreasing IMC, it followed that the mass distribution of the broken kernel fractions would be a function of IMC as well (i.e., at lower IMC, there would be more small-sized brokens than medium-sized or large-sized ones). However, across all cultivars, the mass distributions of the small, medium, and large broken kernel fractions did not vary among IMC levels (Fig. 2). Thus, the mass distributions of the broken kernel fractions did not reflect the trends shown by the frequency distributions of F/K (Table I).

Across all IMC levels, the mass percentage of the medium-sized broken kernel fraction was prominently the greatest for LGs Roy J and CLXL745, whereas the mass percentage of the large-sized broken kernel fraction was the greatest for MG Jupiter. The two LG cultivars also differed in the mass distribution trends of broken kernel fractions; for Roy J, medium > small > large (corroborating \results of Mukhopadhyay and Siebenmorgen 2014), whereas for CL XL745, medium > large > small. These results indicate that the size distribution of broken kernels may differ even among LG cultivars. For Jupiter, the mass percentages of the broken kernel fractions were large > medium > small. This knowledge may be useful if processors need to fractionate brokens of different sizes for specific purposes.

An initial analysis showed that IMC did not affect the pasting properties of the kernel fractions (results not shown). Pasting

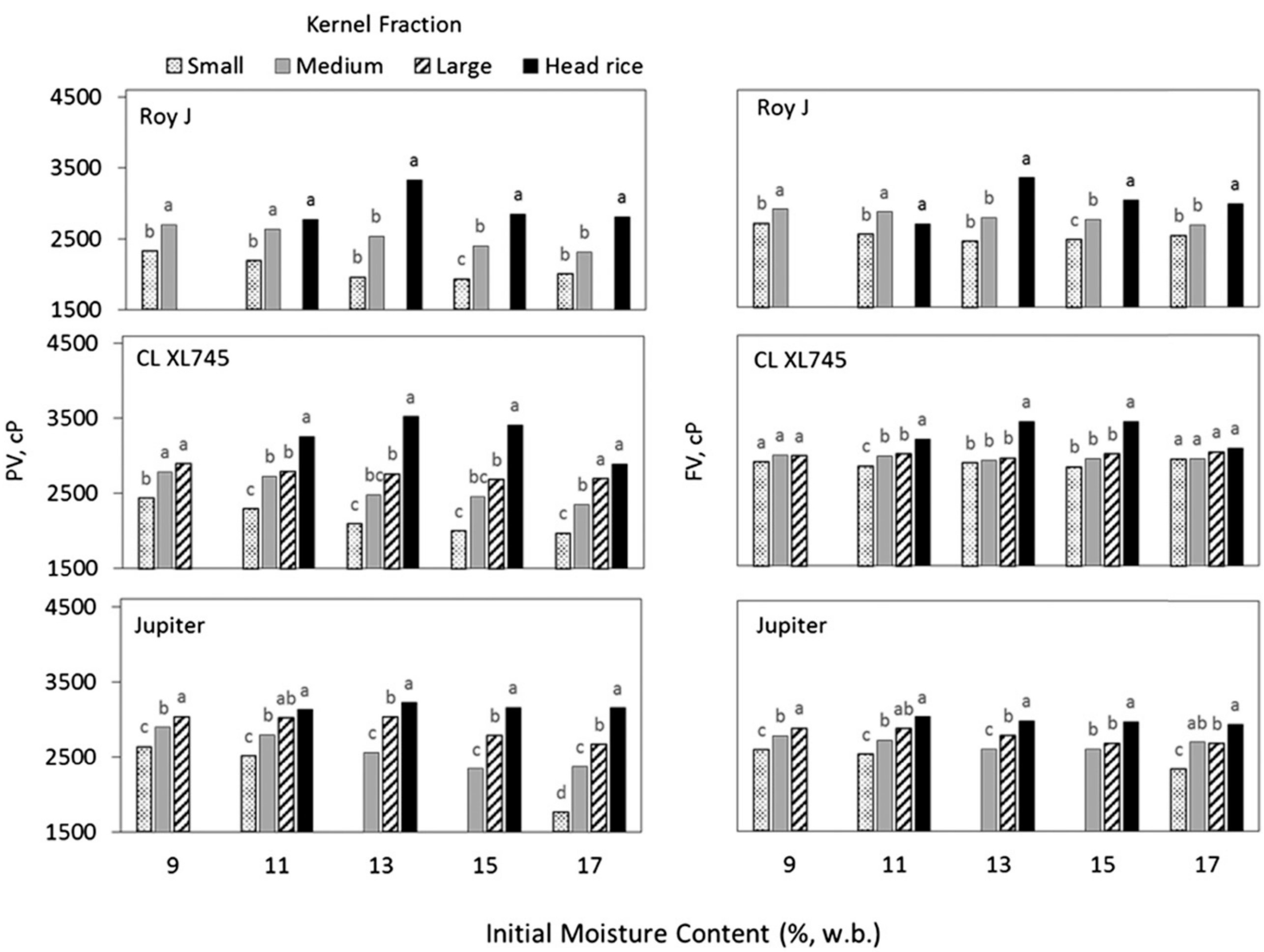

Fig. 3. Peak (PV) and final (FV) viscosities of head rice and small, medium, and large broken kernel fractions in centipoises (cP) for the indicated cultivar–initial moisture content (IMC) combinations. Within each cultivar–IMC–kernel fraction set, values followed by the same letter are not significantly different ($P > 0.05$). Missing bars are a result of insufficient quantities of samples for analysis with the viscometer.

temperature was not significantly different among the kernel fractions for any cultivar–IMC combination (data not shown). However, for all cultivar–IMC sublots, both PV and FV were greatest for head rice and decreased significantly with decreasing size of brokens (Fig. 3). Interestingly, SBV also showed the same trends as PV and FV (data not shown). Hence, progressively smaller brokens apparently have starch granules with lower swelling capacities (indicated by decreasing PV) as well as lower retrogradation (indicated by decreasing SBV).

Brokens were also reported to have less PV and FV compared with head rice in earlier studies (Proctor and Goodman 1985; Wang et al. 2002). Interestingly, although the paste viscosity trends obtained in these studies were similar, the source of brokens used in these studies was different than the current study. The brokens used by Proctor and Goodman (1985) were produced by milling MG and LG cultivars at 9.3–11.2% MC, whereas the brokens used by Wang et al. (2002) were created in the laboratory by subjecting rice lots to severe drying conditions (60°C and 17% RH) until 12% MC was attained and then immediately allowing the rice to cool in a room maintained at 5°C to induce breakage.

Proctor and Goodman (1985) attributed these trends of brokens having lower PV and FV compared with head rice to 1) differences in the relative amounts of amylose and amylopectin in head rice versus brokens and 2) the prominence of a protein–phytin complex in brokens compared with head rice. However, they did not report the amounts of amylose and amylopectin in head rice or brokens. Additionally, they did not discuss the mechanism of action of the protein–phytin complex in lowering PV and FV. However, they did report lower hardness values for brokens compared with head rice and concluded that brokens were softer and more porous. Thus, they proposed that there were "some differences in hardness among rice kernels within a cultivar that truly existed prior to milling" and that "weak/soft kernels" broke during subsequent processing.

Although Wang et al. (2002) also reported similar results, they did not observe any differences in the relative amounts of amylose and amylopectin in head rice and brokens, as was conjectured by Proctor and Goodman (1985). Wang et al. (2002) concluded that "it was not clear what caused the low pasting viscosities in the broken rice flour," even after comparing the gelling and thermal properties, X-ray diffraction patterns, high-performance size-exclusion chromatography, and anion-exchange chromatography with pulsed amperometric detection data between head rice and brokens.

Although speculative, the differences in RVA profiles among the different broken kernel fractions could be a result of the variation in the individual kernels that broke to create the brokens. It is known that thicker kernels within a bulk are more susceptible to fissuring by moisture adsorption than the thinner kernels (Jindal and Siebenmorgen 1994). It has further been shown that physicochemical properties vary among kernel thickness fractions (Siebenmorgen et al. 2006a). Thus, as the extent of fissuring increases with decreasing IMC, the kernel population that produces brokens would change, as would the properties of the brokens. Another plausible explanation could be that the positions at which a kernel fissures and consequently breaks to generate the broken pieces dictates the physical characteristics (size and shape) and chemical composition of the broken pieces. This, in turn, affects the relative amounts of starch, protein, and lipid in brokens because the surface area/interior ratio would change, which happens because a rice kernel is not uniform in its properties and composition throughout. This causes inherent differences between broken kernel pieces that eventually manifest themselves in the different RVA trait values.

Although the reason for brokens having lower PV and FV compared with that of head rice is rather unclear, it is confirmed that kernels that broke during milling had lower viscosity values compared with the kernels that did not break (i.e., head rice), even when the brokens were created by moisture adsorption-induced fissuring. Moreover, this study found that decreasing sizes of brokens had decreasing PV, SBV, and FV. Thus, these viscosity trends indicate that size-fractioning of brokens might be beneficial for different end-use applications.

CONCLUSIONS

The following conclusions were drawn from this study:

1. As IMC prior to rewetting decreased below 15%, the extent of fissuring increased, in terms of both the percentage of kernels having fissures and the number of fissures per kernel.
2. As IMC decreased, although the frequencies of fissures per kernel increased, the mass distributions of the broken kernel fractions generated thereof was not affected. The latter was affected by cultivar, with the mass percentage of the medium-sized broken kernel fraction and the large-sized broken kernel fraction being the greatest for the LG and MG cultivars, respectively. The size distribution of brokens was also different between the two LG cultivars studied.
3. Regardless of IMC, the PV, SBV, and FV were greatest for head rice and significantly decreased with decreasing size of brokens. Hence, it may be beneficial to direct size-fractioned brokens to different end-use applications.

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