

Rheological and Pasting Properties of Buckwheat (*Fagopyrum esculentum* Möench) Flours With and Without Jet-Cooking¹

George E. Inglett,¹ Jingyuan Xu,¹ David G. Stevenson,^{1,2} and Diejun Chen¹

ABSTRACT

Cereal Chem. 86(1):1–6

Pasting, rheological, and water-holding properties of buckwheat (*Fagopyrum esculentum*) flour obtained from whole achenes separated into three particle sizes, and three commercial flours (Fancy, Supreme, and Farinetta) were measured with or without jet-cooking. Fancy had instantaneous paste viscosity (measured using RVA) after jet-cooking that was not observed for Supreme or Farinetta, and paste viscosity was lower for the latter two flours. Supreme jet-cooked flour exhibited higher peak viscosity than flour without jet-cooking, and paste exhibited high shear-thinning. Fancy exhibited strongest viscoelastic properties (measured using

a rheometer). Jet-cooking damaged buckwheat flour structure, thereby reducing viscoelasticity. Buckwheat flour pastes experienced shear-thinning over a wide range of shear rates. Jet-cooking greatly enhanced water-holding capacity. Buckwheat flour particle size did not greatly influence paste viscosity. Study showed buckwheat flours have unique pasting and rheological characteristics that have different food applications, which could especially be useful for people with celiac disease as buckwheat is gluten-free.

Buckwheat seeds, known as achenes, have a hard outer shell and a soft interior, making it possible to obtain very useful flours for food use. Common food uses of buckwheat include soba noodles in Japan, a jelly known in Korea as *sae me duk* (a steamed cake), and *memilmuk*, a type of porridge referred to as *kasha* in eastern Europe, and as a pancake known as *blini* in Russia and *galette* in France. Buckwheat is a widely cultivated seed crop, primarily in Russia, Poland, China, Korea, Japan, and Canada. It has outstanding antioxidant capacity (Holasová et al 2002; Morishita et al 2007). Primary antioxidant components of buckwheat are rutin, quercetin, hyperin, and catechins (Watanabe et al 1997; Wijngaard and Arendt 2006), which have demonstrated many health benefits including antimutagenic and anticarcinogenic effects (Yoo et al 2006; Kim et al 2007). Furthermore, buckwheat is gluten-free, which makes it an important ingredient of foods formulated for sufferers of celiac disease (Petr et al 2003).

Very little research has been conducted on the pasting and rheological properties of buckwheat flour. Many studies published reports on studies of rheological properties for modified buckwheat flour or buckwheat flour blended with other components or buckwheat flour incorporated into a whole food product. Rheological properties have been studied in fermented buckwheat flour incorporated into noodles (Handoyo et al 2006), wheat gluten and buckwheat flour noodles (Kim et al 2000; Horigane et al 2004; Lu and Yin 2005a,b) and conversion of digestible to resistant starch within buckwheat flour (Feng et al 2007). There have also been studies on physicochemical and rheological properties of buckwheat starch (Qian et al 1998; Qian and Kuhn 1999; Yoshimoto et al 2004; Liu et al 2006), a major component of buckwheat flour, but rheological and pasting properties of the entire flour were not studied. Two studies reported the pasting viscosity of buckwheat flour (De Francischi et al 1994; Hara et al 2007). Using a farinograph and amylograph, De Francischi et al (1994) reported buckwheat flour had three times the peak viscosity and two times the final viscosity of wheat flour, whereas Hara et al

(2007) reported a buckwheat flour peak viscosity range of 84–428 RVU using a Rapid Visco-Analyser, with variation related to rainfall during cultivation.

We have previously studied the rheological and pasting qualities of oats and demonstrated the importance of these physicochemical properties on textural properties of food (Lee et al 2005a,b; Lee and Inglett 2006a,b, 2007; Stevenson and Inglett 2007). In this study, we investigated the rheological and pasting properties of buckwheat flour to evaluate the potential for incorporating buckwheat flour in food formulations to improve human nutrition.

MATERIALS AND METHODS

Materials

Whole buckwheat achenes and three buckwheat flours (Fancy, Supreme and Farinetta) were obtained from Minn-Dak Growers (Grand Forks, ND). Fancy flour is composed of inner endosperm excluding hull, aleurone layer, and embryo. Supreme flour includes a certain percentage of hull and endosperm. Farinetta flour consists of a fine granulated mixture of aleurone layer of hulled achene and achene embryo, which are the richest parts of the achene. Oil content of buckwheat achenes and ground buckwheat flours was determined using a Soxtec system (HT 1043 extraction unit, Tecator, Herndon, VA). Protein content of buckwheat achenes and flour was determined using an elemental analyzer (CHN-2000 series, Leco Corp., St Joseph, MI). Official method 925.10 (AOAC 2000) was used to determine moisture content in flour; Official method 920.86 (AOAC 2000) was used to determine crude fiber content of flour; and Official method 923.03 (AOAC 2000) was used to determine ash content. Carbohydrate content was calculated from difference after subtraction of protein, fat, and ash content.

Jet-Cooking Procedure

Jet-cooking of buckwheat flour was performed by mixing 500 g of flour with 4.5 L of water using a blender (Waring Laboratory, Torrington, CT) and then jet-cooking (448 kPa, 141°C, 1.2 L/min flow rate). Jet-cooked slurry was subsequently drum-dried at 140°C using speed rate of 3 and then ground to powder. Buckwheat achenes were jet-cooked by first grinding achenes to a fine powder using a grinder (Fritsch, Idar-Oberstein, Germany) with different screen sizes (0.5 mm [20 mesh], 1 mm [8 mesh], and 2 mm [6 mesh]). Ground achene flours (100 g) with different particle sizes corresponding to the grinder screen sizes were stirred with 900 mL of water and jet-cooked (448 kPa, 141°C, and 1.2 L/min flow rate). Jet-cooked slurry was subsequently sieved through a

¹ Cereal Products & Food Science Research Unit, National Center for Agricultural Utilization Research, ARS, USDA, 1815 N. University Street, Peoria, IL 61604. Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may also be suitable.

² Corresponding author. Phone: +1 309-681-6447. Fax: +1 309-681-6685. E-mail address: David.Stevenson@ars.usda.gov

50-mesh sieve and filtrate was drum-dried at 140°C using speed rate of 3. Drum-dried material was ground to powder.

RVA Measurements

Pasting properties of ground whole buckwheat achenes or Fancy, Supreme and Farinetta buckwheat flours were measured using a Rapid Visco-Analyser (RVA-4, Perten Scientific) with or without jet-cooking. Buckwheat flour or jet-cooked buckwheat flour (2.24 g, db) was adjusted to 28 g with addition of deionized water in an RVA canister to make a suspension containing 8% solids. Buckwheat suspensions were equilibrated at 30°C for 1 min, heated to 95°C at a rate of 6.0°C/min, maintained at 95°C for 5.5 min, and cooled to 50°C at rate of 6.0°C/min, and held at 50°C for 5 min. For all test measurements, a constant paddle rotating speed (160 rpm) was used throughout the entire analysis, except for a speed of 920 rpm for the first 10 sec to disperse samples. Each sample was analyzed in duplicate.

Rheological Measurements

Buckwheat flour pastes measured in RVA experiments were cooled to 25°C and equilibrated overnight. Pastes were then loaded on a rheometer (AR 2000, TA Instruments, New Castle, DE) using a 6-cm diameter parallel acrylic peltier plate geometry (part number 516600.901). The plate edge was sealed with a thin layer of mineral oil (Sigma Chemical, St Louis, MO) to prevent dehydration during testing. All rheological measurements were conducted at 25°C using a circulation system within $\pm 0.1^\circ\text{C}$. The linear dynamic viscoelastic properties of pastes were conducted to investigate the effect of buckwheat flours with or without jet-cooking. Storage modulus (G') and loss modulus (G'') were obtained at frequencies of 0.01–10 Hz. A strain of 0.1%, which was within the linear viscoelastic range, was used for the dynamic experiments. G' represents the nondissipative component of mechanical properties and reflects the elastic characteristics of the material. Elastic or “rubber-like” behavior is suggested if the G' spectrum is independent of frequency and greater than G'' over a certain frequency range. The loss modulus (G'') characterizes the dissipative part of the mechanical properties and represents viscous flow of the material. The phase shift (δ) is defined by $\tan\delta (G''/G')$, which indicates whether a material is solid ($\delta = 0^\circ$), liquid ($\delta = 90^\circ$), or inbetween ($0^\circ < \delta < 90^\circ$). Therefore, the values of $\tan\delta$ are from zero to infinity; and $\tan\delta = 1$ means $G' = G''$, $\tan\delta < 1$ represents $G' > G''$, and $\tan\delta > 1$ indicates $G' < G''$. The

steady shear viscosity of the paste with and without jet-cooking was measured as a function of shear rates from 1 to 500 s^{-1} . The steady-shear sweep measurements apply varying steady-shear deformation on sample material, with magnitude of each deformation depending on user-specified shear rates. These rheological measurements can be used to generate flow curves by measuring the stress and viscosity as a function of shear rate. Because rheological measurements were performed on buckwheat pastes from the RVA study, rheological measurements were also performed in duplicate for each buckwheat flour.

Water-Holding Capacity

The effect of jet-cooking on water-holding capacity of buckwheat flours was determined according to the procedure of Ade-Omowaye et al (2003) with modifications. Flour samples (2 g) with or without jet-cooking were mixed with 25 g of deionized water and vigorously mixed using a vortex to make a suspension, then let stand for 2 hr, followed by centrifugation at $1,590 \times g$ for 15 min. The supernatant was decanted and the weight of residue was measured. Each treatment was replicated twice. Water-holding capacity was calculated as: Water holding capacity (%) = $[(\text{sample weight after centrifugation} - \text{dry sample weight}) / \text{dry sample weight}] \times 100$.

Statistical Analysis

Standard deviation is reported for all measurements where applicable.

RESULTS AND DISCUSSION

Composition of buckwheat achenes and three buckwheat flours are shown in Table I. Supreme flour, which is a mixture of millings from hull and endosperm, had a composition similar to whole buckwheat achenes. Farinetta flour, which includes a greater proportion of millings from bran, had substantially higher protein and fiber content than the other flour samples or whole achenes, but had considerably less total carbohydrate content.

Pasting Properties

Pasting properties of three buckwheat flours and ground whole buckwheat achene flour (1 mm) with or without jet-cooking, and also ground buckwheat achene flours through screens of 1, 0.5, and 2 mm without jet-cooking are shown in Table II. Fancy flour

TABLE I
Composition of Buckwheat Achenes and Flour (% dw)

| Product | Protein | Oil | Fiber | Ash | Carbohydrate |
|----------------------------|---------|-----|-------|-----|--------------|
| Achenes | 12.3 | 2.3 | 10.9 | 2.1 | 73.3 |
| Supreme flour | 11.5 | 3.2 | 10.0 | 2.0 | 68.6 |
| Fancy flour | 9.3 | 1.9 | 2.2 | 2.2 | 72.0 |
| Farinetta commercial flour | 35.0 | 3.9 | 15.1 | 1.2 | 41.9 |

TABLE II
Pasting Properties of Ground Whole Buckwheat Achenes with Different Particle Size Flour and Three Buckwheat Flours^a

| Buckwheat Sample | Peak Viscosity ^b | Setback ^b | Trough ^b | Breakdown ^b | Final Viscosity ^b |
|---|-----------------------------|----------------------|---------------------|------------------------|------------------------------|
| Fancy flour | 81.3 \pm 1.4 | 80.5 \pm 1.5 | 0.9 \pm 0.1 | 132.4 \pm 0.6 | 51.9 \pm 0.8 |
| Fancy flour (jet-cooked) | 158.7 \pm 0.6 | 20.2 \pm 1.1 | 138.4 \pm 0.5 | 55.5 \pm 1.1 | 35.3 \pm 0.0 |
| Farinetta commercial flour | 17.1 \pm 1.1 | 15.0 \pm 1.0 | 2.1 \pm 0.2 | 21.6 \pm 0.3 | 6.6 \pm 0.6 |
| Farinetta commercial flour (jet cooked) | 7.2 \pm 1.7 | 5.4 \pm 1.2 | 1.8 \pm 0.5 | 8.6 \pm 0.6 | 3.3 \pm 0.6 |
| Supreme flour | 48.7 \pm 2.3 | 47.5 \pm 2.1 | 1.2 \pm 0.2 | 79.5 \pm 2.8 | 32.0 \pm 0.7 |
| Supreme flour (jet-cooked) | 112.0 \pm 0.2 | 11.8 \pm 0.3 | 100.2 \pm 0.5 | 48.2 \pm 0.2 | 36.4 \pm 0.1 |
| Ground whole buckwheat (1 mm) | 14.4 \pm 0.0 | 13.3 \pm 0.1 | 1.1 \pm 0.1 | 24.2 \pm 0.8 | 10.9 \pm 0.9 |
| Ground whole buckwheat (1 mm), jet cooked | 63.8 \pm 0.6 | 6.8 \pm 0.6 | 57.0 \pm 0.1 | 17.3 \pm 2.2 | 10.5 \pm 1.6 |
| Ground whole buckwheat (0.5 mm) | 16.4 \pm 0.5 | 14.8 \pm 0.2 | 1.5 \pm 0.3 | 27.4 \pm 1.8 | 12.5 \pm 1.7 |
| Ground whole buckwheat (2 mm) | 12.0 \pm 1.4 | 10.6 \pm 0.9 | 1.4 \pm 0.5 | 18.9 \pm 0.9 | 8.3 \pm 0.0 |

^a 8% (w/w) buckwheat flour suspension measured in duplicate for all buckwheat flour samples.

^b Viscosity expressed in Rapid Visco-Analyser units (RVU), 1 RVU = 12 cp.

had substantially higher peak, trough, setback, and final viscosity than Supreme or Farinetta flour. The relatively lower total carbohydrate content but higher fiber content of Farinetta flour is the most likely reason for its very low gradual increase in paste viscosity. Likewise, Supreme flour most likely had lower paste viscosity than Fancy because of the slightly lower total carbohydrate content. But greater fiber content indicates that Fancy flour has a higher starch content that would be a major contributor to paste viscosity in all buckwheat flours.

Although peak viscosity was not high relative to cereal flours, breakdown viscosity of buckwheat paste from Fancy, Supreme, and Farinetta flour that was not jet-cooked was very low, reflecting high stability under heat and shear. Jet-cooked Farinetta flour had decreased peak viscosity that was not observed for the two other commercial buckwheat flours and is most likely because Farinetta has considerably less total carbohydrate but more fiber, thereby less starch was present to form complexes, and the higher protein and fiber levels could inhibit complex formation. Jet-cooking of both Fancy and Supreme buckwheat flours resulted in considerably higher peak viscosity and lower final viscosity (Figs. 1 and 2), suggesting that jet-cooking resulted in entanglement of molecules that formed a matrix which held together during initial heating under shear, then experienced a high degree of breakdown. But enough entanglement of molecules remained during cooling to hinder molecular mobility to reorganize in a manner that would allow a high rate of gelation to occur. However, the pasting curves of jet-cooked Fancy and Supreme buckwheat flour were very different. Fancy buckwheat flour peak viscosity oc-

curred almost instantaneously, suggesting that that viscosity was a result of pregelatinized starch that remained in a viscous state after jet-cooking and drum-drying at high temperature. Fancy jet-cooked buckwheat starch had substantial shear-thinning (breakdown viscosity) as heat increased during constant stirring rate, indicating an unstable swollen pregelatinized starch complex. Supreme jet-cooked buckwheat flour exhibited a pasting temperature similar to native starch, but the peak is much steeper, plus narrower due to a high degree of shear-thinning. Higher peak viscosity has been reported for oat bran concentrate that was jet-cooked compared with untreated oat bran concentrate, with very similar steep and narrow peak viscosity curve observed for the jet-cooked product that was attributed to a complex formed between gelatinized starch and β -glucans in oats (Stevenson et al 2007). Little is known about the hydrocolloids present in buckwheat achenes but hemicelluloses such as glucuronoxylan and pectin have been reported in buckwheat hulls (Hromádková and Ebringerová 2003). These buckwheat hydrocolloids could interact with gelatinized starch to form a complex during jet-cooking, thereby exhibiting higher peak viscosity during heating, and these complexes may have poor stability under shear. The unchanged or substantially lower setback viscosity and considerably lower final viscosity after all three buckwheat flours were jet-cooked also suggests that the jet-cooking procedure results in greater entanglement of molecules, thereby greatly retarding the mobility of large polymers such as starch, hindering molecular reorganization that would create greater viscosity. A similar trend was observed for buckwheat flour particle size of 1 mm obtained from ground whole achenes, as jet-cooking resulted in higher peak viscosity but lower final and setback viscosity. Although there were some statistical differences in paste viscosity among the buckwheat flours with different particle sizes obtained from ground whole achenes (for final and setback viscosity), in general, differences were small, indicating that particle size was not an important factor influencing buckwheat paste viscosity (Fig. 3). Final paste viscosity was higher with decreasing particle size, which can be attributed to smaller particles having a greater ratio of surface area to volume, enabling greater water absorption and corresponding higher viscosity. Similar to Fancy buckwheat flour, jet-cooking buckwheat flour with particle size of 1 mm obtained from ground whole achenes resulted in substantially higher initial paste viscosity (Fig. 4), which can be attributed to pregelatinized starch remaining in highly viscous state after drum-drying. Additionally, the similar pasting curves of jet-cooked Fancy buckwheat and whole achene ground flour (Figs. 1 and 4) indicates that they have similar composition. Table I indicates that whole achene ground flour and Fancy buckwheat flour have very similar pro-

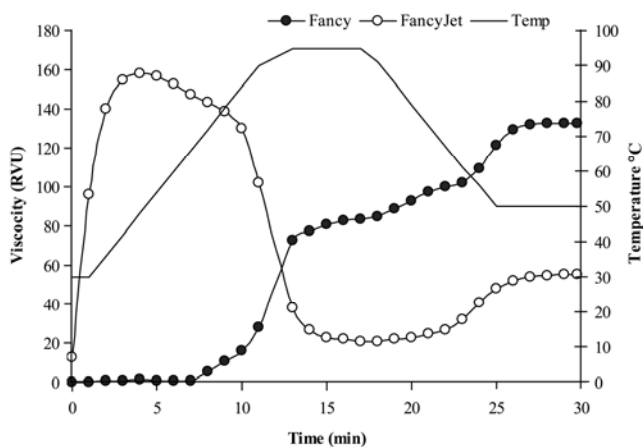


Fig. 1. Rapid Visco-Analyzer pasting curves of Fancy buckwheat flour with (FancyJet) or without (Fancy) jet-cooking.

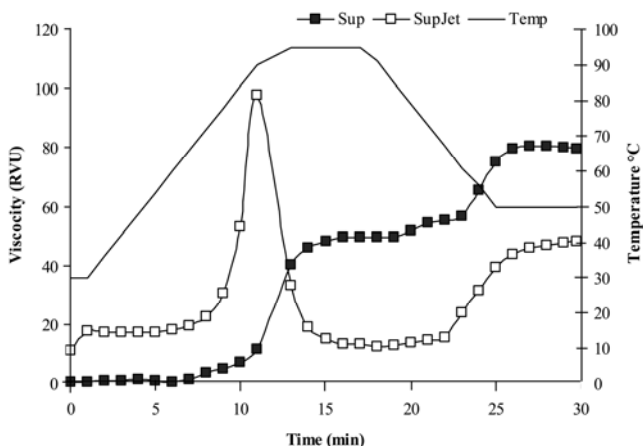


Fig. 2. Rapid Visco-Analyzer pasting curves of Supreme buckwheat flour with (SupJet) or without (Sup) jet-cooking.

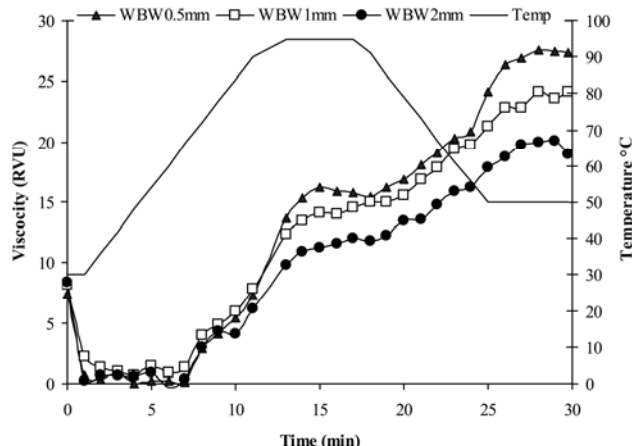


Fig. 3. Rapid Visco-Analyzer pasting curves of ground whole achene buckwheat flour (WBW) with particle sizes of 0.5, 1.0, and 2 mm.

tein, oil, ash, and total carbohydrate content, but Fancy buckwheat flour has considerably lower fiber content, suggesting fiber has no involvement in the initially high paste viscosity.

The RVA data provides information for food processing and product development. Initial paste viscosity of jet-cooked whole achene ground and Fancy buckwheat flour implies suitability as ingredients for instant puddings and food formulations requiring little heat during processing such as yogurt, smoothies, and ice cream. High protein and low paste viscosity of Farinetta flour could allow mixing with cereal flour such as wheat flour to make products with low water content such as breads and cookies. Modification of textural properties of food using a blend of buckwheat and wheat flour has been reported (Kim et al 2000; Horigane et al 2004; Lu and Yin 2005a,b).

Rheological Properties

Linear dynamic frequency sweep results of storage (G') and loss (G'') modulus for Fancy, Supreme and Farinetta buckwheat flour paste without jet-cooking are displayed in Fig. 5. G' for all three of buckwheat flour pastes was greater than G'' , indicating viscoelastic solid behavior, with Fancy buckwheat flour paste exhibiting strongest viscoelasticity. Curves of Fancy buckwheat flour moduli were almost independent of measured frequencies, with a plateau of G' at $\approx 1,000$ Pa (Fig. 5). $\tan\delta$ values were in the range of 0.09–0.15 (Fig. 6). Farinetta flour paste exhibited weakest viscoelastic solid properties among three buckwheat flours, with moduli curves dependent on frequency. Plateau of Farinetta G' was ≈ 50 Pa and short. $\tan\delta$ values for Farinetta were 0.47–0.62.

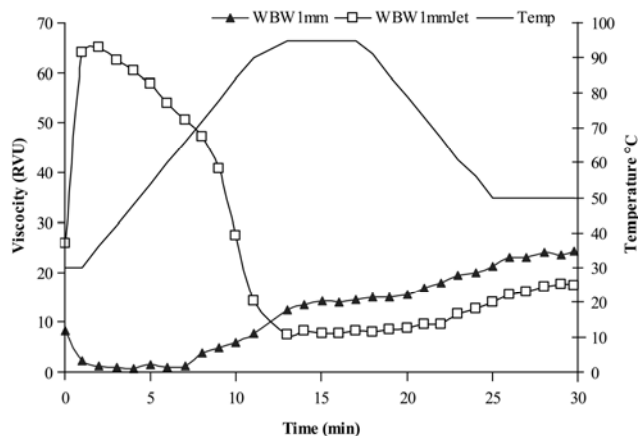


Fig. 4. Rapid Visco-Analyzer pasting curves of ground whole achene buckwheat flour (particle size 1 mm) with (WBW1mmJet) or without (WBW1mm) jet-cooking.

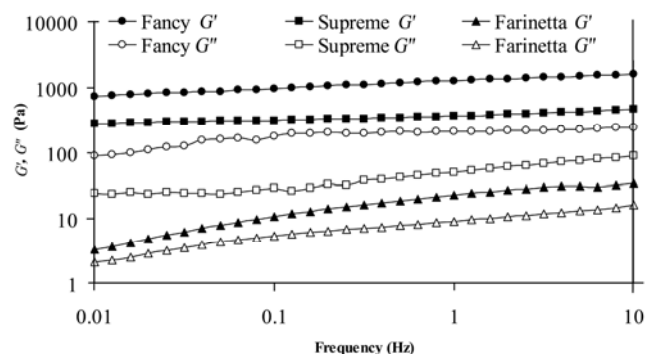


Fig. 5. Linear dynamic viscoelastic properties at 25°C of three buckwheat flour pastes without jet-cooking. Filled and open symbols represent G' and G'' , respectively.

Supreme buckwheat flour paste showed considerably stronger viscoelastic solid properties than Farinetta, but slightly weaker than Fancy. Supreme buckwheat flour paste moduli curves were similar to Fancy, and were almost independent of frequency with plateau of G' slightly lower than Fancy (700 Pa). Supreme buckwheat flour paste $\tan\delta$ values were similar to Fancy at 0.12–0.21.

Linear viscoelastic properties of jet-cooked buckwheat flour pastes were substantially weaker than pastes without jet-cooking. Both G' and G'' for Fancy, Supreme, and Farinetta jet-cooked buckwheat flour pastes were considerably lower than without jet-cooking (Figs. 5 and 7). Jet-cooked Fancy and Supreme pastes exhibited almost identical behavior. G' were higher than G'' at all measured frequencies, indicating that viscoelastic solid properties were retained. Moduli curves of jet-cooked Fancy and Supreme buckwheat flour paste were slightly more frequency-dependent than pastes without jet-cooking. Plateau G' for jet-cooked Fancy and Supreme buckwheat flour paste was more than one order of magnitude less than without jet-cooking (70 Pa). $\tan\delta$ of jet-cooked Fancy and Supreme buckwheat flour pastes were 0.27–0.55, which was more than double the $\tan\delta$ values of pastes without jet-cooking, suggesting pastes shifted from more solid-like to more fluid-like (Fig. 8). Jet-cooked Farinetta paste exhibited viscoelastic fluid or liquid properties with G'' predominantly greater than G' within measured frequencies (Fig. 7). Moduli curves were very frequency-dependent with a slope close to unity, indicating that paste had more fluid or liquid behavior. $\tan\delta$ values for jet-cooked Farinetta flour paste were 0.67–3.49, with a majority >1 , suggesting that flour shifted from viscoelastic solid to viscoelastic liquid during jet-cooking. From our results, we can conclude that jet-cooking could damage, modify, and rearrange structure of buckwheat flours and weaken their viscoelastic properties.

Linear rheological properties of flour relates to quality of baked and other food products (Xu et al 2001, 2007). Because buck-

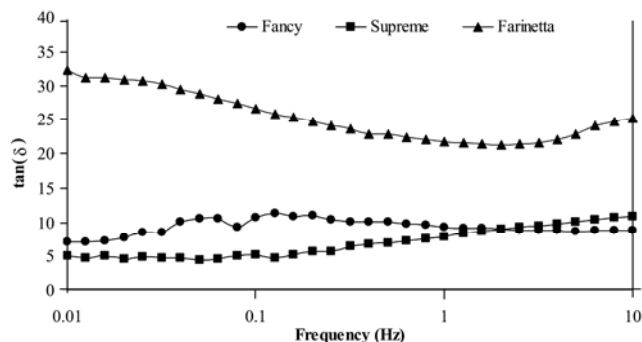


Fig. 6. Values of $\tan(\delta)$ vs. frequency at 25°C for three buckwheat flour pastes without jet-cooking.

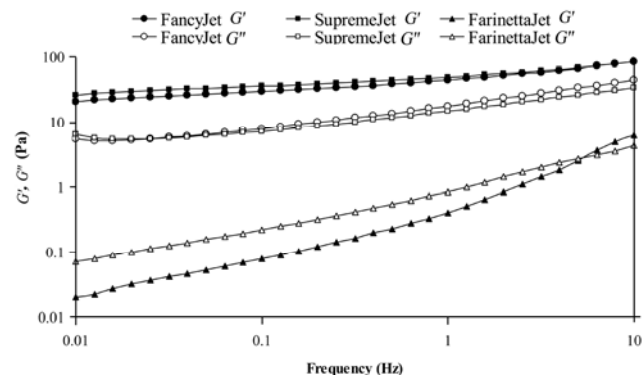


Fig. 7. Linear dynamic viscoelastic properties at 25°C of three buckwheat flour pastes with jet-cooking. Filled and open symbols represent G' and G'' , respectively.

wheat flours have low gluten content, their baking quality mainly comes from their starch and interactions of starch with other compounds. Our results indicate that Fancy buckwheat flour would have the best baking quality and Farinetta would have the worst baking quality among the three buckwheat flours studied. We can also conclude that jet-cooking will weaken structure and therefore reduce volume expansion of baked foods using buckwheat flour.

Rheological performance of food products can be evaluated by viscosity during processing (Salvador et al 2002). To better understand chewing and processing behavior, nonlinear steady-shear viscoelastic properties of buckwheat flour pastes were studied in a range of 1–500/sec (Prinz et al 2007). Most food processing and mastication occur in shear rate range of 1/sec to 100/sec. The steady shear sweep applies varying magnitudes of steady-shear deformation, with magnitude of each deformation depending on user-specified shear rates. Nonlinear shearing viscoelastic properties of the three buckwheat flour pastes with and without jet-cooking are illustrated in Figs. 9 and 10, respectively. All buckwheat flour pastes exhibited shear-thinning behavior over the entire measured shear rates at 25°C. Shear-thinning behavior can be observed in many food biomaterials such as soy, rice, and wheat flour (Mohamed et al 2004; Dogan et al 2005; Lee and Inglett 2006a). For buckwheat flour pastes without jet-cooking, Fancy had highest viscosity and Farinetta had lowest viscosity among three pastes, while viscosity of Supreme was intermediate (Fig. 9) which agreed with findings of pasting properties measured using a RVA (Table II and Figs. 1 and 2). As expected, this trend was same as the linear dynamic viscoelastic behavior. For jet-cooked buckwheat flour pastes, Fancy and Supreme exhibited nearly identical viscosities, which were higher than that of Farinetta (Fig. 10). Similar trends were observed during linear rheological measurements. We also noticed that shear viscosity for buckwheat flour pastes with and without jet-cooking were very similar, especially at higher shear rates (Fig. 9 and 10), suggesting that high shear rate shearing can have a similar effect on flour as jet-cooking. Because the experimental conditions we adopted were similar to actual processing situations, all our findings on rheological characteristics should be beneficial in developing and processing new food applications of buckwheat flours.

Water-Holding Capacity

Water-holding capacity of buckwheat flours with or without jet-cooking is shown in Fig. 11. Water-holding capacity of all three buckwheat flours studied without jet-cooking was similar (59–64%). Jet-cooking dramatically increased water-holding capacity, with Fancy and Supreme (90–91%) higher than Farinetta (81%). Jet-cooking procedure gelatinizes starch and provides thermal-mechanical shear forces resulting in molecular breakdown occurring (Lee and Inglett 2006a). Fancy buckwheat flour with the highest total carbohydrate content had the highest water-holding capacity. Farinetta buckwheat flour, which had lowest total carbohydrate content and the highest protein content among the three buckwheat flours studied, had the lowest water-holding capacity, suggesting that starch and fiber are predominant contributors. This also suggested that molecular breakdown and reorganization of molecules during jet-cooking create a structure that significantly increases the ability to retain water. Studies of water-holding are necessary for supplying fundamental information to food processors and also help to explain results from RVA and rheological measurements.

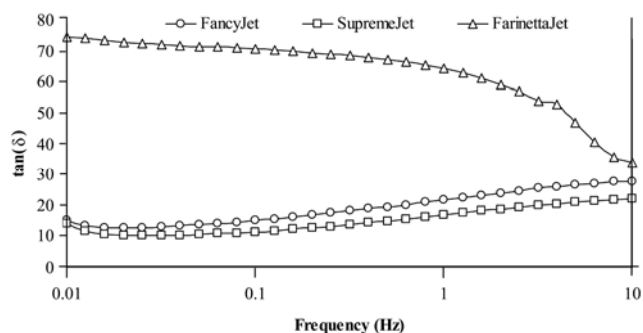


Fig. 8. Values of $\tan(\delta)$ vs. frequency at 25°C for three buckwheat flour pastes with jet-cooking.

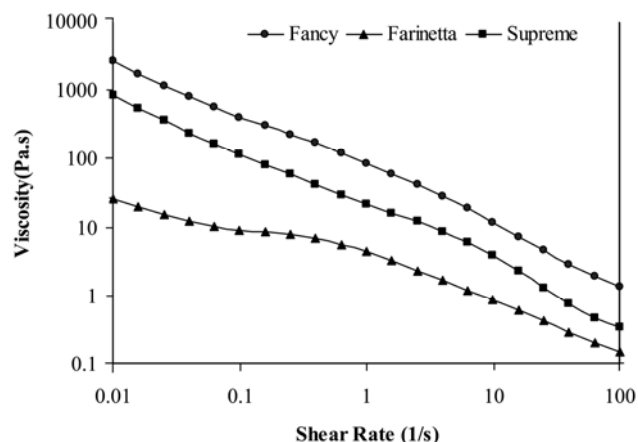


Fig. 9. Nonlinear steady shear viscosity vs. shear rate at 25°C for three buckwheat flour pastes without jet-cooking.

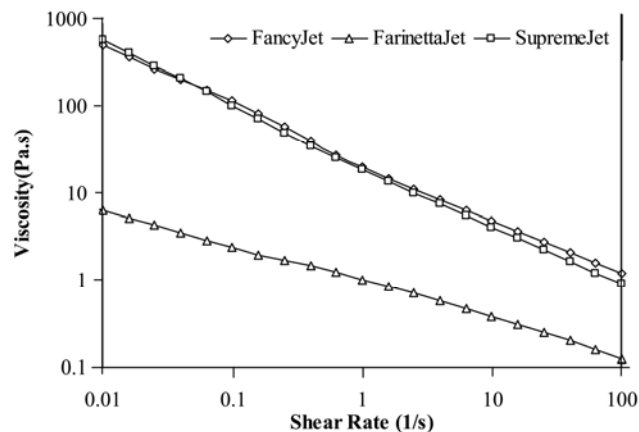


Fig. 10. Nonlinear steady shear viscosity vs. shear rate at 25°C for three buckwheat flour pastes with jet-cooking.

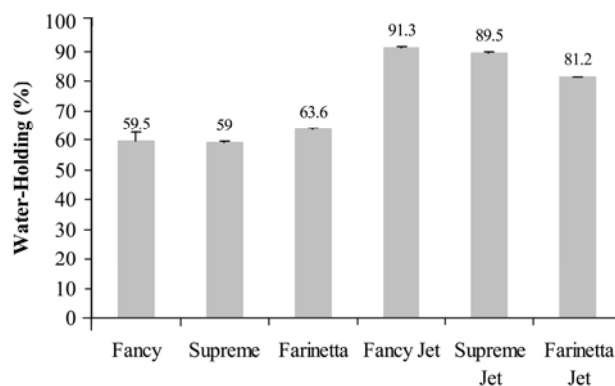


Fig. 11. Water-holding capacity.

CONCLUSIONS

Buckwheat has potential to be a nutritionally beneficial crop due to its high phenolic content, antioxidant capacity, and gluten-free character which makes it suitable for celiac sufferers. Commercially refined buckwheat flours (Fancy, Supreme, and Farinetta) obtained from different parts of achene and flour obtained from whole achenes had different pasting, rheological, and water-holding characteristics before and after jet-cooking. Fancy flour, which appeared to have highest starch content, had instantaneous paste viscosity after jet-cooking and drum-drying, most likely due to pregelatinized starch. This initially high paste viscosity was not observed for Supreme or Farinetta flour. Supreme buckwheat flour after jet-cooking had a very steep and narrow peak viscosity that we attributed to complex forming between starch and hydrocolloids during jet-cooking and drum-drying that had poor shear stability. Fancy buckwheat flour showed strongest viscoelastic properties and jet-cooking reduced viscoelasticity of all buckwheat flours. Jet-cooking buckwheat flour enhanced water-holding capacity. Our study showed that buckwheat flour has unique pasting and rheological properties that could be used in a wide range of food applications. The initial paste viscosity of jet-cooked whole achene ground and Fancy buckwheat flour, suggests suitability as ingredients in food formulations requiring little heat during processing, while low viscosity of Farinetta flour could allow mixing with cereal flour, thereby modifying texture of foods.

ACKNOWLEDGMENTS

We wish to thank Minn-Dak Growers Ltd., Grand Forks, ND, for providing the Fancy, Supreme, and Farenatta buckwheat flours and A. J. Thomas for rheology assistance.

LITERATURE CITED

Ade-Omowaye, B. I. O., Taiwo, K. A., Eshtiagi, N. M., Angersbach, A., and Knorr, D. 2003. Comparative evaluation of the effects of pulsed electric field and freezing on cell membrane permeabilisation and mass transfer during dehydration of red bell peppers. *Innov. Food Sci. Emerg. Technol.* 4:177-188.

AOAC. 2000. Official method 925.10: Solids (total) and moisture in flour. air oven method. Official method 920.86: Fiber (crude) in flour. Official method 923.03: Ash of flour. In: *Official Methods of Analysis of AOAC International*, 17th Ed. W. Horwitz, ed. AOAC International: Washington, DC.

De Francischi, M. L. P., Salgado, J. M., and Leitão, R. F. F. 1994. Chemical, nutritional and technological characteristics of buckwheat and non-prolamine buckwheat flours in comparison of wheat flour. *Plant Foods Hum. Nutr.* 46:323-329.

Doğan S. F., Şahin S., and Sumnu, G. 2005. Effects of soy and rice flour addition on batter rheology and quality of deep-fat fried chicken nuggets. *J. Food Eng.* 71:127-32.

Feng, F., Zhang, G., and Gong, F. 2007. Processing of buckwheat resistant starch and its effect on rheological property of flour. *Cereal Feed Indus.* 2007:17-19,40.

Handoyo, T., Maeda, T., Urisu, A., Adachi, T., and Morita, N. 2006. Hypoallergenic buckwheat flour preparation by *Rhizopus oligosporus* and its application to soba noodle. *Food Res. Int.* 39:598-605.

Hara, T., Matsui, K., Noda, T., and Tetsuka, T. 2007. Effects of preharvest sprouting on flour pasting viscosity in common buckwheat (*Fagopyrum esculentum* Moench). *Plant Prod. Sci.* 10:361-366.

Holasová, M., Fiedlerová, V., Smrcinová, H., Orsak, M., Lachman, J., and Vavreimová, S. 2002. Buckwheat—The source of antioxidant activity in functional foods. *Food Res. Int.* 35:207-211.

Horigane, A., Yamada, S., Hikichi, Y., Ohba, S., Matsukura, U., and Imai, T. 2004. Analysis of mixing process of hydrated buckwheat flour. Development of quality evaluation method of buckwheat noodle. *I. J. Jpn. Soc. Food Sci. Technol.* 51:346-351.

Hromádková, Z., and Ebringerová, A. 2003. Ultrasonic extraction of plant materials—Investigation of hemicellulose release from buckwheat hulls. *Ultrasonics Sonochem.* 10:127-133.

Kim, B.-R., Choi, Y.-S., and Lee, S.-Y. 2000. Rheological properties of buckwheat-wheat flour mixture. *J. Kor. Soc. Food Sci. Nutr.* 29:369-374.

Kim, S.-H., Cui, C.-B., Kang, I.-J., Sun, Y. K., and Ham, S.-S. 2007. Cytotoxic effect of buckwheat (*Fagopyrum esculentum* Moench) hull against cancer cells. *J. Medic. Food* 10:232-238.

Lee, S., and Inglett, G. E. 2006a. Rheological and physical evaluation of jet-cooked oat bran in low calorie cookies. *Int. J. Food Sci. Technol.* 41:553-559.

Lee, S., and Inglett, G. E. 2006b. Functional characterization of steam jet-cooked barley flour as an oil barrier in frying batters. *J. Food Sci.* 71:E308-E313.

Lee, S., and Inglett, G. E. 2007. Effect of an oat β -glucan-rich hydrocolloid (C-trim30) on the rheology and oil uptake of frying batters. *J. Food Sci.* 72:E222-E226.

Lee, S., Kinney, M. P., and Inglett, G. E. 2005a. Rheological characterization of a new oat hydrocolloid and its application in cake baking. *Cereal Chem.* 82:717-720.

Lee, S., Warner, K., and Inglett, G. E. 2005b. Rheological properties and baking performance of new oat β -glucan hydrocolloids. *J. Agric. Food Chem.* 53:9805-9809.

Liu, H., Eskin, N. A. M., and Cui, S. W. 2006. Effects of yellow mustard mucilage on functional and rheological properties of buckwheat and pea starches. *Food Chem.* 95:83-93.

Lu, M., and Yin, Y. 2005a. Study on material factors affecting properties of Korean cold noodles. *Cereal Feed Indus.* 2005:29-30.

Lu, M., and Yin, Y. 2005b. Effect of the addition of buckwheat flour on the properties of Korean noodle. *J. Henan Univ. Technol. Natur. Sci. Edit.* 26:34-36.

Mohamed, A. A., Rayas-Duarte, P., Gordon, S. H., and Xu, J. 2004. Estimation of HRW wheat heat damage by DSC, capillary zone electrophoresis, photoacoustic spectroscopy and rheometry. *Food Chem.* 87:195-203.

Morishita, T., Yamaguchi, H., and Degi, K. 2007. The contribution of polyphenols to antioxidative activity in common buckwheat and tartary buckwheat grain. *Plant Prod. Sci.* 10:99-104.

Petr, J., Michalík, I., Tlaskalová, H., Capouchová, I., Famera, O., Urminská, D., Tucková, L., and Knoblochová, H. 2003. Extension of the spectra of plant products for the diet in celiac disease. *Czech. J. Food Sci.* 12:59-70.

Prinz, J. F., Janssen, A. M., and de Wijk, R. A. 2007. In vitro simulation of the oral processing of semi-solids foods. *Food Hydrocolloids* 21:397-401.

Qian, J. Y., and Kuhn, M. 1999. Evaluation on gelatinization of buckwheat starch: A comparative study of bra bender viscoamylography, rapid visco-analysis, and differential scanning calorimetry. *Eur. Food Res. Technol.* 209:277-280.

Qian, J., Rayas-Duarte, P., and Grant, L. 1998. Partial characterization of buckwheat (*Fagopyrum esculentum*) starch. *Cereal Chem.* 75:365-373.

Salvador, A., Sanz, T., and Fiszman, S. 2002. Effect of corn flour, slat, and leavening on the texture of fried, battered squid rings. *J. Food Sci.* 76:730-733.

Stevenson, D. G., Eller, F. J., Radosavljević, M., Jane, J., and Inglett, G. E. 2007. Characterisation of oat bran products with and without supercritical carbon dioxide extraction. *Int. J. Food Sci. Technol.* 42:1489-1496.

Stevenson, D. G., and Inglett, G. E. 2007. Effect of various thermal treatments on the pasting properties of enriched β -glucan oat products. *J. Food Sci. Technol.* 44:168-173.

Watanabe, M., Ohshita, Y., and Tsushida, T. 1997. Antioxidant compounds from buckwheat (*Fagopyrum esculentum* Moench) hulls. *J. Agric. Food Chem.* 45:1039-1044.

Wijngaard, H. H., and Arendt, E. K. 2006. Buckwheat. *Cereal Chem.* 83:391-401.

Xu, J., Bietz, J. A., and Carrière, C. J. 2007. Rheological properties of wheat gliadin and glutenin suspensions. *Food Chem.* 101:1025-1030.

Xu, J., Bietz, J. A., Felker, F. C., Carrière, C. J., and Wirtz, D. 2001. Rheological properties of vital wheat gluten suspensions. *Cereal Chem.* 78:181-185.

Yoo, K.-H., Kim, S.-H., Ham, Y.-A., Yoo, S.-J., Oh, H.-T., and Ham, S.-S. 2006. Antimutagenic and cytotoxic effects of *Fagopyrum esculentum* Moench noodles extracts. *J. Kor. Soc. Food Sci. Nutr.* 35:1291-1296.

Yoshimoto, Y., Egashira, T., Hanashiro, I., Ohinata, H., Takase, Y., and Takeda, Y. 2004. Molecular structure and some physicochemical properties of buckwheat starches. *Cereal Chem.* 81:515-520.

[Received December 11, 2007. Accepted February 26, 2008.]