Rheological and Physicochemical Properties of Starches from Moist- and Dry-Type Sweetpotatoes

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Although starch makes up from 50 to 70% of sweetpotato (SP) dry matter, its role in cooked texture is unknown. The purpose of this research was to characterize raw starches isolated from SP cultivars and experimental selections (C/S) with a wide range of textural properties when cooked and to investigate the relationship between textural properties of the cooked roots and characteristics of the isolated starches. Shear stress measured by uniaxial compression of cooked SP cylinders served as an objective measure of SP texture. Starches were isolated from C/S representing three SP texture types: moist (Jewel and Beauregard); intermediate (NC10-28 and NC2-26); and dry (NC6-30 and NC8-22). The following parameters of isolated starches were measured: amylose content by colorimetric and differential scanning calorimetric (DSC) methods; swelling power, solubility, gelatinization enthalpy (ΔH), and pasting properties by Brabender amylograph (BA) and rapid viscoanalyzer (RVA). Pasting temperatures for SP C/S measured by BA and RVA were significantly correlated. Due to high shear degradation in RVA, RVA viscosities of starch suspensions decreased as much as 40% during cooking at 95 °C, whereas the BA viscosities changed little at this temperature. There were no statistically significant differences among the C/S for amylose or ΔH. However, significant C/S differences in swelling power, solubility, and pasting properties were observed. Although differences in some rheological and physical properties were observed for C/S starches, shear stress was statistically correlated only with DSC onset temperature ($r = 0.78$), indicating that factors other than the properties measured on isolated starches are mainly responsible for the texture of cooked SP C/S.

Keywords: *Sweetpotato starch; texture; differential scanning calorimetry; Brabender amylograph; rapid viscoanalyzer*

INTRODUCTION

Texture is an essential factor in consumers' perception of food quality and has been studied for several decades. Unlike white potatoes, only limited research has been conducted on the texture of cooked sweetpotatoes (SP; Anderson et al., 1994; McComber et al., 1994). Cooked SP have a much wider range of textural properties than do white potatoes (McLauren and Kays, 1992; Truong et al., 1997). To distinguish between commercially grown SP, which had two very different sets of sensory properties when baked, early workers arbitrarily classified these as "moist" or "yam" types, which have a soft, syrupy texture, or "dry" types, which exhibit a firm, mealy texture. However, in recent years it has been recognized that, in actuality, SP textural properties form a continuum (Rao et al., 1975; Morrison et al., 1993). Truong et al. (1997) studied cooked SP cultivars and experimental selections (C/S) with a wide range of sensory textural properties, which included "moist", "intermediate", and "dry" textural types. Using a trained texture profile panel and principal component analysis, they found that sensory texture attributes could be grouped into three categories, namely, moistness−firmness, particles, and fiber. Analysis of the samples from the same study using the instrumental texture profile analysis (TPA) procedure (Bourne, 1978) and uniaxial compression showed that, among the instrumental parameters, shear stress of compression and fracturability, hardness, and gumminess were highly correlated with both mouthfeel and mechanical-type sensory notes. This indicated that some instrumental parameters might be good predictors of cooked SP texture.

SP contain 52−85% moisture, with carbohydrates making up 80−90% of total dry matter. Starch, a major component of SP, can comprise from 50 to 70% of SP dry matter and has been reported to significantly affect textural properties (Woolfe, 1992). The physicochemical properties of SP starches of various cultivars have been reported by many investigators (Garcia and Walter, 1998; Kitahara et al., 1996; Tian et al., 1991). However, little information on starch characteristics and texture of cooked SP exists. Truong and Nagahama (1994) reported that the Brabender amylograms of starches isolated from SP cultivars, which have different degrees of dryness/moistness after cooking, had similar patterns. Walter et al. (1975) reported that texturally perceived moistness of baked SP was influenced by the extent of starch degradation by endogenous α-amylase and was not directly related to the dry matter content.

It was the purpose of the present research to deter-

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10.1021/jf990963l CCC: $19.00
Published on Web 06/28/2000

mine if differences in the properties of starches isolated from SP C/S are significant contributors to the textural characteristics of the cooked SP. To accomplish this, relationships between the textural properties of cooked SP C/S and selected chemical, physical, and rheological properties of the isolated starches were determined.

MATERIALS AND METHODS

On the basis of a previous study (Truong et al., 1997), six C/S, representing the two main SP texture types and intermediate types, were selected. These were "moist" (Jewel and Beauregard), "intermediate" (NC10-28 and NC2-26), and "dry" (NC6-30 and NC8-22). Number-designated materials were selections of SP lines developed in the Department of Horticulture at North Carolina State University. Cylindrical samples 1.35 cm in diameter and 3.5 cm thick were cut from the interior of the raw roots. The cylinders were steamed for that period of time corresponding to the inflection point of the firmness−steaming curve established for each of the C/S (Truong et al., 1997).

Tissue Texture Measurement. Uniaxial compression measurements were performed on cylinders of cooked tissue (1.35 cm in diameter and 2.2 cm thick) using a TA.XT2 texture analyzer (Texture Technologies Corp., Scarsdale, NY; Stable Microsystems, Hoslemere, Surrey, U.K.). All tests were conducted at 25 °C and with a crosshead speed of 1.6 mm/s. Data were electronically collected and used for calculating shear stress at failure (Hamann, 1983). Shear stress at failure was measured on 15−20 specimens for each of the two replicates of each C/S.

Starch Isolation. Starches were isolated by peeling 1 kg batches of raw SP, cutting into ~32 mm slices, mixing with 3 parts of distilled, deionized water, and grinding for 30 s (Dynamics Corp. of America, Hartford, CT). The slurry was poured through three layers of Miracloth and then allowed to settle for 4 h. The supernatant was discarded and the sediment suspended in 18 L of distilled, deionized water and allowed to settle for 4 h. This procedure was repeated two additional times. After the final decantation, the top layer of starch was scraped off and discarded. The purified starch was allowed to air-dry for 2−3 days. Moisture content of the starches was determined on weighed samples, and sample weight corrections were made prior to analysis. Two replicate extractions were performed for each C/S.

Starch Analyses. The amylose content of the starches was measured according to two methods. The first of these was the colorimetric iodine binding procedure (Knutson, 1986). Starch samples (1−5 mg) were dissolved in 10 mL of 90% dimethyl sulfoxide (DMSO) containing 6 μmol of iodine. One milliliter was then mixed with 8 mL of water. After 30 min, the absorbance at 600 nm was measured. The amylose concentration was determined by reference to a standard curve prepared in the same way as were the samples, except that the samples were pure amylose in amounts ranging from 1 to 10 mg.

The second method for amylose determination was a differential scanning calorimetric (DSC) method based on measurement of the enthalpy of melting of the complex between l-α-lysophosphatidylcholine (LPC) and amylose (Mestres et al., 1996). Weighed starch samples (~11 mg) were put into a DSC pan, 50 μL of 2.5% LPC was added, and the pan was sealed. Samples were scanned at a rate of 10 °C/min using a Perkin-Elmer DSC (model DSC-7). Enthalpy of melting of the LPC−amylose complex served as the standard. The percent amylose of the starch samples was calculated by dividing the enthalpy of melting of the LPC−starch sample by the enthalpy of melting of the LPC−amylose complex and multiplying the result by 100 (Kugimiya and Donovan, 1981).

Starch minor constituents were determined by the Plant Analysis Service Unit at North Carolina State University. Nitrogen was determined with a Perkin-Elmer CHN analyzer. The concentrations of phosphorus, calcium, magnesium, potassium, and sodium were determined after dry combustion and dissolution of the residue in acid using a Perkin-Elmer inductively coupled Plasma 2 instrument. Analyses were done on each of the two replicates of each C/S.

Starch granule size was determined on aqueous starch suspensions using a Shimadzu centrifugal particle size analyzer (model SA-CP4, Shimadzu Corp., Kyoto, Japan). Granule size was determined in triplicate for each of the two replicates of each C/S.

Starch thermal properties were measured using a Perkin-Elmer DSC (model DSC-7) that had been calibrated with indium and dodecane. Starch samples (~5−6 mg) were weighed into DSC pans, 50 μL of deionized water added, and the pans were sealed. Heating was carried out at 10 °C/min. Onset, peak, and final temperatures and gelatinization enthalpy were measured. DSC runs were performed in duplicate for each of the two replicates of each C/S.

Starch Paste Properties. Starch swelling power and solubility were determined by heating starch−water slurries in a water bath at temperatures ranging from 60 to 95 °C in 5 °C intervals (Schoch, 1964; Numfor et al., 1996). Briefly, weighed starch samples were slurried with deionized water and heated with constant agitation for 30 min. The slurries were then centrifuged, the supernatant was removed, and the soluble material was isolated by evaporation of the liquid. The amount of this material was used to calculate the starch solubility. The swelling power was obtained by measuring the amount of residue from the centrifugation and calculating the amount of water absorbed by the starch (percent weight increase) after correction for the amount of solubilized starch (Schoch, 1964).

Starch paste viscosities were measured on 6% (w/v) starch−water mixtures with a Brabender amylograph (BA; C. W. Brabender, South Hackensack, NJ) and a rapid viscoanalyzer (RVA; Newport Scientific Pty., Ltd., NSW, Australia). The heating, cooking, and cooling schedules were as follows: amylograph (constant stirring at 75 rpm), heat from 25 to 95 °C at 1.5 °C/min, hold at 95 °C for 15 min, and cool to 50 °C at 1.5 °C/min; RVA (constant stirring at 160 rpm), heat to 95 °C at 13 °C/min, hold at 95 °C for 8 min, cool to 50 °C at 9 °C/min, and hold at 50 °C for 6 min.

Statistical Analysis. Data were analyzed using the Statistical Analysis System (SAS Institute, 1988). Analysis of variance and means separations were calculated by the general linear models procedure. Differences ($P \leq 0.05$) between treatment variables were evaluated by least squares means procedures.

Table 1. Sensory Texture Assignments and Uniaxial Compression Values for Cooked Sweetpotato Cultivars/Selections

cultivar/selection	sensory[a]/texture assignment	shear stress[b] (kPa)
Jewel	moist	8.61d
Beauregard	moist	11.76c
NC10-28	intermediate	14.24c
NC2-26	intermediate	26.94b
NC6-30	dry	39.28a
NC8-22	dry	27.80b

[a] From Truong et al. (1997). [b] Within columns values having the same letter are not statistically different ($P \geq 0.05$).

Table 2. Amylose Content[a] of Sweetpotato Starches

cultivar/selection	% amylose (colorimetric)	% amylose (DSC)
Jewel	23.0a	23.2a
Beauregard	24.4a	23.1a
NC10-28	24.2a	23.5a
NC2-26	24.2a	21.7a
NC6-30	22.5a	23.5a
NC8-22	25.3a	22.6a

[a] Within columns values having the same letter are not statistically different ($P \geq 0.05$).

Table 3. Minor Constituents of Sweetpotato Starches[a]

cultivar/selection	N (mg/100 g)	P (mg/100 g)	Ca (mg/100 g)	K (ppm)	Na (ppm)	Mg (ppm)
Jewel	37.5 ± 2.1	14.0 ± 1.8	58.3 ± 6.9	11.5 ± 3.5	12.0 ± 1.4	12.0 ± 0.2
Beauregard	16.5 ± 0.7	12.7 ± 2.1	29.2 ± 5.3	7.5 ± 0.7	9.5 ± 2.1	15.0 ± 1.7
NC10-28	13.5 ± 2.1	14.8 ± 1.1	16.9 ± 1.1	42.5 ± 7.8	10.0 ± 4.2	17.5 ± 3.5
NC2-26	41.0 ± 2.5	19.1 ± 1.1	7.1 ± 0.8	19.0 ± 7.1	10.5 ± 2.1	17.5 ± 0.2
NC6-30	16.5 ± 0.7	17.3 ± 1.1	29.3 ± 2.8	28.5 ± 5.5	8.5 ± 0.7	26.3 ± 1.2
NC8-22	21.5 ± 7.8	15.1 ± 0.1	32.8 ± 6.7	31.0 ± 1.4	10.5 ± 0.7	15.9 ± 0.9

[a] Mean ± standard deviation.

RESULTS AND DISCUSSION

Shear Stress and Textural Properties. Shear stress values for cooked SP C/S extended from a low of 8.61 to 39.28 kPa, which encompasses a large range of firmness values (Table 1). In general, a sensory texture assignment of "moist" is characterized by low shear stress values, whereas "dry" C/S have higher shear stress values (Truong et al., 1997). In fact, there was a statistically significant correlation coefficient between texture type and shear stress, which accounted for 77% of the variability ($r^2 = 0.77$). Thus, it is evident that the C/S in this study possess a diverse array of instrumental texture properties. In addition, there is a significant relationship between human perception of sensory texture as measured by mastication force and the uniaxial compression force as measured by the TA.XT2 texture analyzer.

Starch Composition. The amylose contents (Table 2) for all C/S were similar and within the ranges reported by others (Tian et al., 1991; Truong and Nagahama, 1994). The colorimetric determination range was from 22.5 to 25.3%, and the DSC range was 21.7−23.5%. No statistically significant differences were observed between C/S within each method or between methods. Our results indicate that both colorimetric and DSC methods measure the same thing. Similar comparability of results has been reported for starches from other plants (Kugimiya and Donovan, 1981).

The SP starches contained various amounts of minor constituents (Table 3). Phosphorus, which has been reported to be covalently linked to the starch (Takeda et al., 1986), ranged from 12.7 to 19.1 mg/100 g. Madamba et al. (1975) reported similar phosphorus concentrations in six SP varieties grown in the Philippines. Nitrogen, generally considered to be due to protein contamination, ranged from 13.5 to 41 mg/100 g, indicating that the starch was relatively pure. Calcium was also present at from 7.1 to 58.3 mg/100 g. Sodium and magnesium were the least abundant of the minor constituents. There was no statistically significant relationship between C/S mineral content and sensory texture type or shear force.

Starch Granule Size. SP starch granules have been reported to consist of nonaggregated particles of varied shape, but generally oval in nature, with diameters ranging from 2 to 41 μm (Madamba et al., 1975). In the present study, we found median diameters for C/S starches ranging 13.3 to 21.3 μm and modal diameters of 12.6−23.3 μm (Table 4). SP starch granules are similar in size to those of cassava but are smaller than those of potato (Nagahama and Truong, 1994). Particle size and size distribution are important because they can affect the functional properties of starch (Rasper, 1971). Statistical analysis of the data indicated that particle sizes of some C/S were different and that the largest granules were those of NC8-22, followed by NC6-30 and NC10-28, which were dry and intermediate SP texture types. Starch from Jewel cultivar, a moist-type SP, had the smallest granule size. However, Beauregard starch had a granular size comparable to that of NC2-26, an intermediate texture type. Thus, it is apparent that the sizes of starch granules were different among the C/S studied and that these differences did not seem to be strongly related to the textural properties of cooked SP.

Table 4. Size of Starch Granules from Sweetpotato Starches[a]

cultivar/selection	median particle size (μm)	range of particle sizes (μm)	model particle size (μm)
Jewel	13.3d	3−60	12.6c
Beauregard	15.1c	3−60	13.0bc
NC10-28	17.9b	3−60	13.3b
NC2-26	14.0cd	4−60	12.6c
NC6-30	16.9b	3−60	13.3b
NC8-22	21.3a	4−60	23.3a

[a] Within columns values having the same letter are not statistically different ($P \geq 0.05$).

Table 5. DSC of Sweetpotato Starches[a]

cultivar/selection	onset temp (°C)	peak temp (°C)	final temp (°C)	enthalpy (J/g)
Jewel	55.69d	70.95ab	80.82b	25.63a
Beauregard	54.17e	62.80d	83.59a	24.94a
NC10-28	53.38f	64.32c	72.34d	23.97a
NC2-26	60.83b	71.86a	80.76b	24.13a
NC6-30	59.75c	69.89b	78.88c	22.61a
NC8-22	62.13a	71.40a	80.47b	25.10a

[a] Within columns values having the same letter are not statistically different ($P \geq 0.05$).

Starch Paste Properties. DSC data represent the transition temperatures at which birefringence is lost and energy required for transformation from the granular (crystalline) to the gelatinized state (Zobel, 1984). Examination of the data in Table 5 indicates that there are statistically significant differences among the C/S starches in DSC onset, peak, and final temperatures. Onset temperatures ranged from 55.7 to 62.1 °C, peak temperatures from 62.8 to 71.9 °C, and final temperatures from 72.3 to 83.6 °C. These differences indicate that there are differences in internal granular organization among the C/S starches. The two moist cultivars, Jewel and Beauregard, had lower DSC onset temperatures than those of the experimental selections. However, the onset temperatures were also different within the texture types. Additionally, there was no relationship between C/S texture type and DSC peak and final temperatures. Enthalpies ranged from 22.61 to 25.63 J/g; however, none were different statistically, indicating that the total energy required for gelatinization is the same for all C/S in this study.

Both swelling power and solubility changed in a similar fashion as the water temperature increased (Figures 1 and 2). The mean coefficients of variation for all temperatures were 8.4% for solubility and 5.2% for

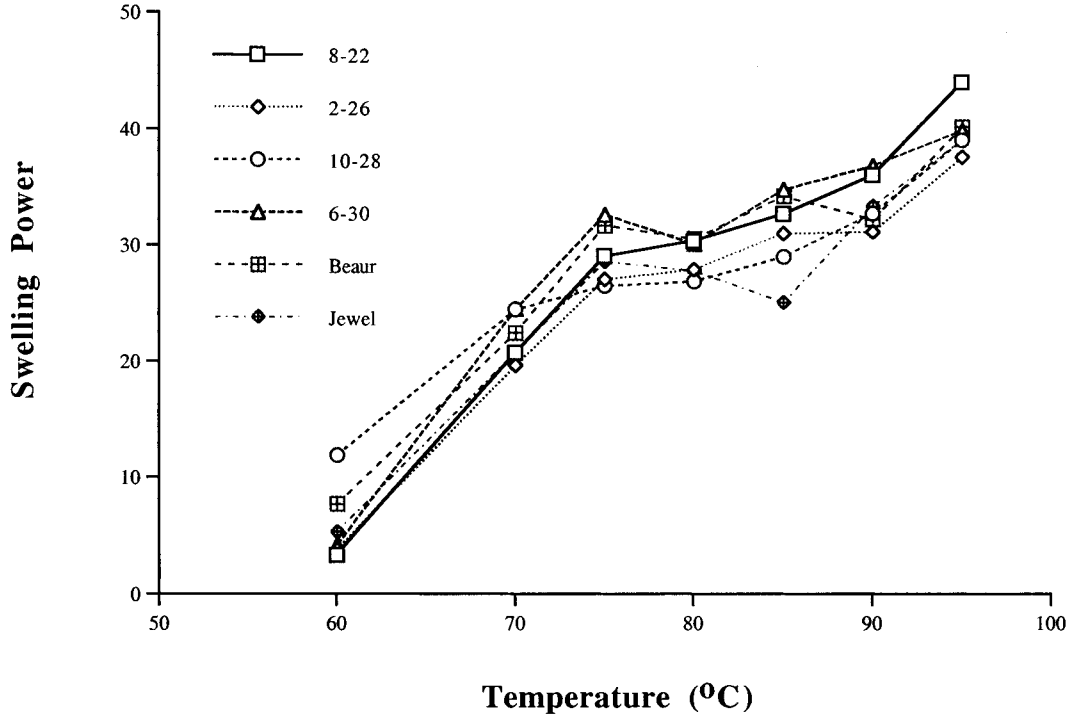

Figure 1. Swelling power of SP starches. The swelling power was obtained by measuring the amount of residue from the centrifugation and calculating the amount of water absorbed by the starch after correction for the amount of solubilized starch.

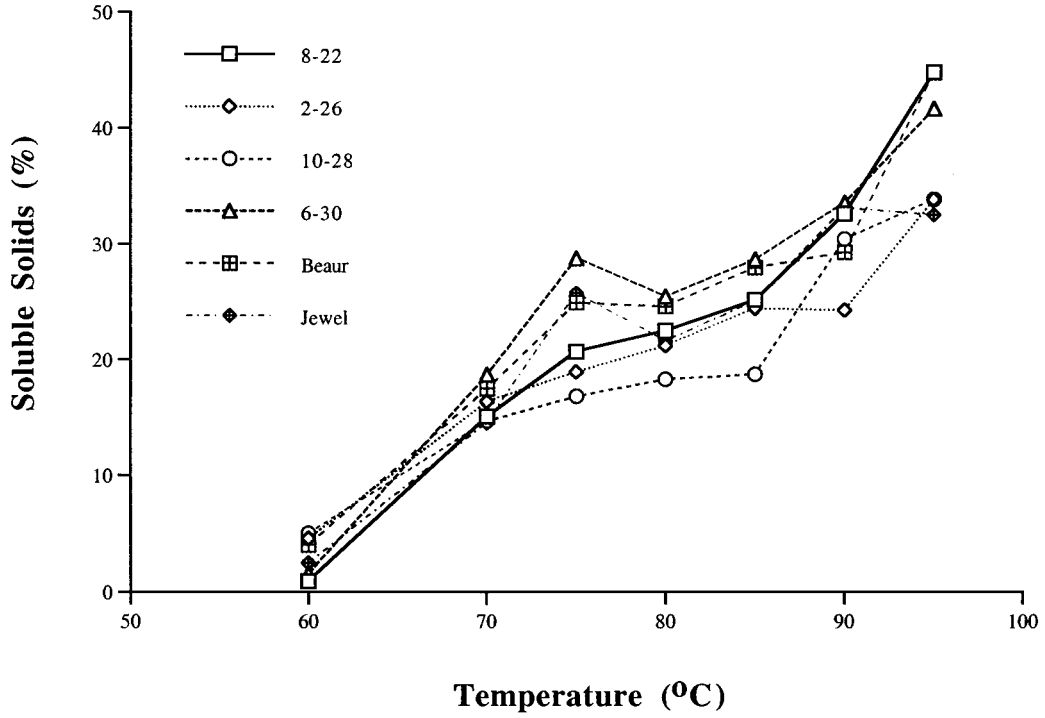

Figure 2. Solubility of SP starches.

swelling power. There was a linear increase in both properties for all SP C/S with increasing temperature until 75 °C was reached. With regard to differences between C/S, the solubility from 75 °C and beyond showed a wider difference among the C/S than did swelling power. For example, at 75 °C the solubilities ranged from 17% for NC10-28 to 29% for NC6-30, which represents a 71% difference. Because amylose has been shown to be the starch component which is solubilized (Leach, 1965), this would indicate that granule organizations of the C/S are different. However, for swelling power, the range was much less, with a low of ~27% for NC2-26 and NC10-28 and a high of ~34% for NC6-30 and Beauregard. Correlation analysis of swelling power versus solubility using pooled data for all C/S resulted in a linear relationship ($R^2 = 0.963$), indicating that swelling of starch granules above the gelatinization temperature is accompanied by leaching of soluble polysaccharides (Kitahara et al., 1996). Because the amylose contents for C/S were similar, we propose that the amount of amylose solubilized is a function of internal granular organization or amylose molecular

Table 6. Brabender Amylograph Parameters for Sweetpotato Starches[a]

cultivar/selection	pasting temp (°C)	peak viscosity (BU)[b]	viscosity at 95 °C (BU)	viscosity at cooling onset (BU)	viscosity at end of cooling (BU)	setback viscosity[c] (BU)
Jewel	73.8a	no peak	638c	643d	1100c	458d
Beauregard	71.4b	no peak	720a	685c	1215b	530c
NC10-28	67.0c	no peak	685b	753ab	1390a	638a
NC2-26	73.6a	no peak	575d	570e	1025d	455d
NC6-30	71.8b	no peak	735a	750a	1340a	590b
NC8-22	73.7a	no peak	683b	720b	1375a	655a

[a] Within columns values having the same letter are not statistically different ($P < 0.05$). [b] BU, Brabender units. [c] Setback viscosity = viscosity at end of cooling minus viscosity at cooling onset.

Table 7. Rapid Viscoanalyzer Parameters for Sweetpotato Starches[a]

cultivar/selection	pasting temp (°C)	peak viscosity (RVU)[b]	viscosity at cooling onset (RVU)	breakdown viscosity[c] (RVU)	viscosity at end of cooling (RVU)	setback viscosity[d] (RVU)
Jewel	74.8	87.4d	67.3bc	20.1c	101.0c	33.8c
Beauregard	74.2	101.2b	60.4d	40.9a	95.0d	34.7c
NC10-28	68.0	99.5b	80.8a	18.7c	126.4a	45.6a
NC2-26	74.5	85.9d	63.5cd	22.5c	102.3c	38.8b
NC6-30	72.9	109.4a	71.5b	37.9a	108.1b	36.6b
NC8-22	72.8	94.5c	61.9d	32.6b	94.9d	33.0c

[a] Within columns values having the same letter are not statistically different ($P < 0.05$). [b] RVU, rapid viscoanalyzer units. [c] Breakdown viscosity = peak viscosity minus viscosity at cooling onset. [d] Setback viscosity = viscosity at end of cooling minus viscosity at cooling onset.

size differences. Differences in leaching as a result of differences in granular organization or amylose molecular size could explain the differences we observed in BA viscosities for the C/S (Table 6).

The BA was used to subject aqueous suspensions (6% w/w) of the SP starches to standardized pasting, cooking, and cooling conditions. BA parameters for the C/S, with the exception of peak viscosity, were dependent upon C/S (Table 6), reflecting differences in the granular organization of the starches and the resultant differences in the properties of the pastes. No pasting peak (peak viscosity) was observed in agreement with some reports (Shin and Ahn, 1983) and in disagreement with others (Lii and Chang, 1978; Garcia and Walter, 1998). SP starches exhibit a wide range of values for the BA parameters, and the parameters of C/S starches in this study fall within the ranges previously reported (Tian et al., 1991; Takeda et al., 1986). During the cooking period at 95 °C, viscosities for some of the starches decreased slightly (5% or less), whereas viscosities for others increased, again reflecting differences in granule and paste stabilities. Compared to starches from other sources such as potato or cassava, SP starches are relatively stable during cooking at a low shear rate (Zobel, 1984). Setback viscosities also reflected the differences in C/S starch properties, indicating differences in retrogradation rates.

The magnitude of RVA viscosities for the C/S in this study (Table 7) was from 5- to 12-fold lower than corresponding viscosities from the BA (Table 6). The two instruments employ different, arbitrary viscosity units; furthermore, the two methods employ different temperature−time programs, rotation speeds, and stirrer geometry. Two differences in data trends between RVA and BA instruments were particularly evident. The first was that, with the RVA, there was a moderate pasting peak (peak viscosity) observed for all C/S. The second instance was that, during the cooking period at 95 °C, paste viscosities recorded by the RVA decreased from ca. 20 to 40%, depending upon the C/S. The BA viscosities recorded during the cooking phase exhibited changes of 5% or less, with viscosities increasing for some C/S and decreasing for others. Thus, there was greater shear degradation in the RVA. We ran correlation analyses between BA and the corresponding RVA values. These were pasting temperatures, viscosity at cooling onset, viscosity at end of cooling, and setback viscosity. We found that only for the pasting temperatures were statistically significant correlation coefficients observed ($r^2 = 0.803$) between BA and RVA parameters.

Shear rate is neither uniform nor well-defined in either instrument, and the shear rate profiles across the sample holder differ between the two instruments. Thiewes and Steeneken (1997) reported that, for a selected set of native and modified starches cooked using the same temperature−time profiles, comparable rheological properties were obtained. This indicated either that shear rates are comparable or that the temperature−time profile is the more dominant factor. These authors postulated that under the usual operating conditions starches experience less shear degradation in the RVA than the BA because of the shorter exposure times. This is in contrast to what was reported here, as well as by Deffenbaugh and Walker (1989).

We performed a Pearson product−moment correlation coefficient analysis comparing shear stress of the cooked SP cylinders to the compositional and physical properties of the starches isolated from raw C/S. To do this analysis, we used shear force, a more objective measure of textural properties than sensory texture type. Our results, as well as those of Truong et al. (1997), indicated that sensory texture type is linearly related to shear stress. In general, a sensory texture assignment of "moist" is characterized by low shear stress values, whereas "dry" C/S have higher shear stress values.

When we did the correlation analysis, we found that only DSC onset temperature ($r = 0.78$) was statistically correlated with shear stress. This parameter was the sole correlated physical property; all other physical properties, including rheological ones, were not correlated. This indicates that, with the exception of DSC onset temperature, the physical and compositional properties of the starches as measured in this study do not significantly influence the texture of cooked SP C/S. A possible explanation is that most SP C/S contain substantial amounts of α- and β-amylase (Morrison et al., 1993). Degradation of starch by these amylases during cooking results in lowered water-binding capac-

ity of cooked SP, which is sensed by panelists as increased moistness (Walter et al., 1975). Conversely, the lack of starch hydrolysis due to low amylolytic activity is sensed as a dry mouthfeel. Thus, the amount of endogenous amylolytic enzyme activity could be a more important factor than the starch compositional and physical properties.

ACKNOWLEDGMENT

We thank Ms. Kristi Tostenson of the Agricultural and Biosystems Engineering Department, North Dakota State University, Fargo, ND, for performing the Amylograph and RVA analyses.

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Received for review August 26, 1999. Revised manuscript received April 20, 2000. Accepted May 4, 2000. Mention of a trademark or proprietary product does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture or the North Carolina Agricultural Research Service, nor does it imply approval to the exclusion of other products that may be suitable.

JF990963L