

Structural and Functional Characteristics of Selected Soft Wheat Starches¹

Célia M. L. Franco,² Kit-Sum Wong,³ Sang-ho Yoo,³ and Jay-lin Jane^{3,4}

ABSTRACT

Cereal Chem. 79(2):243–248

Starches from eight soft wheat samples (two parent lines and six offspring) were isolated; relationships between their structures and properties were examined. Branch chain-length distributions of amylopectins were determined by using high-performance anion exchange chromatography equipped with an amyloglucosidase reactor and a pulsed amperometric detector (HPAEC-ENZ-PAD). Results showed that the average chain length of the eight samples varied at DP 25.6–26.9. Starch samples of lines 02, 60, 63, 95, and 114 consisted of amylopectins with more long chains (DP \geq 37) and longer average chain length (DP 26.2–26.9) than that of other samples. These starch samples of longer branch chain length

displayed higher gelatinization temperatures (55.3–56.5°C) than that of other samples (54.4–54.9°C) and higher peak viscosity (110–131 RVU) and lower pasting temperature (86.3–87.6°C) than others (83–100 RVU and 88.2–88.9°C, respectively). The M_w of amylopectins, determined by using high-performance size exclusion chromatography equipped with multiangle laser-light scattering and refractive index detectors (HPSEC-MALLS-RI), were similar for all samples (6.17×10^8 to 6.97×10^8). There were no significant differences in amylose and phosphorus contents between samples. These results indicated that physical properties of wheat starch were affected by the branch-chain length of amylopectin.

Wheat cultivars of different characteristics are desirable for different final product applications. Because starch is the major component (80%) of soft wheat flour (Lin and Czuchajowska 1997), starch properties are important for the quality of products. Studies have shown that functional properties of starch are critical to the quality of white-salted noodles (Bhattacharya et al 1997; Sasaki and Matsuki 1998; Akashi et al 1999), whereas the protein content and quality are the most important factors for breadbaking (Bhattacharya et al 1997).

Starch structures such as amylose contents, branch chain length distribution of amylopectin (Jane et al 1999), phosphate monoester, phospholipid and lipid contents (Tester and Morrison 1990; Lim et al 1994; Morrison 1995; Lin and Czuchajowska 1998), starch granule size distribution (Raeker et al 1998), crystalline structures (Hizukuri et al 1997), and granular architecture (Tester 1997) affect the functional properties of starch. Relationships between fine structures and thermal and pasting properties of starch have been established by using high-performance anion-exchange chromatography equipped with a pulsed amperometric detector (HPAEC-PAD), high-performance size-exclusion chromatography (HPSEC), differential scanning calorimetry (DSC), and amylography. Starch that consists of amylopectin with a larger proportion of long branch-chains displayed higher gelatinization temperatures and enthalpy changes (Sanders et al 1990; Jane et al 1992; Yuan et al 1993; Shi et al 1994; Kasemsuwan et al 1995; Sasaki and Matsuki 1998; Jane et al 1999). Pasting properties of starch are also affected by the branch chain length distribution of amylopectin (Jane et al 1992; Wang et al 1993; Jane et al 1999). Jane and Chen (1992) reported synergistic effects between amylopectin chain length and amylose molecular size on the viscosity of starch paste.

Normal wheat starch has relatively larger contents of amylose and phospholipids (Shi et al 1994; Lim et al 1994). Starches with larger amylose, lipids and phospholipids contents have higher pasting temperature, lower peak viscosity and shear-thinning, and higher setback viscosity (Zeng et al 1997; Jane et al 1999, Yoo and Jane, *in press*).

Relationships between structural characteristics and functional properties of starches have received much attention. It is important to have a thorough understanding of how starch functional properties are affected by structural characteristics. This information should

provide a basis for more adequate manipulation of quality attributes through breeding or genetic modification to produce new lines with desirable properties for various applications of soft wheat flour.

This study was a part of a project on a comprehensive understanding of soft wheat structures, properties, and applications led by the USDA, Soft Wheat Quality Laboratory (Wooster, OH). In this study, we aimed to investigate the structures and functions of starches isolated from eight different soft wheat samples. Two parent lines and six hybrid lines of wheat were used in this study. Results obtained from this study will be related to characteristics of milling, baking, and other applications of the soft wheat flour samples to be reported later.

MATERIALS AND METHODS

Eight wheat samples from 1994 crop, grown at the same location and conditions, were used in this study. Two parent lines, Clarkes (a hard wheat cultivar that has a soft equivalent index [SE] of 42.69) and New York (soft wheat, SE 52.01) were designated as Line 109 and Line 114, respectively. Six hybrid lines, derived from Clarkes and New York and displaying different hardness values, were assigned as Lines 02 (SE 52.88), 39 (SE 36.86), 60 (SE 48.1), 63 (SE 40.33), 95 (SE 41.08), and 106 (SE 55.62). The SE indices of the wheat samples were analyzed in the USDA Soft Wheat Laboratory and were provided by P. Finney (Wooster, OH). Crystalline *Pseudomonas isoamylase* (EC 3.2.1.68, Hayashibara Shoji, Okayama, Japan) was used as received. Sepharose CL-2B gel was a product of Pharmacia (Piscataway, NJ). Other chemicals, all reagent-grade, were used without further purification.

Starch Isolation

Starch was isolated using a method reported by Badenhuizen (1964) and Kasemsuwan et al (1995) with modification. Wheat grains were steeped in 0.01M mercuric chloride solution and then ground and separated from cellulosic material by using a 53- μ m screen. The starch was recovered and purified by centrifugation and resuspended in a NaCl (0.1M) solution with 10% volume of toluene, stirred for at least 1 hr, and allowed to stand until the starch precipitated. The NaCl solution and toluene were removed, and the procedure was repeated until the starch sediment became clean. The starch was recovered by filtration, washing two times, rinsed with ethanol and dried in a convection oven at 35°C for 48 hr.

Fractionation of Amylose and Amylopectin

Fractionation of amylose and amylopectin followed the procedure of Schoch (1942) and Jane and Chen (1992). Amylose was precipitated as amylose-1-butanol complex, and amylopectin was purified by recrystallization to remove amylose.

¹ Journal Paper No. J-18915 of the Iowa Agriculture and Home Economic Experiment Station, Ames, IA. Project No. 3258.

² Dept of Food Engineering and Technology, Universidade Estadual Paulista (IBILCE/UNESP), São José do Rio Preto, SP, Brazil, 15054-000.

³ Dept of Food Science and Human Nutrition, Iowa State University, Ames, IA 50011.

⁴ Corresponding author. E-mail: jjane@iastate.edu

Molecular Weight Distribution of Starch by GPC

Starch (100 mg) was prewetted with water and then dispersed in 90% DMSO solution (10 mL) following the procedure of Song and Jane (2000). An aliquot (2.5 mL) containing 7.5 mg of starch and 1 mg of glucose (as a marker) was loaded onto a column (1.0 i.d. × 70.0 cm) packed with Sepharose CL-2B gel following the procedure reported by Wang et al (1993). The column was eluted in the ascending mode. The eluent consisted of NaCl (25 mM) and NaOH (1 mM) with a flow rate of 0.5 mL/min. Fractions of 2.5 mL each were collected and subjected to total carbohydrate and amylose content analyses using phenol sulfuric (Dubois 1956) and iodine staining reactions (Juliano 1971), respectively, to reveal molecular weight distribution of amylopectin and amylose.

Absolute Molecular Weight of Amylopectin by HPSEC-MALLS-RI

Amylopectin was separated from amylose using HPSEC, and absolute molecular weight was determined by using a multiangle

laser-light scattering detector (MALLS) (model Dawn-F, Wyatt Technology, Santa Barbara, CA) with He-Ne laser-light at 632 nm and a refractive index detector (RI, HP1047A, Hewlett Packard). A fresh starch solution (0.4 mg/mL) was prepared by the same procedure used for GPC and filtered through a nylon filter (5 μm) before injection. An isocratic pump (HP1050) equipped with an injection valve (model 7125, Rheodyne), a 100-μL sample loop and online eluent filter kit using 0.2- and 0.1-μm membrane filters (Millipore, Bedford, MA) was used for the analysis. Two sequentially connected analytical columns (Shodex KB-806 and KB-804, Showa Denko, Tokyo) with a Shodex OH pack KB-G guard column were maintained at 55°C in a CH-460 column heater with a TC-50 controller (Eppendorf, Madison, WI). The temperature of the RI detector was set at 30°C. Pure deionized water was used as mobile phase at a flow rate of 0.7 mL/min. The weight-average molecular weight (M_w) and the radius of gyration (R_z) were calculated by using a ASTRA 4.7 software (Wyatt Technology).

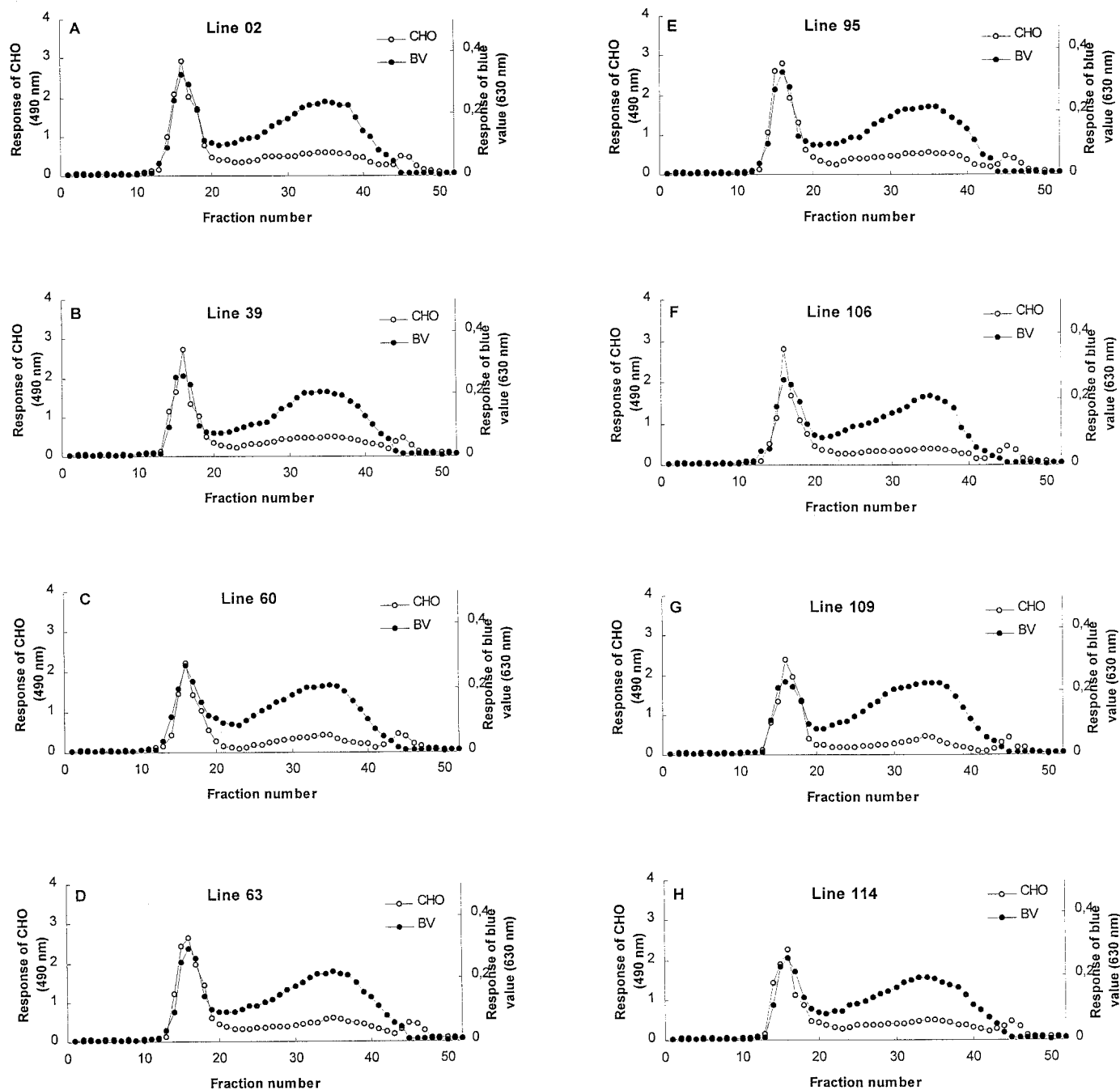


Fig. 1. Elution profiles of soft wheat starches on Sepharose CL-2B column. A–H: Lines 02; 39; 60; 63; 95; 106; 109; and 114, respectively.

Branch Chain-Length Distribution of Amylopectin

The branch chain-length distribution of wheat amylopectin was determined following the method of Wong and Jane (1997). Whole starch samples were debranched using isoamylase and analyzed by high-performance anion exchange chromatography (Dionex DX-300 system, Sunnyvale, CA) equipped with a postcolumn amyloglucosidase reactor and a pulsed amperometric detector (HPAEC-ENZ-PAD). An anion-exchange column (CarboPac PA-100 column) and a guard column were used for the analysis. A gradient composed of eluent A (100 mM NaOH) and eluent B (100 mM NaOH, 300 mM NaNO₃) was programmed as follows. At 0 min, the mobile phase consisted of 99% A and 1% B. The concentration of eluent B in mobile phase was linearly increased to 5, 8, 30, and 45% at 30, 50, 160, and 220 min, respectively. The flow rate of the eluent was at 0.5 mL/min through out the analysis. The pulsed potential and duration for the PAD were:

$E_1 = 0.05V$ (duration time $t_1 = 480$ msec), $E_2 = 0.60V$ ($t_2 = 120$ msec), and $E_3 = -0.60V$ ($t_3 = 60$ msec).

Iodine Affinity and Amylose Content

Starch samples were defatted by dispersing starch in 90% DMSO solution in a boiling water bath with stirring for 1 hr. Starch was precipitated from DMSO solution with absolute ethanol and was collected by centrifugation. Precipitated sample was washed with ethanol, recovered by filtration, and dried in a convection oven at 35°C for 24 hr. Iodine affinities of defatted whole starch and purified amylopectin were determined as in by Kasemsuwan et al (1995). A potentiometric autotitrator (702 SM Titrino, Brinkmann Instrument, Westbury, NY) was used to measure iodine affinity. Apparent amylose contents were calculated by dividing the iodine affinity of starch by 19.9% (Takeda and Hizukuri 1987). Absolute amylose contents were calculated by the method of Kasemsuwan et al (1995).

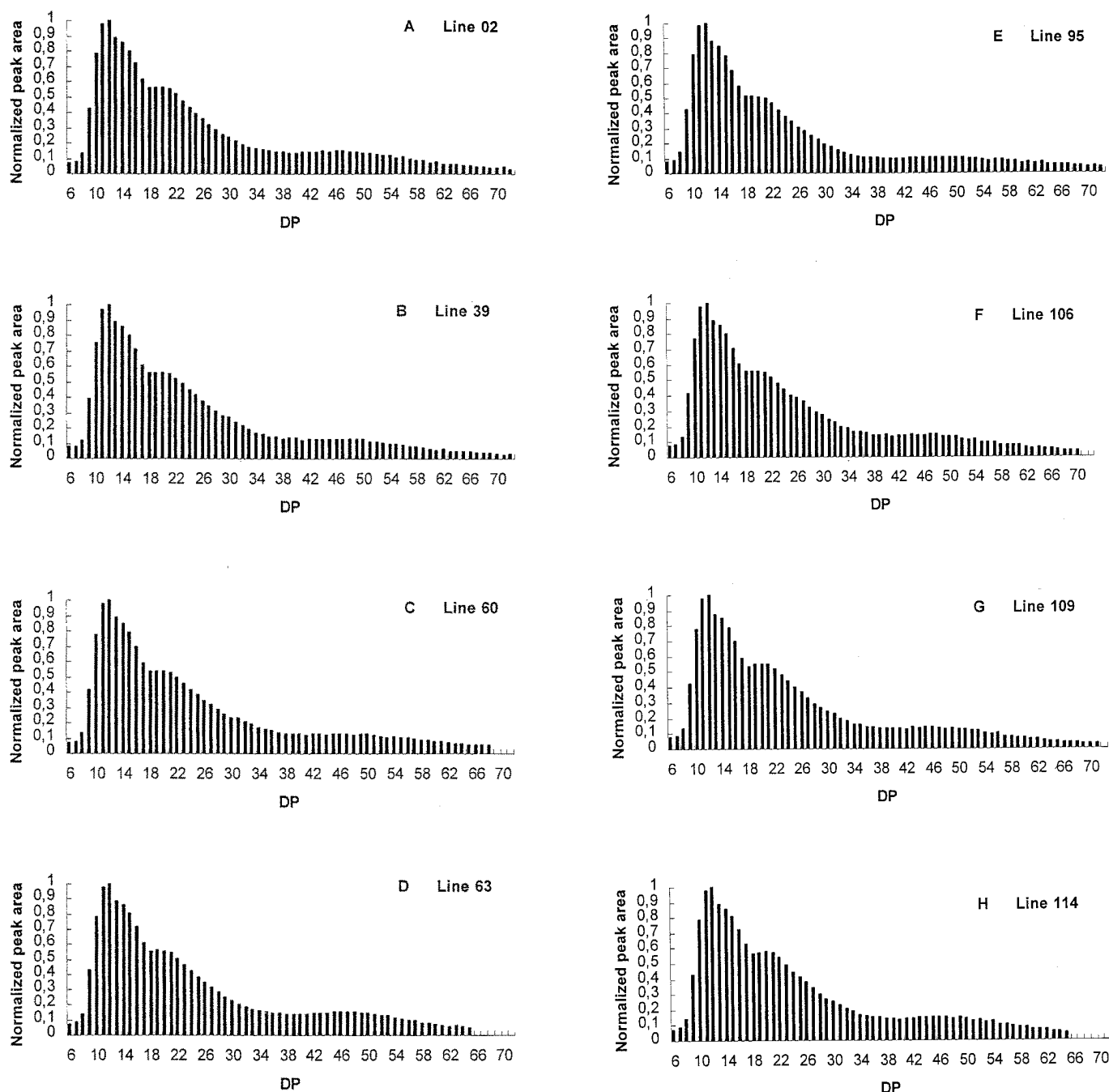


Fig. 2. Branch-chain length distributions of soft wheat amylopectins analyzed by HPAEC-ENZ-PAD. A-H: Lines 02; 39; 60; 63; 95; 106; 109; and 114. Average of two replicates.

TABLE I
Chain Length (CL) Distribution of Wheat Amylopectins^a

Line	Peak I	Peak II	CL Average	Chain Length Distribution (%) ^b			
				DP 6–12	DP 13–24	DP 25–36	DP ≥ 37
02	12	47	26.6	19.1c	41.5a–c	16.0b	23.4a
39	12	49	25.6	19.2bc	42.7a	17.7a	20.4c
60	12	50	26.9	19.3bc	40.9c	16.4b	23.4a
63	12	48	26.2	19.4bc	41.7a–c	15.8b	23.1a
95	12	51	26.2	21.0a	42.3ab	14.4c	22.3ab
106	12	48	26.2	19.1c	41.2bc	17.7a	22.0a–c
109	12	46	25.6	19.8b	42.1ab	16.8ab	21.2bc
114	12	47	26.4	18.9c	41.6a–c	16.7ab	22.8ab

^a Average of two replicates per sample.

^b Sum of peak-area ratios (%) of group with degree of polymerization (DP).

^c Values followed by the same letter in the same column are not significantly different ($P < 0.05$).

TABLE II
Weight-Average Molecular Weight (M_w) and Radius of Gyration (R_z) of Wheat Starch Amylopectins^{a,b}

Line	M_w (10^8 g/mol)	R_z (nm)
02	6.65a ^c	317.6ab
39	6.29a	310.4ab
60	6.73a	322.3ab
63	6.65a	314.3ab
95	6.17a	300.3b
106	6.97a	324.9a
109	6.76a	323.8a
114	6.84a	320.4ab

^a Averages of two replicates per sample.

^b Peak on retention volume at 8.7–9.7 mL.

^c Values followed by the same letter in the same column are not significantly different ($P < 0.05$).

Phosphorus Content

Phosphorus contents of wheat starches were determined by the spectrophotometric method of Smith and Caruso (1964).

Thermal Properties

Gelatinization properties of wheat starch samples were determined using a DSC-7 (Perkin Elmer, Norwalk, CT). Wheat starches (2 mg, dsb) were weighed in aluminum pans, mixed with distilled water (6 μ L) and sealed. The weighed samples were kept at room temperature for 2–3 hr to equilibrate and scanned at a rate of 10°C/min over a temperature range of 25–100°C. An empty pan was used as a reference. Each gelatinized sample remained in was kept in the pan in an individually marked vial and stored at 4°C for seven days. The samples were then analyzed for starch retrogradation using the same instrument and parameters.

Pasting Properties of Wheat Starches

Pasting properties of wheat starch samples were obtained using a Rapid Visco Analyser (RVA) (model RVA-4, Newport Scientific, Australia). A starch suspension (8%, dsb, w/w; 28 g total weight) was equilibrated at 30°C for 1 min, heated to 95°C at a rate of 6°C/min, held at 95°C for 5.5 min, cooled down to 50°C at a rate of 6°C/min, and finally held at 50°C for 2 min. The suspension was stirred at 160 rpm throughout the experiment.

Statistical Analysis

All samples were analyzed in duplicate. Statistical analyses were performed using the data analysis tools of Statistics for Windows (v. 5.0, Statsoft, Tulsa, OK). Analysis of variance was conducted using Tukey's studentized range test at the 5% level.

RESULTS AND DISCUSSION

GPC elution profiles of wheat starches are shown in Fig. 1. Amylopectin, with large molecular mass, was eluted at the void volume and shown as the first peak. The second peak, evident in a great

blue value response, corresponded to amylose. The last peak was glucose added to mark the end of the elution. Results showed that ratios of blue value to total carbohydrate (BV/CHO) of the amylopectins of Lines 02, 60, 63, 95, and 114 (Fig. 1A, 1C, 1D, 1E, and 1H, respectively) were 0.11–0.12 and were larger than that of Lines 39, 106 and 109 (Fig. 1B, 1F, and 1G, respectively, BV/CHO = 0.09). The results suggested that the amylopectin of Lines 02, 60, 63, 95, and 114 consisted of larger proportions of longer branch chains. Normalized chain length distributions of debranched amylopectins of the wheat starch samples determined by HPAEC-ENZ-PAD are shown in Fig. 2 and the results are summarized in Table I. All eight samples showed 1st and 2nd peak chain-length at DP 12 and 46–51, respectively. The average chain length varied from DP 25.6 to 26.9. The peak area ratios of DP 6–12, 13–24, 25–36 and DP ≥ 37 were 18.9–21.0, 40.9–42.7, 14.4–17.7, and 20.4–23.4%, respectively. Lines 02, 60, 63, 95, and 114 consisted of larger proportions of chains with DP ≥ 37 (22.3–23.4%) compared with three other samples with DP ≥ 37 (20.4–22.0%). These results confirmed those observed in GPC profiles (Fig. 1). With exception of Line 95, there was no difference in the proportion of short branch chain of amylopectin among all wheat starch samples. Sasaki and Matsuki (1998) reported that among 12 amylopectins isolated from wheat starches, four had higher proportions of long chains, whereas Lin and Czuchajowska (1997) found no detectable difference in amylopectin structure of 191 club and soft white winter wheat starch samples.

Amylopectins have gigantic molecular weights. The M_w and R_z of the amylopectins of the wheat samples are shown in Table II. The M_w and R_z varied from 6.17 to 6.97 $\times 10^8$ and from 300.3 to 324.9 nm, respectively. The results agreed with those reported by Buléon et al (1998). These data showed no significant difference between the M_w of the samples. You et al (1999) reported lower values with larger differences between the M_w of amylopectins of eight wheat cultivars, which varied from 4.2 to 7.3 $\times 10^7$.

Apparent amylose contents of the starch samples varied from 27.2 to 28.7% as shown in Table III. The Lines 60 and 109 displayed the highest values. These results were in agreements with those reported by Raeker et al (1998) and Akashi et al (1999), with amylose contents of normal wheat starches varying from 26.7 to 28.8% and from 25.7 to 28.7%, respectively. Zeng et al (1997) reported similar values for amylose contents of 14 different normal wheat cultivars, with exception of two cultivars that displayed lower values. To determine how significant long branch-chains of amylopectin were in overestimating the amylose content, starches of Lines 02, 60, 63, and 95 were selected for the study. The starches were fractionated to amylose and amylopectin and purified by recrystallization. The iodine affinities of the purified amylopectin samples were determined (Table III). The absolute amylose contents were also calculated. Because of limited amounts available for fractionation of starch, only Lines 02, 60, 63 and 95 were fractionated and their absolute amylose contents determined. The iodine affinities of these amylopectins were considered low, indicating that the apparent

TABLE III
Iodine Affinities (IA), Amylose, and Phosphorus Contents of Wheat Starches^a

Line	IA _S	IA _{AP}	Apparent Amylose ^b (%)	Absolute Amylose ^c (%)	Phosphorus Content (%)
02	5.54b ^d	0.39	27.8	26.4	0.049bc
39	5.45b	nd ^e	27.2	nd	0.049bc
60	5.70a	0.39	28.6	27.2	0.047bc
63	5.55b	0.50	27.9	26.0	0.049bc
95	5.56b	0.22	27.9	27.1	0.047c
106	5.50b	nd	27.5	nd	0.049b
109	5.74a	nd	28.7	nd	0.053a
114	5.52b	nd	27.6	nd	0.050b

^a Averages of at least two replicates per sample.

^b % Apparent amylose = (IA_S/19.9) × 100.

^c % Absolute amylose = [(IA_S - IA_{AP})/(19.9 - IA_{AP})] × 100.

^d Values followed by the same letter in the same column are not significantly different ($P < 0.05$).

^e Not determined.

amylose contents of wheat starches were not significantly overestimated over the absolute amylose contents.

Phosphorus in most normal cereal starches is mainly in the form of phospholipids that affect the starch pasting properties (Jane et al 1996). Differences in phosphorus content are related to genetic variations within each species (Lim et al 1994). Phosphorus content of the wheat starch samples (Table III) varied from 0.047 to 0.053%. The starch of Line 109 showed the largest phosphorus content, whereas Lines 60 and 95 showed the smallest. These results were in agreement with 0.048–0.060% reported by Raeker et al (1998) for 12 soft wheat cultivars. There was no significant correlation between amylose content and phosphorus content of the samples analyzed.

Thermal properties of wheat starches are shown in Tables IV and V. Starch of Lines 02, 60, 63, 95, and 114, with larger proportions of long branch chains in the amylopectins, displayed higher gelatinization temperatures (Table IV) and melting temperatures of retrograded starches (Table V). These results further confirmed those reported by Jane et al (1992 and 1999), Yuan et al (1993), Shi et al (1994), Kasemsuwan et al (1995), and Sasaki and Matsuki (1998). However, there was no significant difference observed in the enthalpy change of starch gelatinization and melting of retrograded starches among all eight samples. Significant correlation was observed between the percentage of long branch-chains of amylopectin (LBCL) (DP ≥ 37) and onset gelatinization temperature and melting temperature of retrograded starches ($r = 0.655$; $P < 0.01$, and $r = 0.788$; $P < 0.01$, respectively). DSC measures the melting of double helical crystallites with the loss of molecular order (Cooke and Gidley 1992). Gelatinization temperature is related to crystallite perfection (Tester and Morrison 1990). Amylopectins with more long branch chains (Lines 02, 60, 63, 95, and 114) produce more-ordered double-helical crystallites, which require higher temperatures to uncoil and dissociate (Yuan et al 1993; Song and Jane, 2000).

Pasting properties of different wheat starches are summarized in Table VI. The peak viscosity and pasting temperature ranges of the starch samples were 83–131 RVU and 86.3–88.9°C, respectively. Lines 02, 60, 63, 95 and 114 that had amylopectins of more long branch chains (DP ≥ 37) displayed larger peak viscosity (110–131 RVU), lower pasting temperature (86.3–87.6°C), and larger shear-thinning (40–52 RVU) than three other samples: peak viscosity (83–100 RVU), pasting temperature (88.2–88.9°C), and shear thinning (21–30 RVU). Correlations were determined between the %LBCL (DP ≥ 37) and peak viscosity ($r = 0.785$, $P < 0.01$) and between %LBCL and pasting temperature ($r = -0.616$, $P < 0.01$). Sasaki and Matsuki (1998) suggest that a larger number of hydrogen bonds can be formed between longer chain amylopectins and water, which contribute to increased swelling of starches.

CONCLUSIONS

The results showed that the branch chain length of amylopectin had effects on the thermal and pasting properties of wheat starches.

TABLE IV
Thermal Properties^a of Native Soft Wheat Starches^b

Line ^c	T _o	T _p	T _c	ΔH
02	56.5a ^d	60.4a	64.4ab	10.2a
39	54.9bc	58.9c	63.1c–e	9.5a
60	55.3b	59.1bc	63.4b–e	9.9a
63	56.5a	60.3a	64.7a	10.5a
95	55.4b	59.3a–c	63.6a–d	10.5a
106	54.4c	58.2c	62.2e	9.5a
109	54.8bc	58.7c	62.6de	9.8a
114	56.3a	60.2ab	64.1a–c	10.4a

^a T_o, T_p, and T_c = onset, peak and complete temperature (°C), respectively; ΔH = enthalpy change (J/g).

^b Averages of at least three replicates per sample.

^c Starches samples (≈2 mg, dsb) and distilled water (6 μL) used for analyses.

^d Values followed by the same letter in the same column are not significantly different ($P < 0.05$).

Starch gelatinization temperature, paste peak viscosity, and shear thinning increased with increasing branch chain-length of amylopectin. The molecular weight of amylopectin and contents of amylose and phosphorus of the starch samples were not significantly different between the eight samples to show effects on the functional properties of these starches.

ACKNOWLEDGMENTS

We thank the Danone and the Fundação de Amparo à Pesquisa do Estado de São Paulo/Brazil (FAPESP) for financial support, and P. Finney for providing samples and background information.

LITERATURE CITED

- Akashi, H., Takahashi, M., and Endo, S. 1999. Evaluation of starch properties of wheats used for Chinese yellow-alkaline noodles in Japan. *Cereal Chem.* 76:50-55.
- Badenhuizen, N. P. 1964. General method for starch isolation. Pages 14-15 in: *Methods in Carbohydrate Chemistry*, Vol. 4: Starch. R. L. Whistler, R. J. Smith, J. N. BeMiller, and M. L. Wolfrom, eds. Academic Press: London.
- Bhattacharya, M., Jafari-Shabestari, J., Quealset, C. O., and Corke, H. 1997. Diversity of starch pasting properties in Iranian hexaploid wheat landraces. *Cereal Chem.* 74:417-423.
- Buléon, A., Colonna, P., Planchot, V., and Ball, S. 1998. Starch granules: Structure and biosynthesis. *Int. J. Biol. Macromol.* 23:85-112.
- Cooke, D., and Gidley, M. J. 1992. Loss of crystalline and molecular order during starch gelatinization: Origin of the enthalpic transition. *Carbohydr. Res.* 227:103-112.
- Dubois, M., Gilles, K. A., Hamilton, J. K., Rebers, P. A., and Smith, F. 1956. Colorimetric method for determination of sugars and related substances. *Anal. Chem.* 28:350-356.
- Hizukuri, S., Takeda, Y., Abe, J., Hanashiro, I., Matsunobu, G., and Kiyota, H. 1997. Analytical developments: Molecular and microstructural characterization. Pages 121-128 in: *Starch: Structure and Functionality*. P. J. Frazier, P. Richmond, and A. M. Donald, eds. R. Soc. Chem.: London.

TABLE V
Thermal Properties^a of Retrograded Soft Wheat Starches^b

Line	T_o	T_p	T_c	ΔH	%R ^c
02	42.9a ^d	50.9a	57.2a	4.3a	41.9
39	38.3b	48.1c	56.4a	4.3a	44.7
60	42.0a	49.1b	57.0a	3.7a	37.8
63	42.6a	51.3a	57.1a	3.9a	37.3
95	43.5a	51.7a	57.3a	3.5a	32.8
106	38.7b	48.3bc	56.4a	3.6a	37.8
109	37.9b	48.4bc	56.8a	3.7a	37.4
114	42.4a	51.1a	56.6a	3.7a	35.1

^a T_o , T_p , and T_c = onset, peak and complete temperature (°C), respectively; ΔH = enthalpy change (J/g).

^b Averages of at least three replicates per sample.

^c %R (retrogradation) = $[\Delta H_{ret} / \Delta H_{gel}] \times 100$.

^d Values followed by the same letter in the same column are not significantly different ($P < 0.05$).

TABLE VI
Pasting Properties of Wheat Starches^a

Line ^b	Pasting Temp (°C)	Peak Time (min)	Viscosity (RVU)			
			Peak	Shear-Thinning	Final	Setback
02	86.9b ^c	12.5a	128a	52a	176b	100b
39	88.2ab	11.9b	83e	21e	132d	71f
60	86.7b	12.4a	131a	48ab	198a	114a
63	87.6ab	12.4a	113b	42bc	158c	88c-e
95	86.3b	12.5a	128a	47ab	179b	98bc
106	88.9a	12.5a	99d	27de	152c	80ef
109	88.9a	12.3ab	100cd	30d	155c	84de
114	86.7b	12.1ab	110bc	40c	163c	93b-d

^a Averages of two replicates per sample.

^b Sample concentrations are 8%, dsb, w/w.

^c Values followed by the same letter in the same column are not significantly different ($P < 0.05$).

- Jane, J., and Chen, J. F. 1992. Effect of amylose molecular size and amylopectin branch chain length on paste properties of starch. *Cereal Chem.* 69:60-65.
- Jane J., Shen, L., Lim, S., Kasemsuwan, T., and Nip, W. K. 1992. Physical and chemical studies of taro starches and flours. *Cereal Chem.* 69:528-535.
- Jane, J., Kasemsuwan, T., and Chen, J. F. 1996. Phosphorus in rice and other starches. *Cereal Foods World* 41:827-832.
- Jane, J., Chen Y. Y., Lee, L. F., McPherson, A. E., Wong, K. S., Radosavljevic, M., and Kasemsuwan, T. 1999. Effects of amylopectin branch chain length and amylose content on the gelatinization and pasting properties of starch. *Cereal Chem.* 76:629-637.
- Juliano, B. O. 1971. A simplified assay for milled-rice amylose. *Cereal Sci. Today* 16:334-340.
- Kasemsuwan, T., Jane, J., Schnable, P., Stinard, P., and Robertson, D. 1995. Characterization of the dominant mutant amylose-extender (*Ael-5180*) maize starch. *Cereal Chem.* 72:457-464.
- Lim, S., Kasemsuwan, T., and Jane, J. 1994. Characterization of phosphorus in starch by ³¹P-nuclear magnetic resonance spectroscopy. *Cereal Chem.* 71:488-493.
- Lin, P.-Y., and Czuchajowska, Z. 1997. Starch properties and stability of club and soft white winter wheats from the Pacific Northwest of the United States. *Cereal Chem.* 74:639-646.
- Lin, P.-Y., and Czuchajowska, Z. 1998. Role of phosphorus in viscosity, gelatinization, and retrogradation of starch. *Cereal Chem.* 75:705-709.
- Morrison, W. R. 1995. Starch lipids and how they relate to starch granule structure and functionality. *Cereal Foods World* 40:437-446.
- Raeker, M. Ö., Gaines, C. S., Finney, P. L., and Donelson, T. 1998. Granule size distribution and chemical composition of starches from 12 soft wheat cultivars. *Cereal Chem.* 75:721-728.
- Sanders, E. B., Thompson, D. B., and Boyer, C. D. 1990. Thermal behavior during gelatinization and amylopectin fine structure for selected maize genotypes as expressed in four inbred lines. *Cereal Chem.* 67:594-602.
- Sasaki, T., and Matsuki, J. 1998. Effect of wheat starch structure on swelling power. *Cereal Chem.* 75:525-529.
- Schoch, T. J. 1942. Fractionation of starch by selective precipitation with buthanol. *J. Am. Chem. Soc.* 64:2957-2961.
- Shi, Y.-C., Seib, P. A., and Bernardin, J. E. 1994. Effects of temperature during grain-filling on starches from six wheat cultivars. *Cereal Chem.* 71:369-383.
- Smith, R. J., and Caruso, J.-L. 1964. Determination of phosphorus. Pages 42-46 in: *Methods in Carbohydrate Chemistry*, Vol. 4. R. L. Whistler, ed. Academic Press: Orlando, FL.
- Song, Y., and Jane, J. 2000. Characterization of barley starches of waxy, normal, and high amylose varieties. *Carbohydr. Polym.* 41:365-377.
- Takeda, Y., and Hizukuri, S. 1987. Structures of rice amylopectins with low and high affinities for iodine. *Carbohydr. Res.* 168:79-88.
- Tester, R. F. 1997. Starch: The polysaccharide fractions. Pages 163-171 in: *Starch: Structure and Functionality*. P. J. Frazier, P. Richmond, and A. M. Donald, eds. R. Soc. Chem.: London.
- Tester, R. F., and Morrison, W. R. 1990. Swelling and gelatinization of cereal starches. I. Effects of amylopectin, amylose, and lipids. *Cereal Chem.* 67:551-557.
- Wang, Y.-J., White, P., Pollak, L., and Jane, J. 1993. Characterization of starch structures of 17 maize endosperm mutant genotypes with Oh43 inbred line background. *Cereal Chem.* 70:171-179.
- Wong, K. S., and Jane, J. 1997. Quantitative analysis of debranched amylopectin by HPAEC-PAD with a postcolumn enzyme reactor. *J. Liq. Chrom. Rel. Technol.* 20:297-310.
- Yoo, S.-H. and Jane, J. *In press*. Structural and physical characteristics of waxy and other wheat starches. *Carbohydr. Polym.*
- You, S., Fiedorowicz, M., and Lim, S.-T. 1999. Molecular characterization of wheat amylopectins by multiangle laser light scattering analysis. *Cereal Chem.* 76:116-121.
- Yuan, R. C., Thompson, D. B., and Boyer, C. D. 1993. Fine structure of amylopectin in relation to gelatinization and retrogradation behavior of maize starches from three wx-containing genotypes in two inbred lines. *Cereal Chem.* 70:81-89.
- Zeng, M., Morris, C. G., Batey, I. L., and Wrigley, C. W. 1997. Sources of variation for starch gelatinization, pasting, and gelation properties in wheat. *Cereal Chem.* 74:63-71.

[Received June 20, 2000. Accepted January 15, 2002.]