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Pasting and swelling properties of wheat flour and starch in relation to amylose content

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Abstract

The influence of the content of total amylose, free amylose and lipid-complexed amylose, and amylopectin chain length distribution, on swelling behavior and pasting properties of wheat (*Triticum aestivum* L.) flour and starch from varieties with increased amylose content was investigated. These wheat starches displayed pasting properties that featured decreasing peak, breakdown and final viscosities with increasing total amylose content. Swelling power of flour was found to be a useful predictive tool of amylose content and pasting characteristics of the wheat starches. Amylopectin chains with degree of polymerization greater than 36 were correlated with increasing peak, minimum and final viscosities of starch pastes. No significant correlations were found between amylopectin chain length distribution and swelling behavior of flours and starches. The results are discussed in relation to the principles underlying swelling tests and pasting behavior of wheat starches.

Keywords: Wheat starch; Pasting; Swelling; Amylose content; Amylopectin chain length distribution

1. Introduction

The major storage polysaccharide of higher plants is starch, which is deposited in partially crystalline granules that vary in morphology and supermolecular structure between and within plant species. Starch is a major constituent of the human diet and owes much of its functionality in foods to the characteristics of two constituent glucose polymers, amylose and amylopectin, and to the physical organization of these macromolecules into the granular structure (Annison & Topping, 1994; Paredes-Lopez, Bello-Perez, & Lopez, 1994). An important property of starch in relation to its functionality is its ability to absorb water, resulting in gelatinization and loss of granular organization. Numerous studies have indicated that relationships between amylose and amylopectin content and molecular structure, and water absorption and pasting properties of starches, are complex and vary considerably amongst starches from the main food cereal crops. Pasting behavior of starch is not only related to genotype, but is also influenced by environmental factors during crop growth (Dang & Copeland, 2004; Geera, Nelson, Souza, & Huber, 2006).

Starches with varying amylose content are of interest for food processing because of the potential to modify the texture and quality of the end-use products. Moreover, starches with increased amylose content are of nutritional interest because they contribute to slow digesting and resistant starch, which are associated with beneficial physiological effects (Hung, Maeda, & Morita, 2006; Regina et al., 2006). Manipulating amylose content by genetic modification to obtain starches differing in their pasting and other industrially relevant characteristics has been successful for some cereal crops such as corn and rice. However, the hexaploid nature of the wheat genome makes finding and combining mutations in genes encoding starch biosynthetic enzymes a challenging proposition (Morell & Myers, 2005; Regina et al., 2006). As an alternative approach, increasing amylose content should be achievable through

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traditional breeding and selection of agronomically well adapted varieties without genetic manipulation of enzymes involved in amylose and amylopectin synthesis. This approach requires the availability of high throughput screening tests for phenotyping.

Swelling tests are simple analyses that measure the uptake of water during the gelatinization of starch. In wheat starches, amylopectin is considered to contribute to water absorption, swelling and pasting of starch granules, whereas amylose and lipids tend to retard these processes (Tester & Morrison, 1990). An inverse correlation was found between amylose content and swelling power (Sasaki & Matsuki, 1998). No correlation was reported between starch lipid content and starch swelling, but a higher proportion of long chains (degree of polymerization (DP) > 35) in amylopectin was reported to contribute to increased starch swelling (Sasaki & Matsuki, 1998).

The Rapid Visco Analyser (RVA) is an effective instrument for measuring the viscous properties of cooked starch and flour, and for relating functionality to structural properties. These relationships are complex, with many reports in the literature describing differing effects depending on the experimental conditions (for example, see reviews by Jane et al., 1999; Lindeboom, Chang, & Tyler, 2004). Jane and Chen (1992) concluded that the amylopectin chain length distribution and amylose molecular size produce synergistic effects on the viscosity of starch pastes. Swelling power has been correlated with pasting characteristics of wheat starch as measured in the RVA (McCormick, Panozzo, & Hong, 1991; Yamamori, Kato, Yui, & Kawasaki, 2006).

In this study, we investigated the influence of starch properties, including total, free and lipid-complexed amylose contents, and amylopectin chain length distribution, on swelling behavior and pasting properties of flour and starch form wheat varieties with varying amylose content. The results are discussed in relation to the principles underlying swelling tests and pasting behavior of wheat starches.

2. Materials and methods

2.1. Materials

Thirty-eight wheat (*Triticum aestivum* L.) varieties were used in the study. Of these, 35 varieties were produced through the Value Added Wheat CRC Pty Ltd. breeding program. This breeding program is based on commercial Australian hard wheat cultivars of diverse genetic background. Samples used in the study were grown in Eastern Australia over three growing seasons. Two varieties were waxy wheat varieties provided by George Weston Technologies. Grain samples from the Value Added Wheat CRC Pty Ltd. breeding program were milled with a laboratory Quadrumat Junior Mill (C.W. Brabender Instrument Inc., South Hackensack, NJ) using the AACC 26-50 method (American Association of Cereal Chemists, 2000). The waxy wheat varieties were provided as flour. A commercial plain white wheat flour obtained from a local supermarket was also included in the analyses. Moisture content of the samples was determined by oven-drying using the AACC 44-15 A method (American Association of Cereal Chemists, 2000).

2.2. Extraction of starch

Starch was extracted from flour using a two-step procedure that involved enzymic removal of proteins and subsequent extraction of free lipids with ethanol based on the method described by Akerberg, Liljeberg, Granfeldt, Drews, and Bjorck (1998). Flour (5 g) was incubated at 37 °C for 1 h in 30 ml centrifuge tubes with 20 ml of 50 mM KCl solution adjusted to pH 1.5 with HCl and containing 1 g of pepsin (porcine gastric mucosa, P7000, Sigma Chemical Company, St. Louis, MO). The mixture was centrifuged at 3000*g* for 10 min, the supernatant was removed, and the pellet dispersed in 20 ml of 95% ethanol. After 10 min, the starch was collected by centrifugation at 3000*g* for 5 min and lipid extraction with ethanol was repeated. The pellet was dispersed in acetone, centrifuged at 3000*g* for 5 min and left to dry at room temperature.

2.3. Determination of amylose content

Total amylose (T-AM) and free amylose (F-AM) content were determined by iodine binding according to Chrastil (1987). A calibration curve was derived using a set of maize starches with zero to 75% amylose. Total and free amylose values were obtained from iodine binding with and without lipid extraction by ethanol, respectively, whereas lipid-complexed amylose (L-AM) was calculated as the difference between T-AM and F-AM.

2.4. Amylopectin chain length distribution

Amylopectin chain length distribution was determined in the laboratories of CSIRO Plant Industry, Canberra, by fluorophore-assisted carbohydrate electrophoresis using the Beckman P/ACE System 5010, as described by Morell, Samuel, and O'Shea (1998) and O'Shea, Samuel, Konik, and Morell (1998).

2.5. Swelling power

Swelling power was determined by measuring water uptake of starch granules using a 40-mg test according to the method of Konik-Rose et al. (2001). The swelling power test for both flour and starch was carried out in 0.1% $AgNO_3$ solution to inhibit α-amylase activity.

2.6. Starch pasting properties

Pasting properties of the starch and flour samples were analyzed using a Rapid Visco Analyser RVA-4 (Newport Scientific, Warriewood, Australia) according to the AACC

76-21 method (American Association of Cereal Chemists, 2000). Standard profile STD1 supplied with the instrument was used with 3.5 g of flour (corrected to 14% moisture content) or 3 g of starch with 25 ml of deionized water. Peak viscosity (PV), viscosity at trough (also known as minimum viscosity, MV), and final viscosity (FV) were recorded, and breakdown (BD, which is PV minus MV) and setback (SB, which is FV minus MV) were calculated using the Thermocline software provided with the instrument.

2.7. Particle size distribution

Particle size distribution was determined in the laboratories of Allied Mills, Sydney using a Mastersizer laser diffraction instrument in wet-cell mode. Prior to analysis, starch samples were dispersed in deionised water and filtered through a 63 μm sieve. Results are presented as the ratio of particles of diameter less than 10 μm (assumed to be mostly B granules) and particles with diameter between 10 and 35 μm (assumed to be mostly A granules).

2.8. Statistical analysis

All analyses were performed in duplicate. For each measured characteristic, mean, minimum and maximum values were calculated across the samples (Table 1). Linear regression analysis was performed using XLStat software (Addinsoft, NY) and Pearson's correlation coefficients were calculated between pairs of individual characteristics. Based on the Pearson's correlation coefficient and a number of data pairs, the significance of the correlation for each pair of characteristics was determined and a correlation matrix was formed (Table 2). Statistical significance was set at $P < 0.05$. The two waxy lines were not included in the statistical analysis so as not to distort the correlation coefficients by artificially increasing in the range of measured characteristics. Waxy lines were used in this study to serve as a distinctive reference point to the remaining samples in order to discuss the pasting properties of starches over a wide range of amylose content.

3. Results and discussion

3.1. Starch and flour properties

All of the flours had between 50% and 64% of particles with size distribution between 10 and 35 μm (presumed to be predominantly A granules). T-AM, F-AM and L-AM varied between 35% and 43%, 26% and 35% and 4% and 14%, respectively. Between 67% and 89% of the amylose was free, that is not complexed with lipids. Swelling power of flours ranged between 7.7 and 11.6, whereas starch swelling power varied between 5.4 and 6.9. No statistically significant correlation was found between the size distribution of starch granules and total or free amylose content (Table 1).

Table 1
Summary of the range of the properties of the starches and flours used in this study

	Minimum	Maximum	Mean
Free amylose (F-AM)	26.3	35.3	31.6
Total amylose (T-AM)	35.2	42.8	38.6
Lipid-complexed amylose (L-AM)	4.1	14.2	7.1
Swelling power of flour	7.7	11.6	9.4
Swelling power of starch	5.4	6.9	6.1
A granules (%)	50.3	64.4	57.6
Starch peak viscosity	171.8	258.5	212.8
Starch trough	137.0	196.3	158.2
Starch breakdown	34.5	90.9	54.6
Starch final viscosity	212.8	294.8	254.8
Starch setback	75.8	111.5	96.6
Flour peak viscosity	158.9	272.0	201.3
Flour trough	102.6	143.7	125.9
Flour breakdown	47.3	134.6	75.4
Flour final viscosity	202.0	262.3	239.5
Flour setback	95.9	134.0	113.6
DP 6–12	42.9	46.2	44.9
DP 13–24	47.3	50.2	48.7
DP 25–36	5.3	6.3	5.7
DP > 36	0.4	1.2	0.7

The percentage of A granules were calculated from the particle size distribution as particles with diameter between 10 and 35 μm. Peak viscosity (PV), minimum viscosity (MV), breakdown (BD), final viscosity (FV) and setback (SB) were obtained from RVA standard profiles. Amylopectin chain length distribution was divided into four groups according to the DP as described in the text.

The chain length distributions in all of the samples were classified into four fractions according to chain length. These were very short chains with DP 6–12, medium length chains with DP 13–24, long chains with DP 25–36, and very long chains with DP greater than 36. The ranges of the chain length distributions were 42–46% of very short chains, 47–50% of medium length chains, 5–6% of long chains and less than 2% of very long chains (Table 1).

The pasting behavior of the starches and flours as characterized by RVA profiles varied considerably. Peak viscosity of the starch pastes ranged from 172 to 259 Rapid Visco Analyser Units (RVUs), whereas for flour pastes the range was from 159 to 272 RVU (Table 1).

3.2. Effect of amylose content on starch and flour characteristics

A strong inverse correlation (significant at $P < 0.001$) was found between flour swelling power and T-AM ($r = -0.73$). For starch swelling power, the correlation with F-AM ($r = -0.48$, $P < 0.01$) was stronger than with T-AM ($r = -0.39$). Lipid-complexed amylose correlated positively with T-AM ($r = 0.68$) and negatively with F-AM ($r = -0.68$).

Several RVA parameters of the starch pastes correlated negatively with T-AM. These were peak viscosity ($r = -0.65$), final viscosity ($r = -0.45$), breakdown ($r = -0.74$) and setback ($r = -0.64$). Weaker but significant correlations were found between T-AM and peak

Table 2
Correlation matrix of the properties of starches and flours (based on Pearson's correlation coefficients)

Property	F-AM	T-AM	L-AM	Flour swelling	Starch swelling	A granules (%)	Starch PV	Starch MV	Starch BD	Starch FV
Free amylose (F-AM)	**1**	0.076	**−0.676**	−0.173	**−0.481**	−0.276	−0.237	**−0.435**	0.129	−0.272
Total amylose (T-AM)	0.076	**1**	**0.683**	**−0.729**	−0.394	0.036	**−0.645**	−0.218	**−0.736**	**−0.447**
Lipid-complexed amylose (L-AM)	**−0.676**	**0.683**	**1**	−0.414	0.066	0.227	−0.288	0.122	**−0.612**	−0.143
Swelling power of flour	−0.173	**−0.729**	−0.414	**1**	0.326	−0.191	**0.773**	**0.525**	**0.661**	**0.625**
Swelling power of starch	**−0.481**	−0.394	0.066	0.326	**1**	0.299	**0.443**	**0.426**	0.206	**0.430**
A granules (%)	−0.276	0.036	0.227	−0.191	0.299	**1**	−0.002	0.046	−0.053	−0.019
Starch peak viscosity (PV)	−0.237	**−0.645**	−0.288	**0.773**	**0.443**	−0.002	**1**	**0.749**	**0.697**	**0.915**
Starch trough (MV)	**−0.435**	−0.218	0.122	**0.525**	**0.426**	0.046	**0.749**	**1**	0.047	**0.911**
Starch breakdown (BD)	0.129	**−0.736**	**−0.612**	**0.661**	0.206	−0.053	**0.697**	0.047	**1**	0.393
Starch final viscosity (FV)	−0.272	**−0.447**	−0.143	**0.625**	**0.430**	−0.019	**0.915**	**0.911**	0.393	**1**
Starch setback (SB)	0.108	**−0.639**	**−0.533**	**0.564**	0.258	−0.118	**0.812**	0.390	**0.801**	**0.735**
Flour peak viscosity (PV)	**−0.492**	**−0.453**	0.042	**0.694**	**0.549**	0.160	**0.845**	**0.804**	0.404	**0.813**
Flour trough (MV)	**−0.502**	−0.096	0.300	0.401	**0.483**	0.240	**0.636**	**0.771**	0.124	**0.726**
Flour breakdown (BD)	**−0.436**	**−0.572**	−0.085	**0.760**	**0.522**	0.106	**0.853**	**0.734**	**0.492**	**0.768**
Flour final viscosity (FV)	−0.191	−0.120	0.111	0.306	0.293	0.120	**0.617**	**0.555**	0.330	**0.644**
Flour setback (SB)	0.388	−0.095	−0.239	0.005	−0.111	−0.104	0.294	-0.012	**0.456**	0.220
DP 6–12	−0.168	−0.331	−0.156	0.244	0.242	0.437	0.067	0.004	0.111	−0.051
DP 13–24	0.231	0.319	0.115	−0.341	−0.262	−0.447	−0.193	−0.203	−0.069	−0.131
DP 25–36	0.094	0.212	0.092	−0.173	−0.143	−0.307	−0.002	0.061	−0.084	0.142
DP > 36	−0.099	0.263	0.284	0.247	−0.111	−0.197	0.346	**0.617**	−0.207	0.505

Property	Starch SB	Flour PV	Flour MV	Flour BD	Flour FV	Flour SB	DP 6–12	DP 13–24	DP 25–36	DP > 36
Free amylose (F-AM)	0.108	**−0.492**	**−0.502**	**−0.436**	−0.191	0.388	−0.168	0.231	0.094	−0.099
Total amylose (T-AM)	**−0.639**	**−0.453**	−0.096	**−0.572**	−0.120	−0.095	−0.331	0.319	0.212	0.263
Lipid-complexed amylose (L-AM)	**−0.533**	0.042	0.300	−0.085	0.111	−0.239	−0.156	0.115	0.092	0.284
Swelling power of flour	**0.564**	**0.694**	0.401	**0.760**	0.306	0.005	0.244	−0.341	−0.173	0.247
Swelling power of starch	0.258	**0.549**	**0.483**	**0.522**	0.293	−0.111	0.242	−0.262	−0.143	−0.111
A granules (%)	−0.118	0.160	0.240	0.106	0.120	−0.104	0.437	−0.447	−0.307	−0.197
Starch peak viscosity (PV)	**0.812**	**0.845**	**0.636**	**0.853**	**0.617**	0.294	0.067	−0.193	−0.002	0.346
Starch trough (MV)	0.390	**0.804**	**0.771**	**0.734**	**0.555**	−0.012	0.004	−0.203	0.061	**0.617**
Starch breakdown (BD)	**0.801**	0.404	0.124	**0.492**	0.330	**0.456**	0.111	−0.069	−0.084	−0.207
Starch final viscosity (FV)	**0.735**	**0.813**	**0.726**	**0.768**	**0.644**	0.220	−0.051	−0.131	0.142	0.505
Starch setback (SB)	**1**	**0.494**	0.352	**0.508**	**0.526**	**0.513**	−0.167	0.094	0.284	0.046
Flour peak viscosity (PV)	**0.494**	**1**	**0.843**	**0.968**	**0.671**	0.109	0.063	−0.158	−0.085	0.399
Flour trough (MV)	0.352	**0.843**	**1**	**0.680**	**0.861**	0.253	0.045	−0.139	0.008	0.250
Flour breakdown (BD)	**0.508**	**0.968**	**0.680**	**1**	**0.511**	0.031	0.067	−0.159	−0.115	0.437
Flour final viscosity (FV)	**0.526**	**0.671**	**0.861**	**0.511**	**1**	**0.710**	−0.016	0.000	−0.002	0.094
Flour setback (SB)	**0.513**	0.109	0.253	0.031	**0.710**	**1**	−0.088	0.177	−0.014	−0.140
DP 6–12	−0.167	0.063	0.045	0.067	−0.016	−0.088	**1**	**−0.953**	**−0.823**	−0.300
DP 13–24	0.094	−0.158	−0.139	−0.159	0.000	0.177	**−0.953**	**1**	**0.662**	0.135
DP 25–36	0.284	−0.085	0.008	−0.115	−0.002	−0.014	**−0.823**	**0.662**	**1**	0.120
DP > 36	0.046	0.399	0.250	0.437	0.094	−0.140	−0.300	0.135	0.120	**1**

Values in bold indicate significant correlations at a significance level $\alpha = 0.05$. The percentage of A granules were calculated from the particle size distribution as particles with diameter between 10 and 35 μm. Peak viscosity (PV), minimum viscosity (MV), breakdown (BD), final viscosity (FV) and setback (SB) were obtained from RVA standard profiles. Amylopectin chain length distribution was divided into four groups according to the DP, as described in the text.

($r = -0.45$) and breakdown ($r = -0.57$) viscosities of flour pastes. In contrast to the starches, there were no apparent correlations between T-AM and final viscosity, minimal viscosity and setback values of the flour pastes, which indicates that proteins, lipids and non-starch polysaccharides make important contributions to the viscosity of the flour pastes. These flour constituents would have been largely removed during the isolation of the starch.

When RVA characteristics were compared between flour and starch samples, the following correlation coefficients were found: peak viscosity $r = 0.85$, final viscosity $r = 0.64$, viscosity at trough $r = 0.77$, breakdown $r = 0.49$ and setback $r = 0.51$. The correlations between the derived RVA characteristics of breakdown and setback values were weaker (Table 2).

For the samples analyzed in this study with amylose content between 35% and 43%, peak, breakdown and final viscosity decreased with increasing amylose content. These findings are in agreement with a limited number of reports on pasting characteristics of wheat and barley starches with increased apparent amylose content (Fujita, Domon, & Doi, 1999; Yamamori et al., 2006). In order to enhance our understanding of how varying amylose content affects pasting properties of starches, RVA profiles of a waxy (2% T-AM), normal (34% T-AM) and high-amylose (43% T-AM) wheat starch, selected from the set of starches used in this study, are shown in Fig. 1. Waxy wheat is characterized by high peak viscosity and low final viscosity compared to starches with normal amylose content. Starches with increased amylose content display peak viscosity lower than that of waxy and normal starches, and final viscosity higher than waxy starches and lower than normal starches. These trends in viscosity changes as a function of amylose content agreed with published data based on native and mutant wheat and barley starches with varying amylose content. Starches with amylose content below about 30% generally display decreasing RVA peak viscosity and breakdown values with increasing amylose content, whereas final viscosity tends to increase with increasing amylose content (Yamamori & Quynh, 2000; Yanagisawa, Kiribuchi-Otobe, & Fujita, 2004; Yanagisawa, Domon, Fujita, Kiribuchi-Otobe, & Takayama, 2006; Zeng, Morris, Batey, & Wrigley, 1997). Combining published data and correlations found in this study, a different pattern seems to emerge for peak and final viscosities. Peak viscosity of starch pastes decreases with increasing amylose content along the whole range of amylose content from waxy to high amylose varieties. Increasing amylose content of starch has been proposed to decrease the melting temperature of granules by disrupting crystallinity in the granular structure (Yuryev et al., 2004), which could affect on the peak viscosity measured with RVA. In contrast, final viscosity increases with increasing amylose content up to a threshold amylose-to-amylopectin ratio, above which final viscosity decreases slightly.

Viscoelastic characteristics of starch pastes and gels arise from the chemical structure of amylose and amylopectin and the way these two molecules interact in a hydrated environment. When a combination of heat and shear is applied to starch granules in water, starch granules gelatinize and form a paste in which the starch components are dispersed in the aqueous phase and amylose takes on a random coil configuration. On cooling the starch paste below the coil-to-helix transition temperature, amylose polymers start to aggregate through hydrogen bonding, forming junction zones and creating a gel network. With time, outer branches of amylopectin align and simple junction points may develop into more extensively ordered regions by retrogradation, leading to a crystalline order. Factors such as concentration of starch, degree of polymerisation and branching architecture of amylopectin and amylose, the ratio of these two components, and the

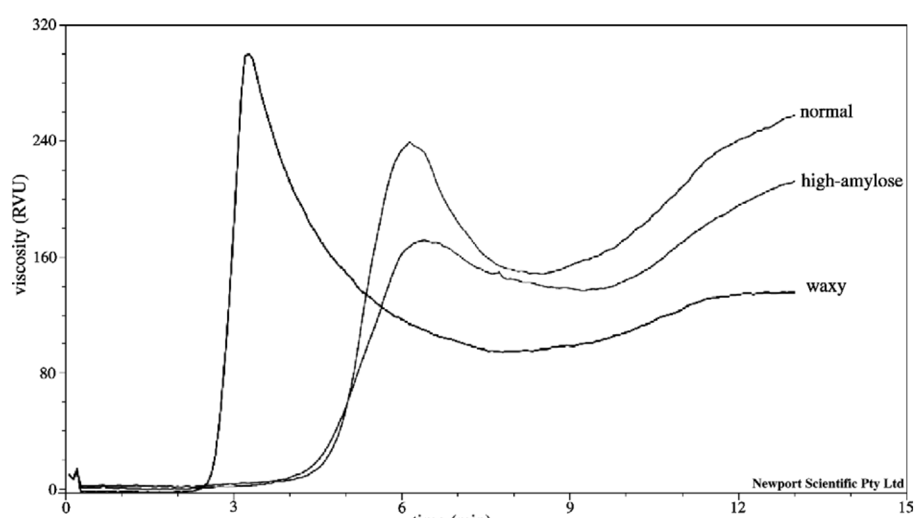

Fig. 1. Rapid Visco Analyser profiles of waxy (2% total amylose content, T-AM), normal (34% T-AM) and high-amylose (43% T-AM) wheat starches. Standard STD1 profiles available at Thermocline software supplied with the instrument.

presence of small molecules that can complex with amylose, such as lipids, influence pasting behavior of gels (Tester & Morrison, 1990; Vandeputte, Derycke, Geeroms, & Delcour, 2003). Waxy starches, consisting mainly of amylopectin, produce highly gelatinous dispersions when cooked and form soft, runny gels. In contrast, amylose contributes to gel strength and firmness and reduces stickiness of starch gels. In pure amylose gels, the interaction between molecules involves the formation of interchain B-type aggregated double helices (Gidley, 1989; Richardson, Kidman, Langton, & Hermansson, 2004). Gels prepared in the RVA from wheat starch containing 25% amylose were proposed to contain amylopectin molecules entrapped in a matrix of interacting amylose molecules (Tang & Copeland, 2007).

The extent of aggregation of amylose chains in starch gels influences the dimensions of the starch network in the gel. In starches with low to medium amylose content, the amylopectin molecules may hamper aggregation of free amylose chains. As the proportion of amylose in the starch increases, the final gel viscosity is observed to increase because more free amylose is available for network formation. This trend continues until the proportion of amylose is such that amylopectin no longer hampers the aggregation of amylose. Further increase in amylose would produce a gel, in which there is a higher degree of amylose aggregation with more closely spaced junction zones and a tighter network, which could result in a decrease in gel viscosity.

No significant correlation was found between chain length distribution of amylopectin and swelling power of starch or flour, nor with free or total amylose content. However, the proportion of very long amylopectin chains (DP > 36) was correlated positively with RVA final viscosity of starch paste ($r = 0.51$) and starch viscosity at trough ($r = 0.62$), and to lesser extent, the peak viscosity of starch paste ($r = 0.34$). The ratio of A granules calculated from the particle size distribution analysis correlated positively with the proportion of chains with DP 6–12, and negatively with the proportion of chains with DP 13–24. These findings support the conclusion of Ao and Jane (2007) that composition and chemical structure of the starch are major factors that determine the pasting properties of the starch. As the starches used in this study were not fractioned into A and B granules, the results do not allow us to infer whether the variation in the chain length distribution is related to the effect of granule size distribution or other varietal differences among the starches.

3.3. Swelling characteristics

The swelling power test used in this study measures the uptake of water by largely undisrupted granules in flour or starch at elevated temperature in the absence of shear forces. In comparison, pasting properties in the RVA are measured with the application of heat and shear to disrupt the granules. Statistically significant positive correlations were found between flour swelling power and RVA characteristics of flour and starch pastes (Table 2). The correlation coefficients between swelling power of flour and peak, minimum and final viscosities of starch pastes were 0.77, 0.53 and 0.63, respectively. RVA characteristics of flour pastes were correlated less significantly with swelling power of flour, the strongest correlation being with peak viscosity ($r = 0.69$). Swelling power of starches was also correlated positively with RVA characteristics of flour and starch pastes but the correlations were less strong than for the corresponding values for flour swelling (Table 2).

The method of extraction of starch from flour used in this study was designed to remove lipids and protein from the surface of starch granules. The isolated starch granules may also have been freed to some extent of water-absorbing non-starch polysaccharides, such as pentosans. The extraction procedure seemed to affect the swelling of starch granules and therefore starch swelling power was less indicative of amylose content than flour swelling. On the other

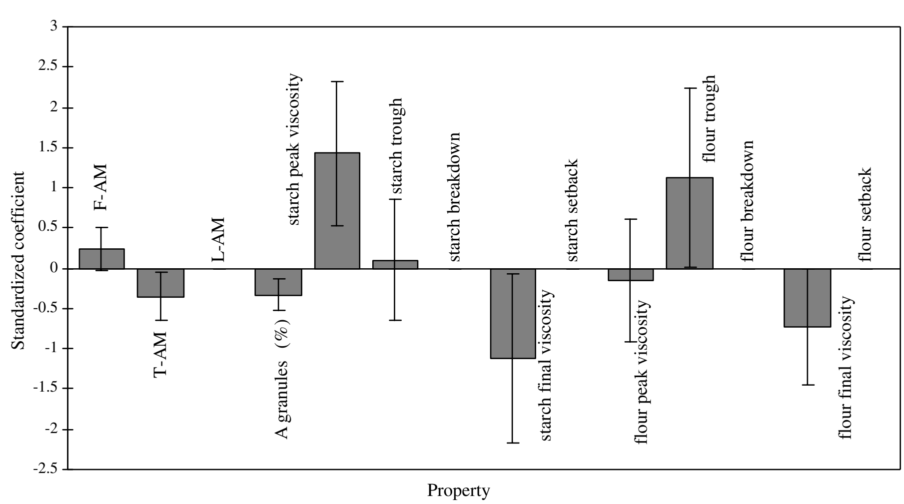

Fig. 2. Multivariate linear regression standardized coefficient of the predictive model of swelling power of flour (95% confidence interval).

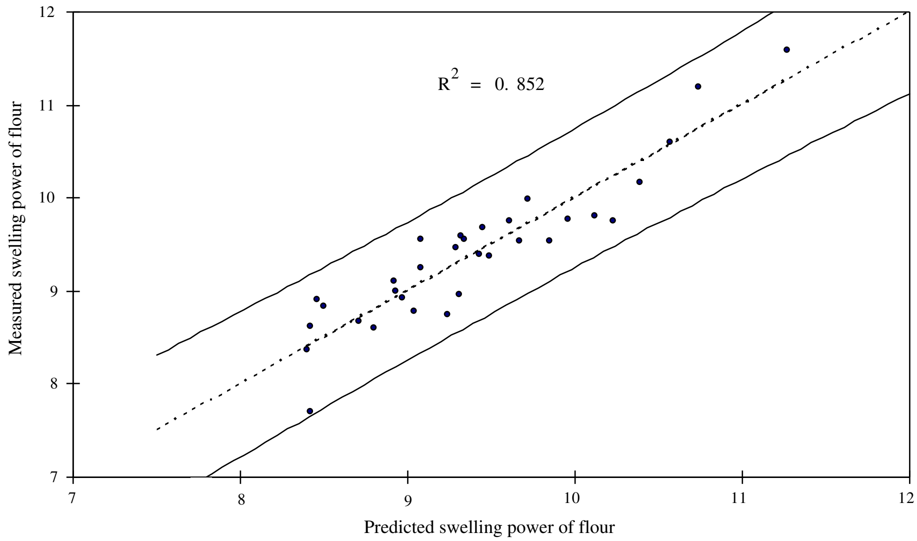

Fig. 3. Multivariate linear regression analysis: predicted vs. measured values of the swelling power of flour (95% confidence interval).

hand, removal of non-starch components of flour provided information about pasting properties of starch free of the effects of proteins and lipids. These studies led to the conclusion that the most significant correlations were between T-AM content, swelling power of flour and RVA characteristics of starch pastes. Therefore, we conclude that the amylose-to-amylopectin ratio of starch is a major factor that influences both swelling and pasting characteristics of starches used in this study. As a result, swelling power of flour can be used as an indicator of amylose content and pasting properties of starch. This approach provides simplicity, speed and high throughput because it does not require extraction of starch from flour.

Multivariate linear regression analysis was performed to determine the extent to which flour swelling power could be predicted from other properties. L-AM, starch breakdown, starch setback, flour breakdown and flour setback were not included in the multivariate analysis due to the multicolinearity of these properties with other characteristics. A model predicting the swelling power of flour was developed with the coefficient of determination between experimental and predicted data of $R^2 = 0.85$ (Figs. 2 and 3). In order to measure the contribution of individual variables without the regression coefficients being dependent on the underlying scale of measurements, standardized regression coefficients were calculated. All variables were standardized by subtracting the respective mean and dividing by its standard deviation. The standardized regression coefficients, then, represent the change in response to a change of one standard deviation in a predictor. The larger the standardized coefficient, the greater is the influence of that parameter in the predictive model. Standardized coefficients for individual explanatory characteristics showed that T-AM content, size distribution of starch granules, starch peak and final viscosity and flour trough and final viscosity had statistically significant predictive capability in the presence of the other variables, although each alone may not correlate with flour swelling power at significance level of $P < 0.05$.

4. Conclusions

This study has shown that swelling power of flour is a simple test that reflects a number of industrially relevant characteristics of starch, and therefore can be used as an indicator of amylose content and pasting properties of starch. Amylose content and amylopectin chain length distribution had a substantial impact on the swelling and pasting properties of the starches. The size distribution of starch granules did not correlate with the swelling power of flour but it improved predictive capability of the multivariate linear regression model predicting flour swelling power from other studied characteristics.

In contrast to waxy starches and starches with normal amylose content, wheat starches with increased amylose content displayed characteristic pasting properties that featured decreasing peak, breakdown and final viscosities with increasing T-AM contents. We propose the existence of a threshold value in amylose content, above which final viscosity of starch paste does not further increase with increasing amylose content. Long amylopectin chains (DP > 36) were found to contribute to the increase of peak, minimum and final viscosities of starch pastes. This may be due to the architecture of amylopectin molecules preventing aggregation of these very long chains, so that they retain their ability to form intermolecular links with other gel components.

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