

# Effect of Amylose Content on Gelatinization, Retrogradation, and Pasting Properties of Starches from Waxy and Nonwaxy Wheat and Their F1 Seeds

Tomoko Sasaki,<sup>1,2</sup> Takeshi Yasui,<sup>1</sup> and Junko Matsuki<sup>1</sup>

## ABSTRACT

Cereal Chem. 77(1):58–63

We studied the effect of amylose content on the gelatinization, retrogradation, and pasting properties of starch using wheat starches differing in amylose content. Starches were isolated from waxy and nonwaxy wheat and reciprocal F1 seeds by crossing waxy and nonwaxy wheat. Mixing waxy and nonwaxy wheat starch produced a mixed starch with the same amylose content as F1 seeds for comparison. The amylose content of F1 seeds ranged between waxy and nonwaxy wheat. Nonwaxy-waxy wheat had a higher amylose content than waxy-nonwaxy wheat. Endothermic enthalpy and final gelatinization temperature measured by differential scanning calorimetry correlated negatively with amylose con-

tent. Gelatinization onset and peak temperature clearly differed between F1 and mixed starches with the same amylose content as F1 starches. Enthalpy for melting recrystallized starches correlated negatively with amylose content. Rapid Visco Analyser measurement showed that F1 starches had a higher peak viscosity than waxy and nonwaxy wheat starches. Mixed starches showed characteristic profiles with two low peaks. Setback and final viscosity correlated highly with amylose content. Some of gelatinization and pasting properties differed between F1 starches and mixed starches.

Most starches consist of two polysaccharide molecules: amylose and amylopectin. Amylose is a predominantly linear molecule linked by  $\alpha$ -1,4 bonds, and amylopectin is a highly branched polymer with branch points linked by  $\alpha$ -1,6 bonds. The ratio of amylose and amylopectin affects the physicochemical properties of starch. Wheat flour with a lower amylose content provides a good texture to white salted noodles (Oda et al 1980; Toyokawa et al 1989a,b). When heated with excess water, starch swells and is gelatinized. After cooling, gelatinized starch starts to reassociate in an ordered structure (Atwell et al 1988) and retrogradation occurs. The ratio of amylose and amylopectin was thought to affect both gelatinization and retrogradation of starch from various botanical sources (Czuchajowska et al 1998, Fredriksson et al 1998, Yuryev et al 1998).

Because some variation of amylose content occurs in wheat starch as compared with other plant sources, including maize, it was difficult to clarify the relationship between amylose content and wheat starch properties. Several waxy wheats lacking waxy proteins Wx-A1, Wx-B1, and Wx-D1 were recently produced by crossbreeding or mutation (Nakamura et al 1995, Yamamori et al 1995, Yasui et al 1997, Kiribuchi-Otobe et al 1997). Waxy wheat was used to produce starch with differing amylose content not found in existing cultivars by reciprocal crossing between waxy and nonwaxy wheat. We studied the variation in gelatinization, retrogradation, and pasting properties of wheat starch differing in amylose content. Mixed starch with the same amylose content as F1 starches was prepared and gelatinization, retrogradation, and pasting properties were compared with those of F1 starches.

## MATERIALS AND METHODS

### Samples

Six waxy wheat lines (*Triticum aestivum* L.), Wx-1, Wx-2, Wx-3, Wx-4, K107Wx1, K107Wx2, and two nonwaxy parent wheats, Kanto 107 and Saikai 173, were grown sheltered from rainfall at the National Agriculture Research Center (NARC) in 1996 and 1997. Wx-1 and Wx-2 are derived from a cross between the Wx-D1 protein-deficient cultivar Bui-Huo and Wx-A1 and Wx-B1 protein-deficient cultivar Saikai 173; Wx-3 and Wx-4 are derived from a cross between Bui-Huo and Wx-A1 and Wx-B1 protein-

deficient cultivar Kanto 107. K107Wx1 and K107Wx2 are mutants of Kanto 107 with ethyl methanesulphonate. Reciprocal crossing between waxy wheat and their nonwaxy parent yielded two types of F1 seeds: waxy-nonwaxy and nonwaxy-waxy.

Starch was isolated from waxy and nonwaxy wheat lines and F1 seeds after degermination by the method of Sulaiman and Morrison (1990) and then freeze-dried. Based on the measured amylose content of F1 seeds, mixed starches were produced by blending waxy and nonwaxy starch at different ratios determined to equal the amylose content of F1 seeds.

### Amylose Content and $\alpha$ -Amylase Activity

Amylose content of starch was determined by the method of Gibson et al (1997) using an amylopectin-amylose assay kit (Megazyme).  $\alpha$ -Amylase activity in isolated starch was determined by the method of McCleary and Sheehan (1987) using an  $\alpha$ -amylase assay kit (Megazyme); one unit of activity was defined as a Ceralpha unit.

### Differential Scanning Calorimetry Measurement

Differential scanning calorimetry (DSC) measurement was conducted using a SSC 5200 with a DSC 120U (Seiko Electronics, Tokyo, Japan) calibrated with indium. For gelatinization studies, 15.0 mg of starch was weighed into silver pans with 35  $\mu$ L of distilled water. After sealing, pans were scanned at 1°C/min from 40 to 120°C (Kohyama and Nishinari 1991). After gelatinization, pans were immediately cooled and stored at 5°C for four weeks and rescanned at 1°C/min from 5 to 120°C for retrogradation studies.

### Starch Pasting Properties

The pasting properties of isolated starch were measured with a Rapid Visco Analyser (RVA, Newport Scientific Pty. Ltd., Warriewood, Australia). Starch, 1.5 g (db), was dispersed in 12.5 mL of distilled water. The suspension was heated at 5°C/min from 34 to 94°C, held at 94°C for 5 min, and cooled at 5°C/min to 34°C and held at 34°C for 10 min.

### Statistical Analysis

All samples were analyzed in duplicate. A general linear model (SAS Institute, Cary, NC) was used to analyze data. Analysis of variance was conducted using Tukey's Student range test at 5%.

## RESULTS AND DISCUSSION

### Amylose Content

The amylose content of waxy wheat lines was 0.8–0.9% and that of nonwaxy wheat 18.3–20.3%, whereas the amylose content

<sup>1</sup> National Agriculture Research Center, MAFF, 3-1-1 Kannondai, Tsukuba, Ibaraki 305-8666, Japan.

<sup>2</sup> Corresponding author. E-mail: tomokos@narc.affrc.go.jp Fax: +81-298-38-8837. Phone: +81-298-38-8868.

of F1 seeds was 7.2–7.7% (waxy-nonwaxy) and 13.5–15.3% (nonwaxy-waxy) (Table I). F1 seed starch had an amylose content not found in existing cultivars. It ranged between that of waxy and nonwaxy wheat. The variation in amylose content was narrow within the same type of starch. None of the six waxy wheats had waxy protein (Nakamura et al 1995, Yamamori et al 1995, Yasui et al 1997), so all F1 seeds were derived from the cross between Wx-A1, Wx-B1, and Wx-D1 protein-deficient cultivars and Wx-A1 and Wx-B1 protein-deficient cultivars. The difference in amylose content between waxy-nonwaxy and nonwaxy-waxy starch in F1 seeds suggests gene dosage effects on amylose content by double fertilization (Table II).

Isolated starch had amylase activity ranging from 0.000 to 0.003 U/g. No sample showed high amylase activity.

### Gelatinization and Retrogradation Properties

Table I shows gelatinization properties determined using DSC. DSC parameters recorded were onset ( $T_o$ ), peak ( $T_p$ ), final ( $T_c$ ) gelatinization temperature, gelatinization enthalpy ( $\Delta H$ ), and melting of the amylose-lipid complex ( $\Delta H_{cx}$ ). Gelatinization temperatures and enthalpies associated with gelatinization endotherms varied between starches.  $T_o$  was 46.0–52.4°C,  $T_p$  was 52.2–57.6°C,  $T_c$  was 58.2–66.1°C,  $\Delta H$  was 14.8–17.9 J/g, and  $\Delta H_{cx}$  0–2.3 J/g. Final gelatinization temperature and gelatinization enthalpy correlated negatively with amylose content in all samples (Fig. 1). No significant correlations were found between amylose content and onset and peak gelatinization temperature (Fig. 2). F1 and mixed starches with the same amylose content as F1 starches showed clearly different gelatinization onset and peak temperature. Mixed starches showed lower onset and peak temperatures than F1 starches with the same amylose content. The gelatinization temperature range ( $T_c - T_o$ ) of F1 starch was 9.4–11.0°C, whereas that of mixed starch was 11.5–16.2°C. Curves of mixed starch were broader than those of F1 starch (Fig. 3). Waxy wheat starch had higher gelatinization temperatures and enthalpy (Yasui et al 1996, Fujita et al 1998), and waxy barley starch showed higher gelatinization temperature and enthalpy than normal barley starch (Gudmundsson et al 1992). The enthalpy of gelatinization reflects the loss of molecular order

(Cooke et al 1992), and gelatinization temperature is considered a parameter of crystallite perfection (Tester and Morrison 1990). Because amylopectin plays a major role in starch granule crystallinity, the presence of amylose lowers the melting temperature of crystalline regions and the energy for starting gelatinization (Flipse et al 1996). More energy is needed to initiate melting in the absence of amylose-rich amorphous regions (Krueger et al 1987). This correlation indicates that starch with higher amylose content has more amorphous region and less crystalline, lowering gelatinization temperature and endothermic enthalpy.

The differences in gelatinization properties between F1 and mixed starches are due to varied homogeneity. Fredriksson (1998) reported that a wide temperature range implied a large amount of crystals with varied stability. The lack of homogeneity of ordered inside structures caused a broader gelatinization range (Yuan et al 1993). We found the gelatinization range of mixed starches broader than F1 starch with the same amylose content, indicating that the crystallite stability of mixed starch differs from that of F1 starch with the same amylose content. Starch granule crystallites that required less energy to melt would melt first (Obanni et al 1997), so nonwaxy starch with higher amylose content would start to melt first and waxy starch melted successively in mixed samples, which results in lowering gelatinization onset and peak temperature of mixed starches. The final gelatinization temperature of mixed starches was similar to that of F1 starches with the same amylose content, suggesting that varied homogeneity does not affect  $T_c$  in these samples.

TABLE II  
Dosage Effect on Amylose Content in Endosperm

Sample	Functional Wx-D1 Allele Dosage in Endosperm	Amylose Content (%)
Nonwaxy	3	18.3–20.3
Nonwaxy-waxy	2	13.5–15.3
Waxy-nonwaxy	1	7.2–7.7
Waxy	0	0.8–0.9

TABLE I  
Amylose Content and Thermal Analysis of Starch Gelatinization<sup>a</sup>

Sample Starch	Amylose (%)	$T_o$ (°C)	$T_p$ (°C)	$T_c$ (°C)	$\Delta H$ (J/g)	$\Delta H_{cx}$ (J/g)
Waxy						
K107Wx1, K107Wx2 <sup>b</sup>	0.9db <sup>c</sup>	48.1d–f	54.7d–h	63.5a–d	17.1a–c	...
Wx-1, Wx-2	0.8d	51.6ab	57.0ab	65.3ab	17.9a	...
Wx-3, Wx-4	0.9d	51.1a–c	56.8a–c	66.1a	17.5a	...
F1 (waxy-nonwaxy)						
K107Wx1, K107Wx2/Kanto 107	7.2c	51.4ab	56.3a–e	61.2b–g	16.0c–e	1.1b–d
Wx-1, Wx-2/Saikai 173	7.5c	52.4a	57.6a	63.4a–e	16.0c–e	1.0c–e
Wx-3, Wx-4/Kanto 107	7.7c	51.8a	56.4a–d	61.2b–g	16.1c–e	1.2bc
F1 (nonwaxy-waxy)						
Kanto 107/K107Wx1, K107Wx2	13.7b	50.3a–d	55.1c–g	59.7d–g	15.3de	2.2a
Saikai 173/Wx-1, Wx-2	15.3b	51.4ab	56.6a–c	61.2b–g	15.7de	2.3a
Kanto 107/Wx-3, Wx-4	13.5b	50.3a–d	55.5b–f	60.1c–g	15.3de	2.1a
Nonwaxy						
Kanto 107	18.3a	48.1d–f	53.6g–k	58.2f	14.8e	2.3a
Saikai 173	20.3a	49.3b–e	54.4f–i	58.8e–g	14.8e	2.2a
Mixed (waxy>nonwaxy)						
K107Wx1, K107Wx2>Kanto 107	7.2	46.1f	52.4jk	60.0c–g	15.6de	0.5e
Wx-1, Wx-2>Saikai 173	7.5	48.2d–f	53.9f–j	64.4a–c	16.3cd	0.5e
Wx-3, Wx-4>Kanto 107	7.7	46.7f	53.1i–h	62.5a–f	15.7de	0.6de
Mixed (nonwaxy>waxy)						
Kanto 107>K107Wx1, K107Wx2	13.7	46.0f	52.2k	57.8g	14.9e	1.5bc
Saikai 173>Wx-1, Wx-2	15.3	47.8ef	53.3h–k	59.3d–g	15.0de	1.5b
Kanto 107>Wx-3, Wx-4	13.5	46.6f	52.9i–k	59.1d–g	15.2de	1.5bc

<sup>a</sup>  $T_o$  (°C)  $T_p$  (°C)  $T_c$  (°C),  $\Delta H$  (J/g) and  $\Delta H_{cx}$  = onset, peak, and final gelatinization temperature, gelatinization enthalpy, and enthalpy of melting amylose-lipid complex (J/g of dry matter).

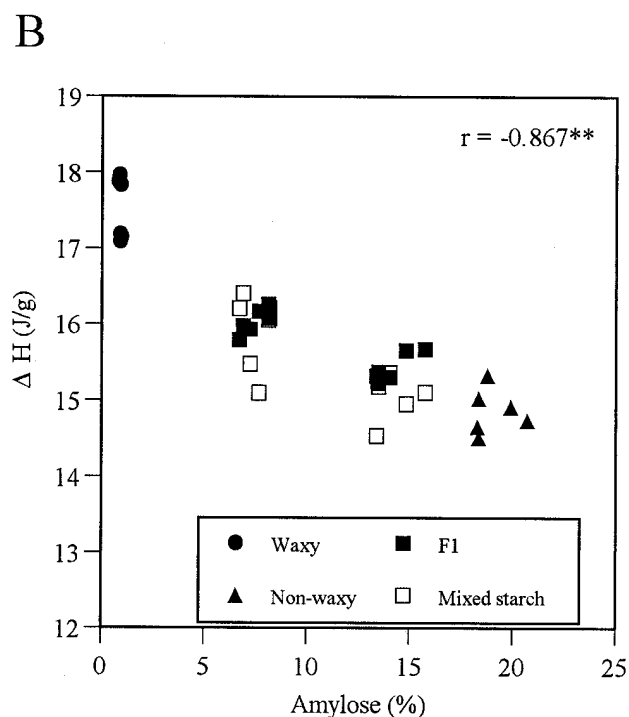
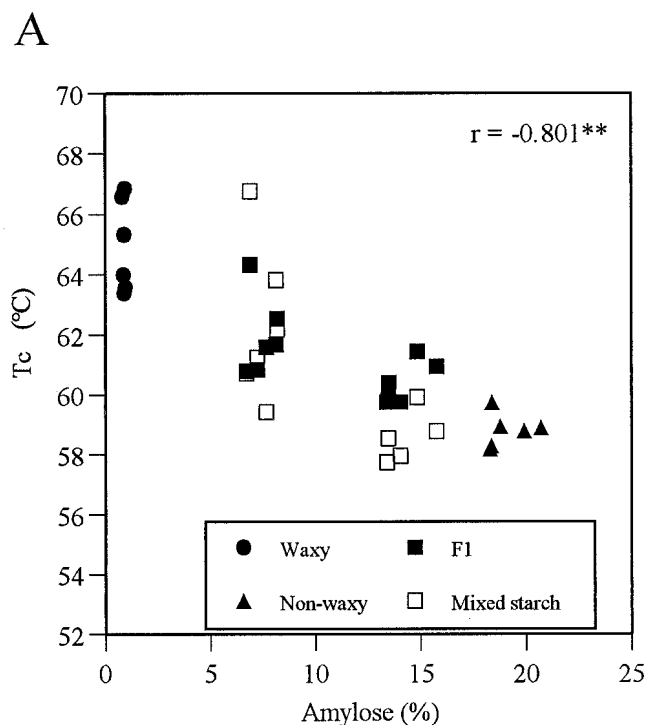
<sup>b</sup> Average of two waxy wheat types using the same parental materials and production. K107Wx1 and K107Wx2 are mutants of Kanto 107, Wx-1 and Wx2 are derived from crossbreeding between Bui-Huo and Saikai 173, and Wx-3 and Wx-4 are derived from crossbreeding between Bai-Huo and Kanto 107.

<sup>c</sup> Values with the same letter in the same column do not differ significantly at  $P < 0.05$ .

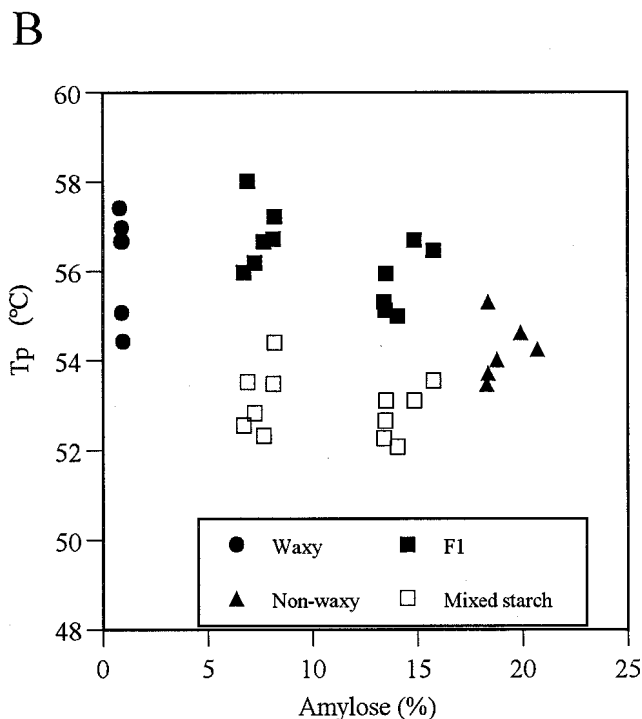
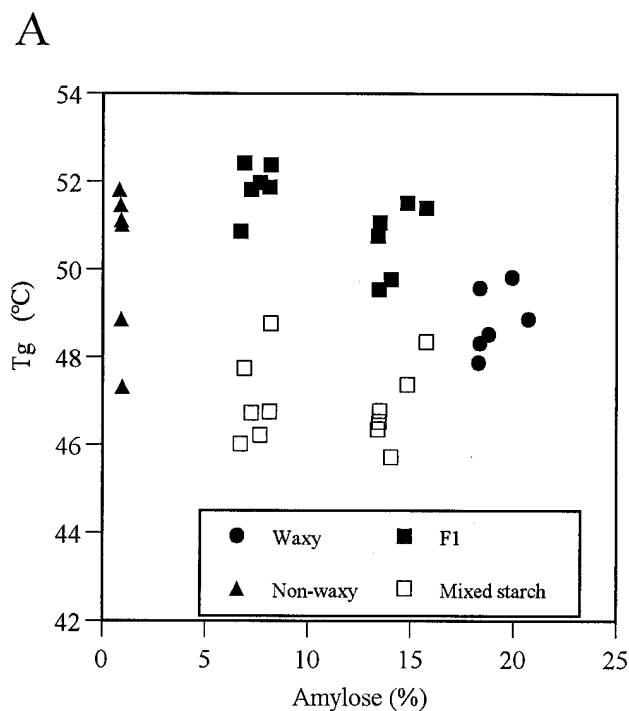
Another endothermic peak was observed at  $\approx 100^\circ\text{C}$  in nonwaxy, F1, and mixed starches, and no corresponding peak was found in waxy wheat starch. This peak is thought to correspond to transition of the amylose-lipid complex (Eliasson 1994). Endothermic enthalpy due to the melting of amylose-lipid complexes correlated significantly with amylose content ( $r = 0.877$ ) as found elsewhere (Wootton et al 1998).

Table III shows gelatinization temperature and enthalpy in retrograded starches. Retrograded starches showed lower gelatinization

temperature and enthalpy than raw starches, so they have weaker starch crystallinity. The enthalpy for melting recrystallized starches correlated negatively with amylose content (Fig. 4), meaning the starch with more amylopectin recrystallized to a greater degree after four weeks of storage at  $5^\circ\text{C}$ . No significant correlation was observed between the gelatinization temperature of retrograded starch and amylose content. Miles et al (1985) reported that the amylose component in starch gels retrogrades rapidly, and the crystallization of amylose reached a limit after two days, whereas



**Fig. 1.** Negative correlation of amylose content with gelatinization properties of starch. **A**, final gelatinization temperature ( $T_c$ ); **B**, enthalpy ( $\Delta H$ ).



**Fig. 2.** Relationship between amylose content and gelatinization temperature. **A**, onset temperature ( $T_o$ ); **B**, peak temperature ( $T_p$ ).

the amylopectin component recrystallizes slowly over time. After a few days of storage, the amylopectin is highly crystallized, and long-term changes in crystallization are mainly associated with the amylopectin fraction (Gudmundsson et al 1992). Because starches with higher amylopectin tend to recrystallize more during a longer storage, higher energy is needed to melt the reformed crystallite. No difference in retrogradation properties was found between F1 and mixed starch, suggesting that the difference in homogeneity between F1 and mixed starch does not affect the recrystallinity of gelatinized starch. Amylose content predominantly affected retrogradation properties in these samples.

### Pasting Properties

RVA profiles varied with the type of starch. The average peak viscosities were 151.4 RVU for waxy starch, 180.2 RVU for waxy-nonwaxy, 178.5 RVU for nonwaxy-waxy, and 156.9 RVU for nonwaxy. F1 starch had higher peak viscosity than nonwaxy wheat starch (Fig. 5), supporting the idea that lower amylose content is associated with higher peak viscosity. Reduced amylose content relates to greater swelling. Greater swelling reduces the quantity of free water and is associated with higher pasting viscosity (Ming et al 1997). In this study, waxy starch showed a lower peak viscosity than F1 starch and a very sharp increase in paste viscosity at lower temperature (Fig. 5). Waxy starch had an amylase activity ranging from 0.000 to 0.003 U/g, similar to that of other starches. Leoup et al (1991) reported that a minimum amylose-to-amylopectin ratio of 0.43 was needed to maintain the gel network during heating in water. At lower amylose content, the structure of starch gel is easily disrupted by heating. Amylose suppresses swelling and maintains the integrity of swollen starch granules (Hermansson et al 1996). Because starch swelling is mainly a property of amylopectin (Tester and Morrison 1990), waxy starch swells rapidly and swollen granules degrade at lower temperature, indicating that waxy starch rapidly develops viscosity but cannot maintain the stability of paste viscosity. For F1 starches, a clearly different step in increasing viscosity was found between nonwaxy-waxy and waxy-nonwaxy starches. Nonwaxy-waxy starch showed a profile similar in increasing viscosity to that of a nonwaxy starch. Waxy-nonwaxy starch, however, showed a sharp increase in viscosity at lower temperature, similar to the profile of waxy starch. This difference would reflect amylose content.

Mixed starch showed characteristic RVA profiles with two low peaks (Fig. 6). The average of the first peak viscosity was 109.8 RVU (waxy>nonwaxy) and 60.3 RVU (nonwaxy>waxy), and that of the second peak viscosity was 89.1 RVU (waxy>nonwaxy) and 112.9 RVU (nonwaxy>waxy). The peak viscosity of mixed starches was much lower than that of waxy and nonwaxy wheat and their F1 starch. In mixed starch including more waxy starch, the first peak was higher than the second, and in mixed starch including more nonwaxy starch, the second peak was higher. The two peaks indicate that waxy starch in the mixed sample started to collapse before nonwaxy starch reached the peak viscosity. As waxy starch granules broke down, nonwaxy starch granules developed a viscosity. The difference in pasting properties between waxy and non-

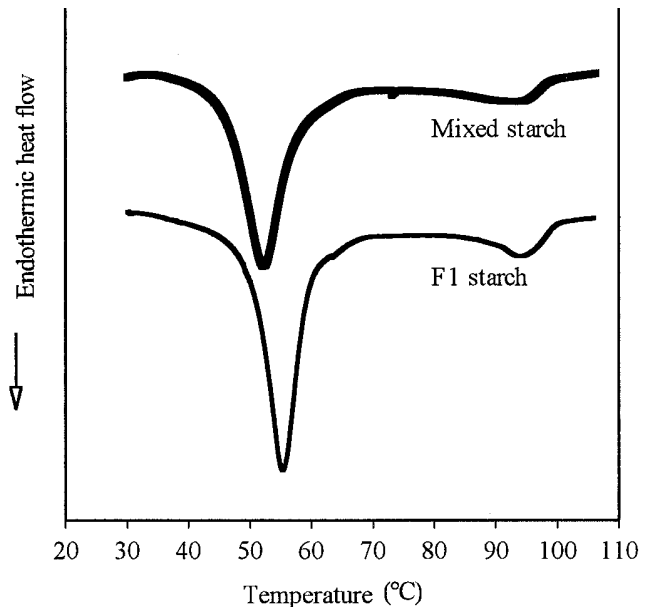


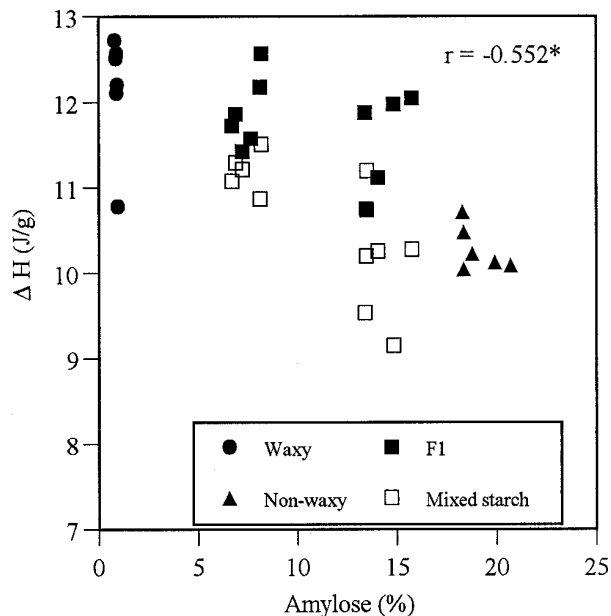
Fig. 3. Differential scanning calorimetry profiles of F1 starch from a cross between Kanto 107 and K107Wx1, and mixed starch with the same amylose content as F1 starch.

TABLE III  
Thermal Analysis of Retrogradation for Starches Stored at 5°C for Four Weeks<sup>a</sup>

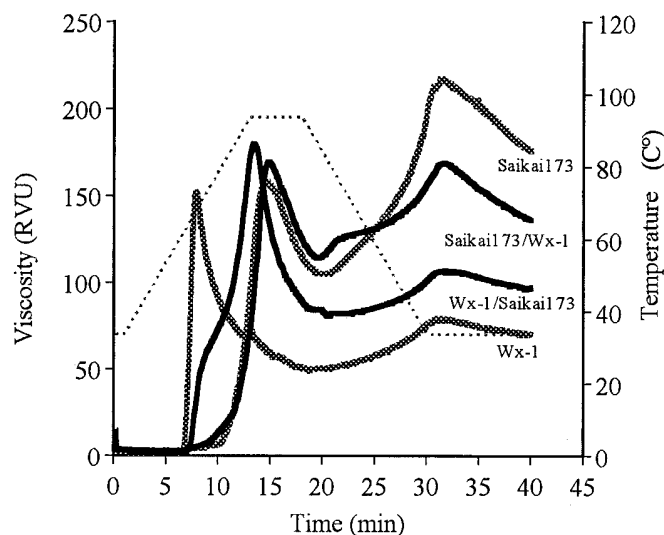
Sample Starch	$T_o$ (°C)	$T_p$ (°C)	$T_c$ (°C)	$\Delta H$ (J/g)
<b>Waxy</b>				
K107Wx1, K107Wx2	19.9 <sup>ab</sup>	33.7 <sup>ab</sup>	50.6 <sup>b</sup>	11.4 <sup>a-d</sup>
Wx-1, Wx-2	20.5 <sup>a</sup>	33.8 <sup>ab</sup>	51.8 <sup>a</sup>	12.6 <sup>a</sup>
Wx-3, Wx-4	20.1 <sup>a</sup>	33.1 <sup>ab</sup>	50.4 <sup>b</sup>	12.4 <sup>a</sup>
<b>F1 (waxy-nonwaxy)</b>				
K107Wx1, K107Wx2/Kanto 107	20.7 <sup>a</sup>	34.0 <sup>ab</sup>	50.7 <sup>ab</sup>	11.6 <sup>a-d</sup>
Wx-1, Wx-2/Saikai 173	20.6 <sup>a</sup>	33.4 <sup>ab</sup>	50.9 <sup>ab</sup>	12.2 <sup>ab</sup>
Wx-3, Wx-4/Kanto 107	20.3 <sup>a</sup>	34.1 <sup>a</sup>	50.6 <sup>b</sup>	11.8 <sup>a-d</sup>
<b>F1 (nonwaxy-waxy)</b>				
Kanto 107/K107Wx1, K107Wx2	20.6 <sup>a</sup>	33.8 <sup>ab</sup>	50.6 <sup>b</sup>	11.5 <sup>a-d</sup>
Saikai 173/Wx-1, Wx-2	20.5 <sup>a</sup>	33.7 <sup>ab</sup>	50.6 <sup>b</sup>	12.0 <sup>a-c</sup>
Kanto 107/Wx-3, Wx-4	20.4 <sup>a</sup>	33.4 <sup>ab</sup>	50.5 <sup>b</sup>	10.7 <sup>a-d</sup>
<b>Nonwaxy</b>				
Kanto 107	20.6 <sup>a</sup>	33.7 <sup>ab</sup>	50.0 <sup>b</sup>	10.6 <sup>a-d</sup>
Saikai 173	20.4 <sup>a</sup>	33.2 <sup>ab</sup>	50.0 <sup>b</sup>	10.1 <sup>b-d</sup>
<b>Mixed (waxy&gt;nonwaxy)</b>				
K107Wx1, K107Wx2>Kanto 107	19.9 <sup>a</sup>	33.2 <sup>ab</sup>	50.4 <sup>b</sup>	11.1 <sup>a-d</sup>
Wx-1, Wx-2>Saikai 173	20.4 <sup>a</sup>	33.5 <sup>ab</sup>	50.9 <sup>ab</sup>	11.4 <sup>a-d</sup>
Wx-3, Wx-4>Kanto 107	20.5 <sup>a</sup>	33.3 <sup>ab</sup>	50.4 <sup>b</sup>	11.0 <sup>a-d</sup>
<b>Mixed (nonwaxy&gt;waxy)</b>				
Kanto 107>K107Wx1, K107Wx2	20.0 <sup>a</sup>	33.4 <sup>ab</sup>	50.4 <sup>b</sup>	9.9 <sup>cd</sup>
Saikai 173>Wx-1, Wx-2	20.2 <sup>a</sup>	33.5 <sup>ab</sup>	49.9 <sup>b</sup>	9.7 <sup>d</sup>
Kanto 107>Wx-3, Wx-4	20.0 <sup>a</sup>	33.0 <sup>b</sup>	50.5 <sup>b</sup>	10.7 <sup>a-d</sup>

<sup>a</sup>  $T_o$  (°C)  $T_p$  (°C)  $T_c$  (°C), and  $\Delta H$  (J/g) = onset, peak, final gelatinization temperature, and gelatinization enthalpy.

<sup>b</sup> Values with the same letter in the same column do not differ significantly at  $P < 0.05$ .



**Fig. 4.** Relationship between amylose content and enthalpy ( $\Delta H$ ) of retrograded starches at 5°C for four weeks.

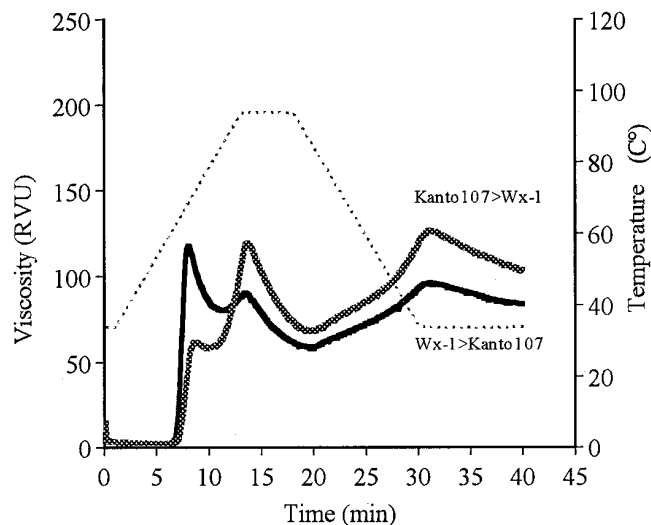


**Fig. 5.** Starch pasting curves of waxy and nonwaxy wheat and their F1 seeds. - - - = Temperature profile.

waxy starch produced two low peaks in the pasting profile of mixed starch. Results also indicate that the association between amylose and amylopectin molecules in mixed starch would differ from that of simple starch. Mixed starch may induce specific starch chain interactions between molecular, starch granules, swollen granules, and granule fragments. For all starches, a significant correlation was found between amylose content and final viscosity ( $r = 0.916$ ) and setback ( $r = 0.801$ ). The increase in viscosity during cooling is induced by leached out amylose rearranging and forming a thin amylose gel layer (Flipse et al 1996). This suggests that starch with lower amylose content decreased the amount of leached out amylose, suppressing viscosity during cooling.

### CONCLUSION

The amylose content of isolated starches from waxy wheat, nonwaxy wheat, and their F1 seeds by reciprocal crossing varied



**Fig. 6.** Starch pasting curves of mixed starches. - - - = Temperature profile.

widely. Two types of F1 starch had amylose content not found in existing cultivars. Mixed starch with the same amylose content as F1 seeds was produced by mixing waxy and nonwaxy wheat starch. Gelatinization enthalpy ( $\Delta H$ ) and final gelatinization temperature ( $T_c$ ) correlated negatively with amylose content. For onset ( $T_o$ ) and peak ( $T_p$ ) gelatinization temperature, mixed starches showed a clearly different trend from F1 starches with the same amylose content as mixed starch. Mixed starch had a broader endothermic peak than F1 starch. In mixed starches, nonwaxy starch tended to start melting first. The enthalpy of the melting amylose-lipid complex correlated positively and enthalpy of retrograded starches correlated negatively with amylose content. The peak viscosity of F1 starch measured by RVA was higher than that of their parent cultivars, nonwaxy and waxy wheat. The difference reflected amylose content. Mixed starches showed characteristic pasting profiles that had two low peaks. In mixed starches, nonwaxy starch and waxy starch developed viscosity at different temperatures. These results suggest that some gelatinization and pasting properties reflect the homogeneity of starch granules in starch in addition to amylose content. After gelatinization, the nonhomogeneity of mixed starch did not influence retrogradation properties of starch.

### LITERATURE CITED

- Atwell, W. A., Hood, L. F., Lineback, D. R., Varriano Marston, E., and Zobel, H. F. 1988. The terminology and methodology associated with basic starch phenomena. *Cereal Foods World* 33:306-311.
- 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.
- Czuchajowska, Z., Otto, T., Paszczyńska, B., and Byung-Kee, B. 1998. Composition, thermal behavior, and gel texture of prairie and tilling starches from garbanzo beans and peas. *Cereal Chem.* 75:466-472.
- Eliasson, A. C. 1994. Interaction between starch and lipids studied by DSC. *Thermochim. Acta* 246:343-356.
- Flipse, E., Keetels, C. J. A. M., Jacobson, E., and Visser, R. G. F. 1996. The dosage effect of the wildtype GBSS allele is linear for GBSS activity but not for amylose content: Absence of amylose has a distinct influence on the physico-chemical properties of starch. *Theor. Appl. Genet.* 92:121-127.
- Fredriksson, H., Silverio, J., Andersson, R., Eliasson, A. C., and Aman, P. 1998. The influence of amylose and amylopectin characteristics on gelatinization and retrogradation properties of different starches. *Carbohydr. Polym.* 35:119-134.
- Fujita, S., Yamamoto, H., Sugimoto, Y., Morita, N., and Yamamori, M. 1998. Thermal and crystalline properties of waxy wheat (*Triticum*

- aestivum* L.) starch. J. Cereal Sci. 27:1-5.
- Gibson, T. S., Solah, V. A., and McCleary, B. V. 1997. A procedure to measure amylose in cereal starches and flours with concanavalin A. J. Cereal. Sci. 25:111-119.
- Gudmundsson, M., and Elliasson, A. C. 1992. Some physical properties of barley starches from cultivars differing in amylose content. J. Cereal. Sci. 95-105.
- Hermansson, A. M., and Svegmak, K. 1996. Developments in the understanding of starch functionality. Trends Food Sci. Technol. 7:345-353.
- Kiribuchi-Otobe, C., Nagamine, T., Yanagisawa, T., Ohnishi, M., and Yamaguchi, I. 1997. Production of hexaploid wheats with waxy endosperm character. Cereal Chem. 74:72-74.
- Kohyama, K., and Nishinari, K. 1991. Effect of soluble sugars on gelatinization and retrogradation of sweet potato starch. J. Agric. Food Chem. 39:1406-1410.
- Krueger, B. R., Walker, C. E., Knutson, C. A., and Inglett, G. E. 1987. Differential scanning calorimetry of raw and annealed starch isolated from normal and mutant maize genotypes. Cereal Chem. 64:187-190.
- Leloup, V. M., Colonna, P., and Buleon, A. 1991. Influence of amylose-amylopectin ratio on gel properties. J. Cereal. Sci. 13:1-13.
- McCleary, B. V., and Seehan, H. 1987. Measurement of cereal  $\alpha$ -amylase: A new assay procedure. J. Cereal Sci. 6:237-251.
- Miles, M. J., Morris, V. J., Orford, P. D., and Ring, S. G. 1985. The roles of amylose and amylopectin in the gelatinization and retrogradation of starch. Carbohydr. Res. 135:271-281.
- Ming, Z., Morris, C. F., 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.
- Nakamura, T., Yamamori, M., and Nagamine, T. 1995. Production of waxy (amylose free) wheats. Mol. Gen. Genet. 248:253-259.
- Obanni, M., and Bemiller, J. N. 1997. Properties of some starch blends. Cereal. Chem. 74:431-436.
- Oda, M., Yasuda, Y., Ozaki, S., Yamauchi, Y., and Yokoyama, Y. 1980. A method of flour quality assessment for Japanese noodles. Cereal Chem. 57:253-254.
- Sulaiman, B. D., and Morrison, W. R. 1990. Proteins associated with the surface of wheat starch granules purified by centrifuging through caesium chloride. J. Cereal Sci. 12:53-61.
- Tester, R. F., and Morrison, W. R. 1990. Swelling and gelatinization of cereal starches. II. Waxy rice starches. Cereal Chem. 67:558-563.
- Toyokawa, H., Rubenthaler, G. L., Powers, J. R., and Schaunus, E. G. 1989. Japanese noodle qualities. I. Flour components. Cereal Chem. 66:382-386.
- Toyokawa, H., Rubenthaler, G. L., Powers, J. R., and Schaunus, E. G. 1989. Japanese noodle qualities. II. Starch components. Cereal Chem. 66:387-391.
- Wootton, M., Panozzo, J. F., and Sung-Hie, H. 1998. Differences in gelatinization behaviour between starches from Australian wheat cultivars. Starch/Staerke 50:154-158.
- Yamamori, M., Nakamura, T., and Nagamine, T. 1995. Inheritance of waxy endosperm character in a common wheat lacking three Wx proteins. Breeding Sci. 45:377-379.
- Yasui, T., Matsuki, J., Sasaki, T., and Yamamori, M. 1996. Amylose and lipid contents, amylopectin structure, and gelatinization properties of waxy wheat (*Triticum aestivum*) starch. J. Cereal Sci. 24:131-137.
- Yasui, T., Sasaki, T., Matsuki, J., and Yamamori, M. 1997. Waxy endosperm mutants of bread wheat (*Triticum aestivum* L.) and their starch properties. Breeding Sci. 47:161-163.
- 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.
- Yuryev, V. P., Kalistratova, E. N., Van Soest, J. G. J., and Niemann, C. 1998. Thermodynamic properties of barley starches with different amylose content. Starch/Staerke 50:463-466.

[Received June 9, 1999. Accepted September 27, 1999.]