

Effects of Granular Structures on the Pasting Behaviors of Starches¹

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ABSTRACT

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Japonica (Tainung 67 [TNU67]) and waxy (Taichung 70 [TCW70]) rice, normal and waxy corn, and cross-linked waxy rice and corn starches were used in an investigation of the influence of the granular structure on the pasting behavior of starch, using small amplitude oscillatory rheometry. Both normal corn and normal rice (TNU67) starches had the highest storage moduli (G'), followed by their cross-linked versions; native waxy corn and rice starches had the lowest. Native waxy starches showed paste characteristics ($G' < 500$ Pa; $\tan \delta > 0.2$) at concentrations of up to 35%. However, cross-linked waxy starches exhibited gel behavior at 10% concentration (cross-linked TCW70) or higher (cross-linked waxy corn starch).

The degrees of swelling power were in the order: TCW70 > native waxy corn > TNU67 \cong cross-linked TCW70 \cong normal corn \cong cross-linked waxy corn starches. Solubilities were in the order: normal corn > TNU67 > native waxy > cross-linked waxy starches. The addition of 2% purified amylose from indica rice (Kaohsiung Sen 7) did not induce gelation of waxy corn starch. Swelling powers of normal corn, TNU67, and cross-linked waxy starches were similar, but normal corn and TNU67 had much higher G' value. Such results implied that the formation of gel structure was governed by the rigidity of swollen granules and that the hot-water soluble component could strengthen the elasticity of the starch gel or paste.

The crystalline order of starch granules is lost during gelatinization. Consequently, substantial rheological alterations occur in starch suspensions during heating. Starch granules absorb water and swell to several times their initial size, and components of starch granules, mainly amylose, leach out (Greenwood and Thompson 1962, Ellis and Ring 1985). Miller et al (1973) and Hoover and Hadziyev (1981) observed the formation of a coarse network from solubilized amylose that linked porous granules. Starch gels are composed of swollen starch granules in an amylose matrix, with the gelatinized granules reinforcing the gel (Ring and Stainsby 1982, Ring 1985, Miles et al 1985, Eliasson 1986, Morris 1990).

The initial stage of starch gelation, lasting only a few hours, is dominated by the formation of gel network from solubilized amylose (Orford et al 1987). The subsequent process, which could continue for several days, was associated with the crystallization of amylopectin within gelatinized granules. However, Evans and Lips (1992) proposed that the phase volume of the swollen granules and their inherent deformability were the key variables in the behaviors of concentrated gelatinized starch dispersion systems, rather than the components released from the granules. Structural differences of swollen granule remnants, commonly referred to as ghosts, correlated strongly with the rheological behavior of starch (Fannon and BeMiller 1992). In addition, the temperature and mechanical treatments used in the pasting procedure could affect the rigidity of cereal starch gels (Collison and Elton 1961, Christianson et al 1986, Doublier and Choplin 1989) and the viscoelastic properties of wheat starch pastes (Wong and Lelievre 1981). High shear caused extensive starch granule rupture (Svegmark and Hermansson 1990). Gels prepared with high shear could result in a lower complex modulus than that of those prepared with low shear (Svegmark and Hermansson 1991). This implied that the integrity of swollen starch granules was the major factor determining the rheological properties of a starch paste or gel.

A previous investigation suggested that the major factors influencing the rheological properties of rice starch pastes and gels were granular structure and composition, followed by the amount of leached-out amylose (Lii et al 1996). For further elucidation of

the effect of granule structure on the pasting behavior of starch, rheological properties of different of native and cross-linked rice and corn starches during pasting were investigated with dynamic rheometry.

MATERIALS AND METHODS

Starches

Rice starches of japonica (Tainung 67 [TNU67]) and waxy (Taichung waxy 70 [TCW70]) varieties were isolated by an alkaline steeping method (Yang et al 1984). Normal corn starch was purchased from Sigma Chemical Co. (St. Louis, MO); native and cross-linked waxy corn (CI-10) starches were obtained from Rhone-Poulenc Inc. (France). All purchased starches were washed with distilled water several times and dried in an oven at 40°C before use.

Preparation of Cross-Linked TCW70 Starch

TCW70 starch was suspended in two volumes of distilled water (w/v). The slurry was stirred and maintained at 45°C, and the pH value was adjusted to 10.5 with 0.1M NaOH. Epichlorohydrin (1% starch dwb) was added. After reaction for 2 hr, the slurry was neutralized to pH 6.5 using 0.1M HCl. The suspension was washed with distilled water until chloride ion was no longer detected and then dried in an oven at 40°C (Chang and Lii 1981, 1982).

Isolation of Amylose

The amylose of indica rice starch (KSS7) was isolated and purified by the method of Takeda et al (1986).

Amylose Content

Amylose contents of starches were determined as described by Chrastil (1987). All tests were performed in triplicate.

Gelatinization Temperature

Starch gelatinization temperature was measured by differential scanning calorimetry using the Du Pont 910 DSC (Du Pont, Wilmington, DE). A 25% starch suspension (w/w) was scanned from 25 to 120°C at rate of 2°C/min. All measurements were performed in triplicate.

Swelling Power and Water Solubility Index

A 1% starch suspension (w/w) was placed into a centrifuge tube with cap. The tube was heated from 55 to 95°C at 5°C intervals and was kept at that temperature for 60 min. The heated sample

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was cooled rapidly to room temperature in an ice-water bath, followed by centrifugation at $8,000 \times g$ for 20 min. Swelling power (SP) was measured by the sedimented paste weight (Leach et al 1959) and the water solubility index (WSI) by the solid content of supernatant (Holm et al 1985).

Effect of Starch Concentration on Rheological Properties

Small amplitude oscillatory rheological measurements were performed with a Carri-Med CSL 100 rheometer (TA Instruments Ltd., Surrey, England) equipped with parallel-plate geometry (20 mm diameter). The gap size and the strain were set at 1.0 mm and 0.5%, respectively. For temperature and time sweeps, frequency was fixed at 1 Hz. All heating and cooling processes were done in the rheometer.

Starch slurries of different concentrations were loaded on the peltier of the rheometer, then the ram was raised to a 1.0-mm gap. The exposed edge of sample was covered with a thin layer of mineral oil. Rheological properties, including storage (G') and loss (G'') moduli and $\tan \delta$, were measured as the temperature was raised from 45 to 95°C at a rate of 1°C/min, then as the temperature was reduced from 95 to 5°C at a rate of 5°C/min, and again after aging the sample at 5°C for 1 hr (Lii et al 1995, 1996). All measurements were performed in triplicate.

Effect of Amylose on Rheological Properties of Waxy Corn Starch

Purified amylose from KSS7 starch (Takeda et al 1986) was applied as the test sample. A 2% amylose solution was prepared

by heating amylose in 8% 1-butanol (w/w) solution in a boiling waterbath (Miles et al 1985). After amylose was solubilized, 1-butanol was removed by continuous heating for ≈ 5 min under a N_2 stream until 1-butanol was not detectable. Additional water was added to make up a 2% amylose concentration (Miles et al 1985, Lii et al 1996). An appropriate amount of waxy corn starch was suspended in the amylose solution through mixing at $\approx 50^\circ C$. The suspension was transferred to a dynamic rheometer immediately. Rheological measurement was performed under the conditions described above.

Frequency Sweep of Gelatinized Starch System

The gelatinized starch samples were prepared by heating native and cross-linked waxy starches from 45 to 95°C at 1°C/min, followed by cooling down to 25°C at 5°C/min in the rheometer. Frequency sweep was performed from 0.01 to 100 rad/sec at 25°C immediately, with 0.5% strain.

RESULTS AND DISCUSSION

Amylose Content and Gelatinization Temperature

The amylose contents of TNu67, TCW70, cross-linked TCW70 (C-TCW70), normal corn, waxy corn, and CI-10 starches were 19.77, 0.79, 0.79, 33.33, 2.72, and 3.17%, respectively (Table I). Corn starches showed higher gelatinization temperatures than did rice starches. Cross-linking raised the onset temperature (T_o) of gelatinization but not the peak (T_p) and completion (T_c) temperatures.

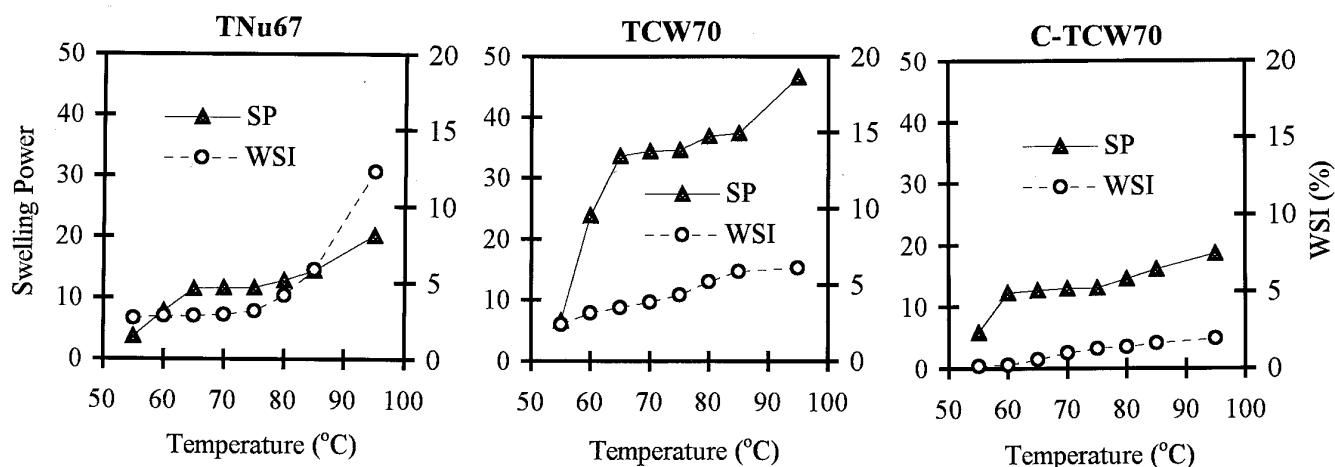


Fig. 1. Swelling powers (SP) and water solubility indices (WSI) of rice starches.

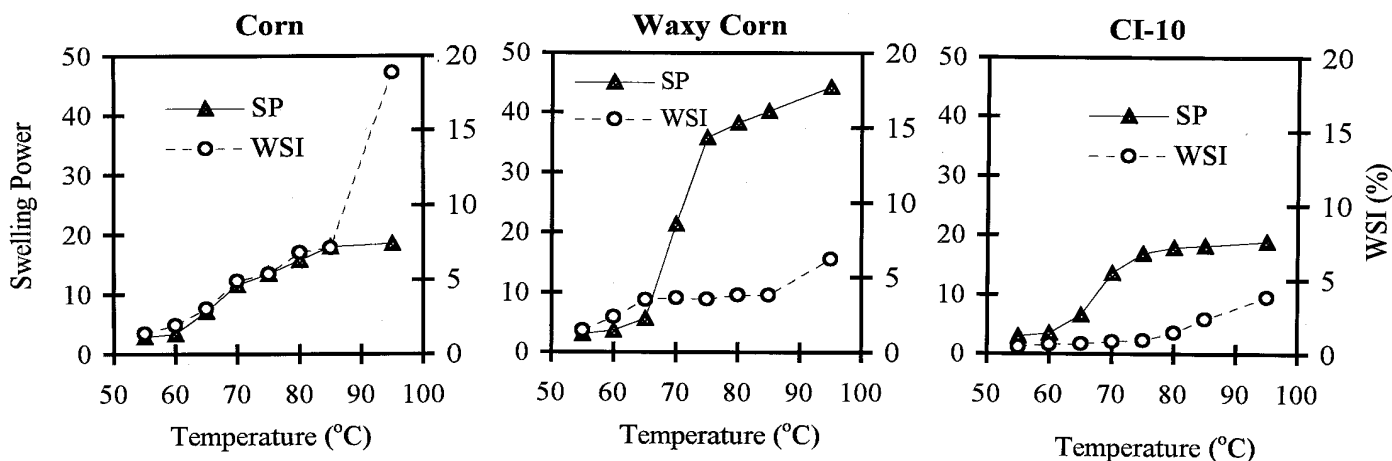


Fig. 2. Swelling powers (SP) and water solubility indices (WSI) of corn starches.

Swelling Power and Water Solubility Index

The change of SP and WSI values of rice and corn starches during heating are shown in Fig. 1 and 2. The TNU67 granule swelled moderately from 55 to 65°C due to the gelatinization process (Table I). Little swelling occurred between 65 and 80°C. The swelling increased again at >80°C. WSI of TNU67 starch increased significantly after 85°C. A two-stage SP was also found in TCW70. The degree of swelling was much higher than that of TNU67 (Fig. 1).

The SP of corn starch (Fig. 2) differed from that of rice starch (Fig. 1). It swelled as the temperature increased from 60 to 85°C, then reached a plateau. The WSI of corn starch increased drastically after 85°C as with TNU67. It might be inferred that the swollen granular structure of corn starch was more rigid than that of TNU67. However, both WSI of TNU67 (Fig. 1) and corn (Fig. 2) starches were less than their amylose contents (Table I). Therefore, some amylose molecules remained in the granule. Waxy corn starch swelled rapidly from 65 to 75°C, followed by a slower swelling from 75 to 95°C. Its WSI was low due to no or a trace amount of amylose (Fig. 2). Sandhya Rani and Bhattacharya (1989) indicated that low-amylose content starch granules, being less rigid, swell freely when heated. A starch granule with higher amylose content, on the other hand, being better reinforced and thus more rigid, probably swells less freely. Tester and Morrison (1990) and Morrison et al (1993) found that the swelling behavior of cereal starches was primarily a property of their amylopectin content; amylose acts as an inhibitor of swelling, especially in the presence of lipids. Lii et al (1996) suggested that the rigidity of starch granular structure might be proportional to its amylose content and inversely proportional to the degree of granular swelling.

Cross-linking with 1% epichlorohydrin restricted the swelling of both TCW70 and waxy corn starches. The second-stage swelling during heating disappeared in C-TCW70. The WSI values of both cross-linked starches decreased significantly.

Dynamic Rheological Property

Heating process. Figures 3 and 4 present changes in storage modulus (G') of the starch samples as a function of temperature during heating of suspensions at rate of 1°C/min in a dynamic rheometer. Both nonwaxy rice and corn starches exhibited similar profiles. G' of the heated starch dispersion increased greatly at a certain temperature to a maximum (G'_{max}), then dropped with continued heating. The initial increase of G' could be attributed to the degree of granular swelling to fill the entire available volume of the system (Eliasson 1986, Keetels and Van Vliet 1994), and intergranule contact might form a network of swollen granules (Evans and Haisman 1979; Wong and Lelievre 1981). For lower concentrations (e.g., 10%), most starch granules could swell under less restriction than could those in higher concentrations (e.g., 25%). Therefore, the rigidity of the swollen granule was related to starch concentration. In addition, the total available surface for the inter-

action among swollen granules in lower concentration systems could be smaller than in higher concentration systems. Consequently, both G' and G'_{max} of lower concentrations were lower than those of higher concentrations during heating.

After reaching G'_{max} , further heating reduced the G' of native and cross-linked waxy rice and corn starch cooks dramatically, followed by a steady mild drop throughout the remainder of the heating process (Figs. 3 and 4). The nonwaxy rice and corn starch cooks behaved differently, showing a continuous decrease after G'_{max} for 25% concentration (Figs. 3 and 4). The temperatures at G'_{max} ($T_{G'_{max}}$) of 25% TNU67, TCW70, C-TCW70, corn, waxy corn, and CI-10 starch systems were 66.3, 62, 62.8, 71.7, 70, and 72.8°C, respectively (Figs. 3 and 4). All of them were lower than their respective completion temperatures of gelatinization (T_c)

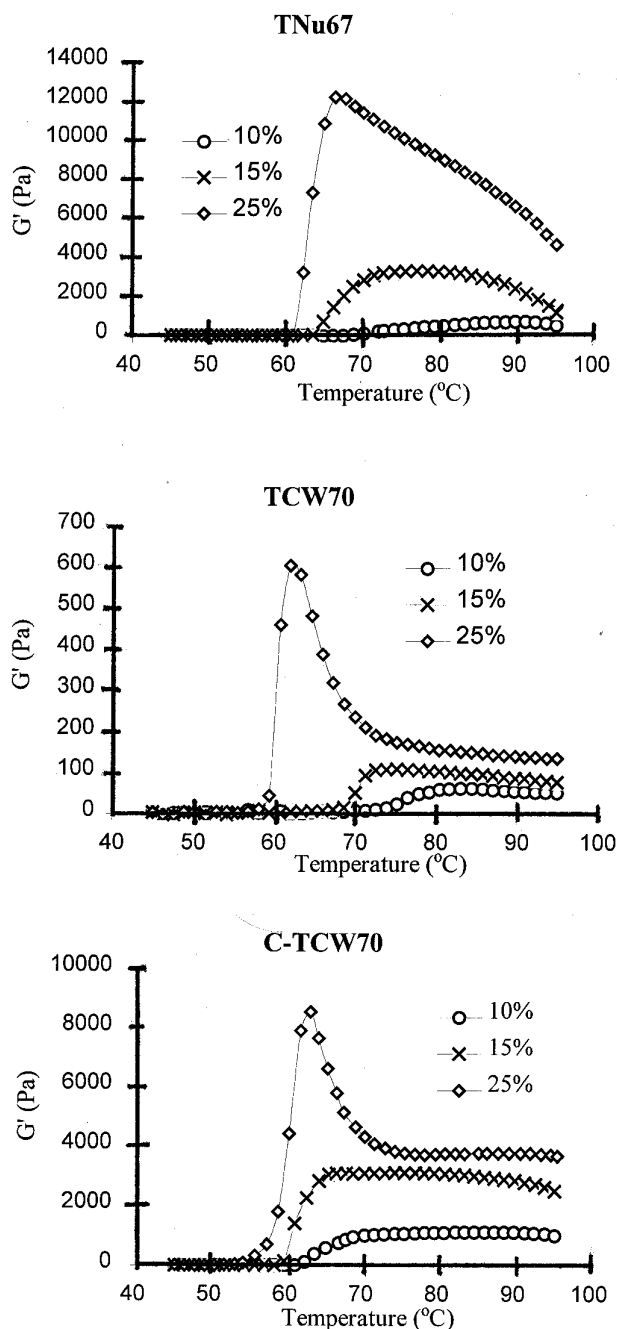


Fig. 3. Storage modulus (G') measurements of rice starches at different concentrations during heating.

TABLE I

Amylose Contents and Gelatinization Temperatures of Starches

Sample	Amylose Content (%)	Gelatinization Temperature (°C) ^a		
		T _o	T _p	T _c
TNU67 ^b	19.77 ± 0.78	56.5 ± 1.0	59.2 ± 1.0	69.8 ± 0.9
TCW70 ^c	0.79 ± 0.14	53.3 ± 0.5	57.5 ± 0.3	66.7 ± 0.4
C-TCW70 ^d	0.79 ± 0.14	54.7 ± 0.1	59.2 ± 0.2	65.6 ± 0.3
Corn	33.33 ± 0.56	61.7 ± 0.5	64.5 ± 0.1	73.5 ± 0.2
Waxy corn	2.72 ± 0.03	61.8 ± 1.1	68.3 ± 0.3	75.5 ± 0.5
CI-10 ^e	3.17 ± 0.15	64.6 ± 0.1	68.4 ± 0.1	75.1 ± 0.7

^a T_o = onset temperature of gelatinization; T_p = peak temperature; T_c = completion temperature.

^b Japonica rice starch.

^c Waxy rice starch.

^d Cross-linked TCW70 starch.

^e Cross-linked waxy corn starch.

(Table I). These results agreed with that both G' and G'' values started to decrease from the later stage of the gelatinization process (Eliasson 1986, Keetels and Van Vliet 1994). The lowering of G' could be attributed to the melting of remaining crystallites, which resulted in swollen granules to become softer. However, this implied that other reactions were also involved in this decrease.

Keetels and Van Vliet (1994) further indicated that the breakdown of amylopectin matrix inside the swollen starch granules due to disentanglement of branches during prolonged heating would cause the granule becoming less rigid. The similar profiles of G' changes for native and cross-linked waxy rice (Fig. 3) and corn starches (Fig. 4) during heating were by reason of the similarity of their basic granular structures. However, the cross-linking treatment would produce intra- or intermolecular covalent bonds

among starch molecules, which contributed to more difficult breakdown of amylopectin matrix and resulted in higher G' than that of native starch. For nonwaxy starch, molecules inside granules were more entangled due to the presence of the unleached-out amylose and the leached-out could be around the swollen granular surface (Hoover and Hadziyev 1981). Both factors would somewhat retard the deformation of swollen granules during heating. The degree of molecule entanglement would reduce as temperature increased. Therefore, G' declined continuously from G'_{max} up to 95°C (Figs. 3 and 4).

In polymer science, viscoelastic measurements have been used for determining the gelling point as the crossover of the viscous and the elastic response ($G' = G''$), i.e., $\tan \delta$ value is 1. The use of the crossover point has been applied for the gelation of biopolymers such as of gelatin (Svegmark and Hermansson 1991)

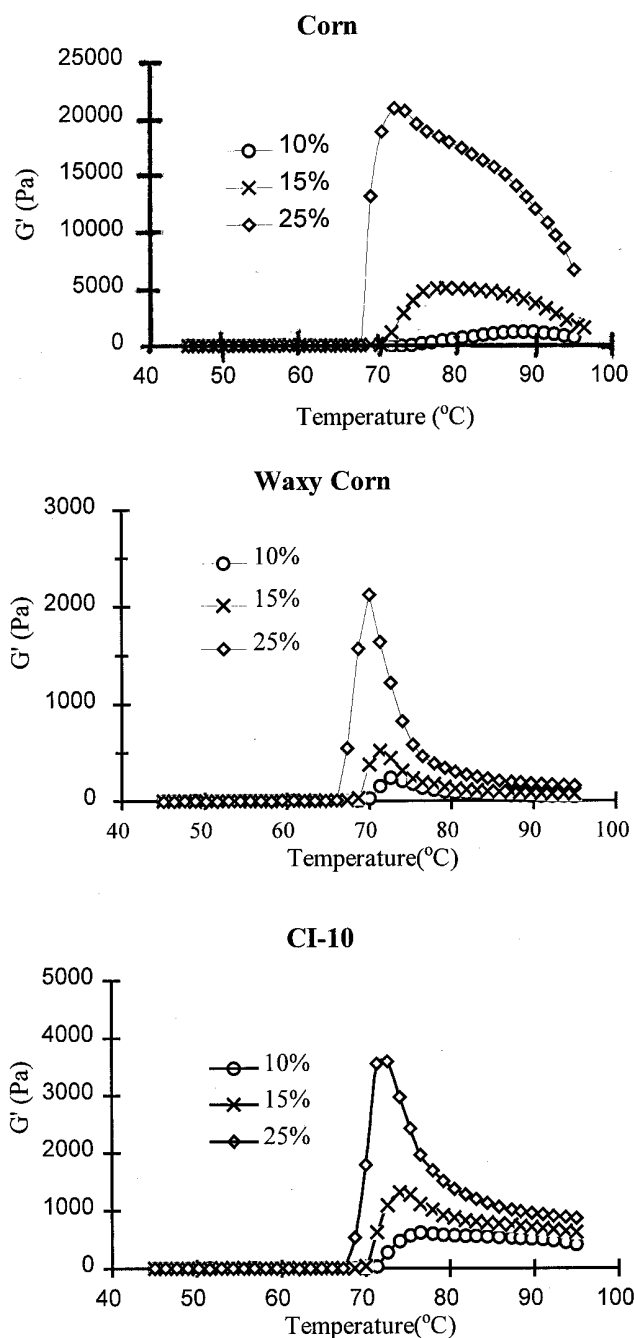


Fig. 4. Storage modulus (G') measurements of corn starches at different concentrations during heating.

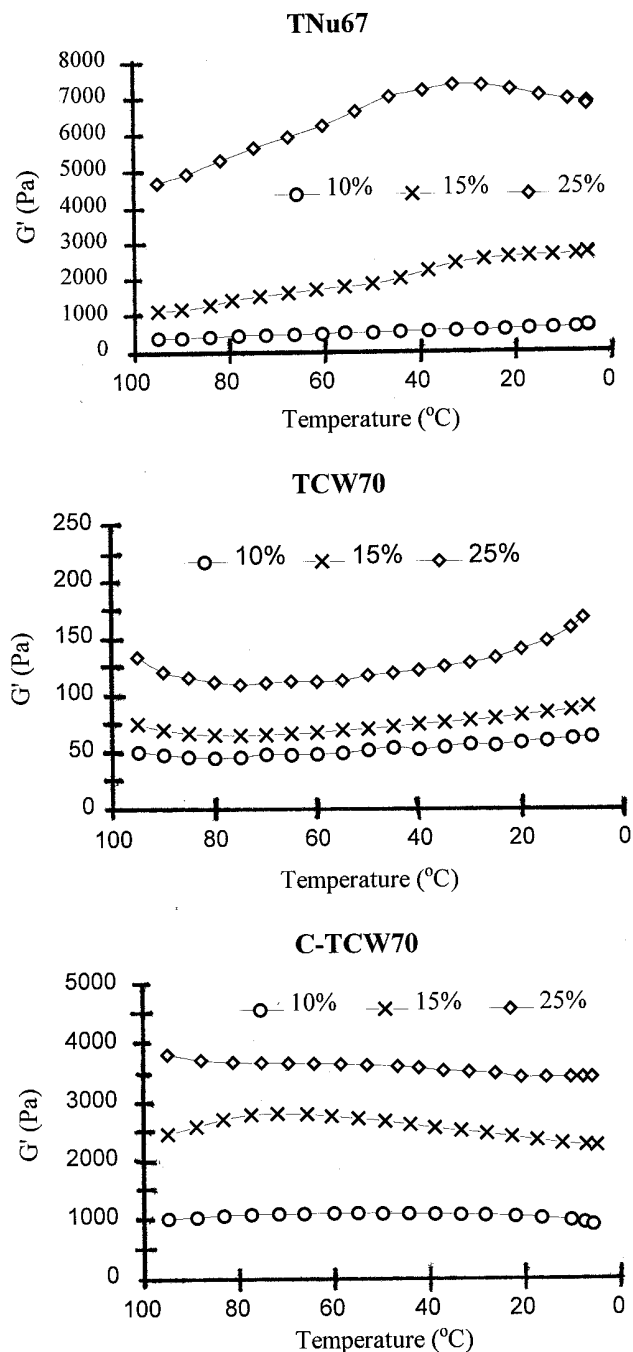


Fig. 5. Storage modulus (G') measurements of rice starches at different concentrations during cooling.

and β -lactoglobulin (Svegmark and Hermansson 1990). In starch dispersions, a phase angle (δ) falling to value close to zero and a sharp increase in complex modulus (G^*) have been used to determine the gelling point (Svegmark and Hermansson 1991, 1993). During the dynamic rheological measurement, a starch cook with G' value > 500 Pa and $\tan \delta$ value < 0.2 can be removed from a rheometer without any deformation. Therefore, G' value > 500 Pa and $\tan \delta$ value < 0.2 are parameters of starch gels (Lii et al 1995, 1996) and are used as the definition of a starch gel in this article; all other cooks are considered to be pastes.

The rheological characteristics of starches at 95°C are given in Tables II and III. Fifteen percent concentrations of TNU67 and CI-10 starches and 10% concentrations of native corn and C-TCW70 starches formed gels at 95°C, according to rheological parameters. Both native waxy starches gave only hot pastes at concentrations up to 35%. The WSI of C-TCW70 was less than that of TNU67 and normal corn starch, but their SP values were similar (Figs. 1 and 2). C-TCW70 still had a higher G' value and formed a gel. This phenomenon is different from that of a normal starch gel, which is often described as a continuous network of amylose in which starch granules are embedded (Ott and Hester 1965; Ring and Stainsby 1982; Ring 1985). It implies that the hot cross-linked waxy starch sample with adequate granular rigidity can build a gel network from swollen granules alone.

Cooling and aging process. Results of temperature sweep investigations of storage moduli for rice and corn starch systems during cooling indicated that G' values of native and cross-linked waxy starches varied only slightly (Figs. 5 and 6). However, nonwaxy starch G' values increased rapidly during cooling, and the rate of increment of the G' value of corn starch was much higher than that of TNU67. The G' of a 25% corn starch sample rose as the temperature dropped, with G' peaking at 50°C, then falling drastically as the temperature continued to drop. This phenomenon might be due to the contraction of gel volume during

the cooling process. From G' and $\tan \delta$, all starch samples, except those of native waxy starches and 10% CI-10, formed gels when they were cooled to 25°C (Tables II and III). During aging of corn starch samples at 5°C, G' increased slightly (Fig. 7). A similar shrinking effect of gel volume occurred with the 25% corn starch aging at 5°C. Therefore, the corn starch sample was only used up to a concentration of 15%.

The SP values of C-TCW70 was similar to that of TNU67 and corn starches, but C-TCW70 did not have any remaining amylose in swollen granules and had less leached-out components. (Figs. 1 and 2). Hence, the G' increment of nonwaxy starches during cooling could be attributed to the leached-out component, which could enhance gel stiffness (Orford et al 1987), and to the amylose remaining in granules (Figs. 3 and 4). Chen (1994) indicated that TNU67 and TCW70 amylopectins had similar chain distributions as well as no extra long branches and similar G' values. Therefore, the higher G' of the TNU67 starch sample could have been due to the presence of a moderate amount of amylose (Table I). Jane and Chen (1992) suggested that corn amylopectin with long branches had a strong tendency to gel. Thus, the high G' of corn starch gel, as compared to TNU67, might be attributed to different amylopectin structures along with different amylose contents.

Effect of concentration on G' and G'' . The effects of concentration on storage (G') and loss (G'') moduli were analyzed from the data listed in Tables II and III. The result demonstrated that the dependence of both G' and $\tan \delta$ at 25°C on starch concentration followed a power law relationship at 10–35% concentrations. For native and cross-linked waxy starches, $\tan \delta$ rose more rapidly than G' with increments of starch concentration, which meant that the dependence of G'' on concentration was greater than the dependence of G' . Also, the dependence of G'' on concentration of the cross-linked waxy starch was less than that of the parent waxy starch ($G' \propto C^{1.28}$ and $G'' \propto C^{2.02}$ for TCW70, $G' \propto C^{1.90}$ and $G'' \propto C^{2.57}$ for waxy corn, $G' \propto C^{1.28}$ and $G'' \propto C^{1.53}$ for C-TCW70,

TABLE II
Rheological Characteristics of Gelatinized Rice Starches at 95 and 25°C

Sample	Concentration (%)	95°C		25°C	
		G' (Pa)	$\tan \delta$	G' (Pa)	$\tan \delta$
TNU67 ^a	10	459 ± 15	0.147 ± 0.002	609 ± 18	0.102 ± 0.002
	15	1177 ± 20	0.135 ± 0.001	2621 ± 113	0.060 ± 0.002
	25	4632 ± 30	0.103 ± 0.001	7109 ± 146	0.063 ± 0.002
TCW70 ^b	10	49 ± 1	0.189 ± 0.004	54 ± 1	0.229 ± 0.009
	15	76 ± 1	0.245 ± 0.008	79 ± 1	0.269 ± 0.007
	25	132 ± 3	0.284 ± 0.007	133 ± 1	0.432 ± 0.019
	35	236 ± 3	0.345 ± 0.004	284 ± 3	0.565 ± 0.009
C-TCW70 ^c	10	1028 ± 48	0.085 ± 0.003	1037 ± 7	0.079 ± 0.003
	15	2548 ± 129	0.079 ± 0.003	2654 ± 277	0.076 ± 0.001
	25	3490 ± 313	0.090 ± 0.002	3452 ± 215	0.098 ± 0.001

^a Japonica rice starch.

^b Waxy rice starch.

^c Cross-linked TCW70 starch.

TABLE III
Rheological Characteristics of Gelatinized Corn Starches at 95 and 25°C

Sample	Concentration (%)	95°C		25°C	
		G' (Pa)	$\tan \delta$	G' (Pa)	$\tan \delta$
Corn	10	657 ± 40	0.094 ± 0.006	1016 ± 21	0.068 ± 0.001
	15	1514 ± 54	0.090 ± 0.007	4416 ± 366	0.037 ± 0.001
Waxy corn	10	47 ± 2	0.174 ± 0.003	46 ± 1	0.201 ± 0.001
	15	67 ± 1	0.232 ± 0.003	68 ± 1	0.292 ± 0.006
	25	178 ± 3	0.245 ± 0.005	189 ± 3	0.391 ± 0.004
	35	332 ± 6	0.268 ± 0.004	496 ± 7	0.468 ± 0.011
CI-10 ^a	10	458 ± 8	0.086 ± 0.002	453 ± 3	0.068 ± 0.000
	15	618 ± 5	0.092 ± 0.000	566 ± 20	0.082 ± 0.005
	25	877 ± 23	0.112 ± 0.003	874 ± 15	0.129 ± 0.002
	35	1342 ± 27	0.130 ± 0.001	1391 ± 25	0.191 ± 0.005

^a Cross-linked waxy corn starch.

and $G' \propto C^{0.88}$ and $G'' \propto C^{1.72}$ for CI-10). Lenk (1978) indicated that G'' increased largely when the adhesion between fillers and continuous phase decreased. In a starch gel, similar effects might appear if interactions between granules and leached-out components were poor (Eliasson 1986). For low-sheared potato and concentrated cereal starch pastes, viscosity may be governed primarily by the deformability of granules and by the friction between them (Doublier et al 1987, Svegmarm and Hermansson 1991). Bibbó and Vallés (1984) suggested that dangling chains (segments of molecules not joined to the junction zones of infinite gel networks) contributed significantly to the growth of loss modulus. Therefore, the covalent bonding in the cross-linked waxy starch granule might lessen the degree of free vibration for dangling chains and result in the dependence decline of G'' on concentration (Papageorgiou et al 1994). In contrast, the effect of concen-

tration on $G'' (\propto C^{2.19})$ of TNU67 was lower than $G' (\propto C^{2.32})$. It may be due to strong interactions between different granular surfaces (Eliasson et al 1981, Eliasson 1986, Kulp and Lorenz 1981, Marsh and Waight 1982). A similar influence was also detected with corn starch.

Effect of amylose on rheological properties. The influence of added 2% amylose on G' of waxy corn starch during aging at 5°C is shown in Fig. 8. Addition of amylose increased the G' , especially at low starch concentration. However, no gelation was detected in any sample examined up to 1 hr. The result agreed with that using waxy rice starch and added amylose (Lii et al 1996). For the low concentration system, added amylose could entangle with the granule to strengthen the structure of the paste matrix. However, the effect of amylose would be diluted at high starch concentrations. The characteristics of swollen granules,

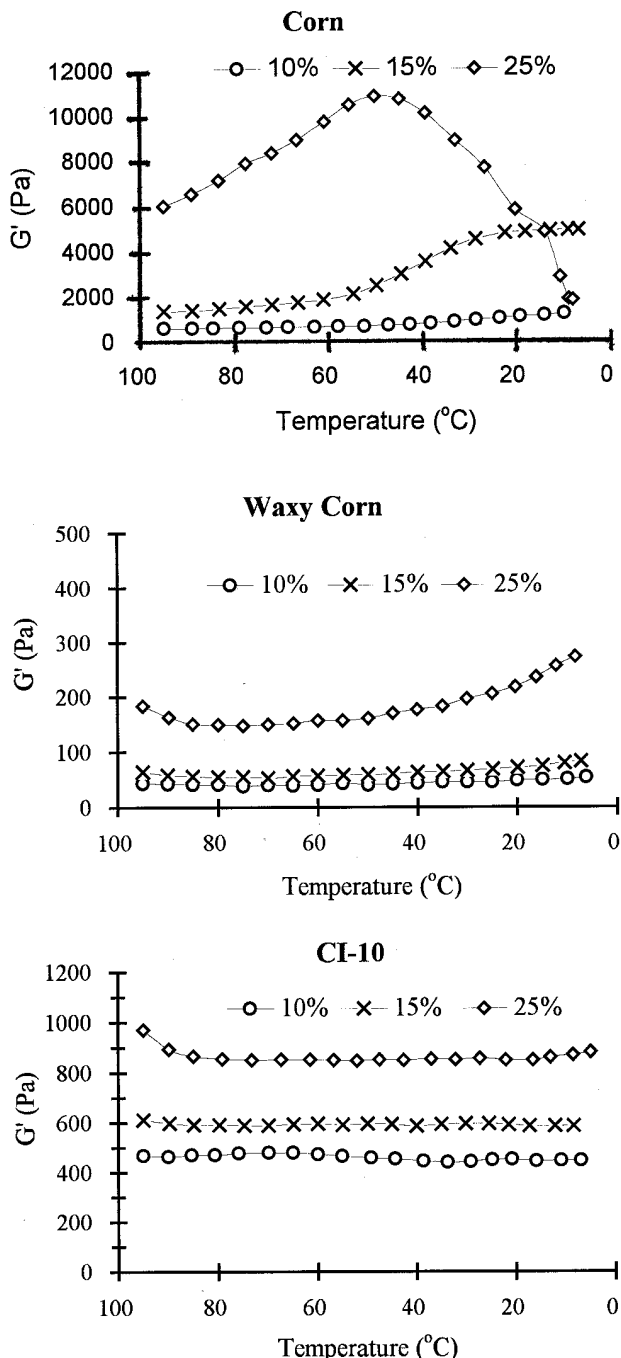


Fig. 6. Storage modulus (G') measurements of corn starches at different concentrations during cooling.

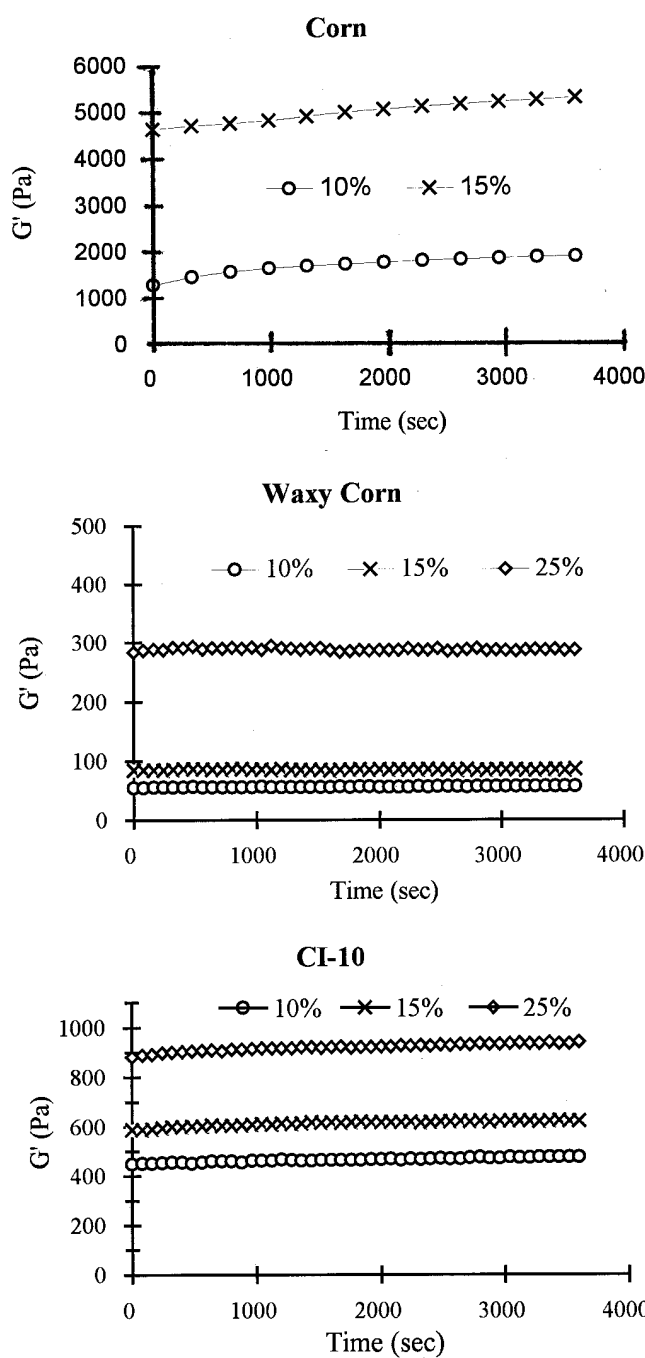


Fig. 7. Storage modulus (G') measurements of corn starches at different concentrations during aging at 5°C.

consequently, still dominated the viscoelastic property of such systems.

Frequency dependence. The frequency sweep test was applied to further determine whether the gelatinized native and cross-linked waxy starches formed a gel or a paste. The starch sample was prepared by heating to 95°C, then cooled down to 25°C for the frequency sweep. The G' and G'' curves of both CI-10 and C-TCW70 at 15% were almost parallel in the frequency range of 0.01 to 100 rad/sec (Fig. 9). Also, G' dominated G'' through the frequency range examined. Both were almost independent of frequency. Such independence is an important characteristic of gels (Morris and Ross-Murphy 1981). However, as revealed in Fig. 9, G' , and especially G'' of 35% TCW70 and waxy corn starches, exhibited great frequency dependence. It is concluded that both

native waxy starches possessed the pseudo gel properties described by Morris and Ross-Murphy (1981). These systems could also be recognized as pastes (Lii et al 1995,1996).

CONCLUSIONS

Waxy rice and waxy corn starches did not form gels as defined by the frequency dependence of G' and G'' even at concentrations up to 35%. This phenomenon was ascribed to a lack of cooked granule integrity and rigidity.

The WSI and remaining amylose content of the swollen granules of the nonwaxy (TNU67 and corn) starches were understandably higher than those of cross-linked waxy starches. Because the G' of cross-linked waxy starch barely changed during the cooling process, but the nonwaxy starch G' rose significantly, it might be hypothesized that retrogradation of leached-out components and interactions of molecules remaining inside the granule reinforced the gel during cooling.

Adding amylose enhanced the G' of waxy corn starch during aging, but it still remained a paste. Therefore, it was concluded that the rigidity of swollen starch granules was a major factor determining the formation of either pastes or gels. Inherent amylose could reduce the loss of granular rigidity during heating. Cross-linked waxy starch could also produce similar decline in the loss of rigidity. Consequently, it could form gels at sufficient concentration. The leached-out component, like the added amylose, reinforced the structure of the system, especially during cooling and aging.

ACKNOWLEDGMENTS

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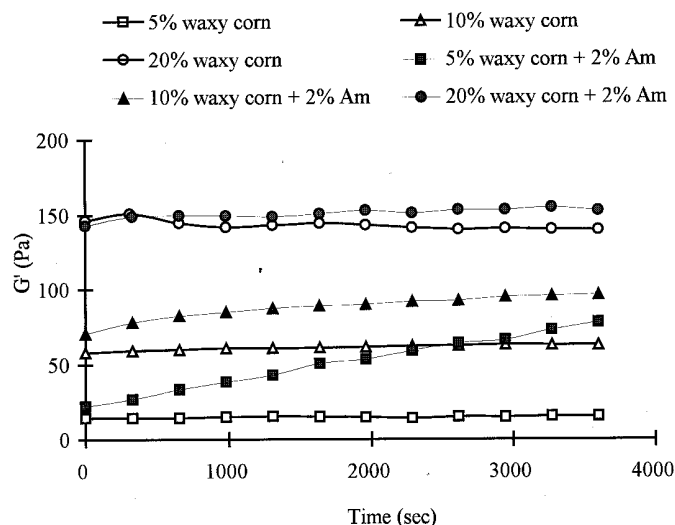


Fig. 8. Effect of amylose on storage modulus (G') of waxy corn starch during aging at 5°C.

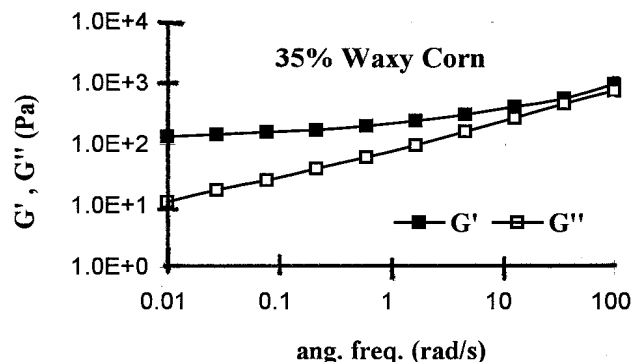
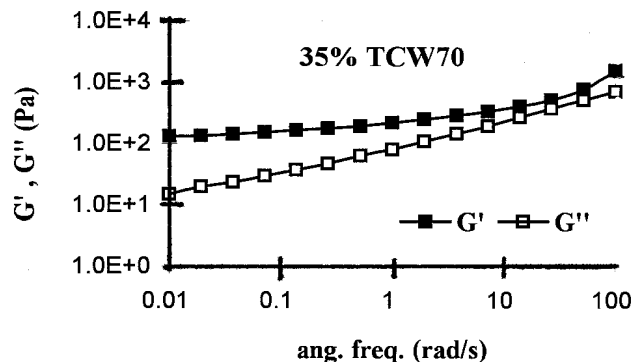
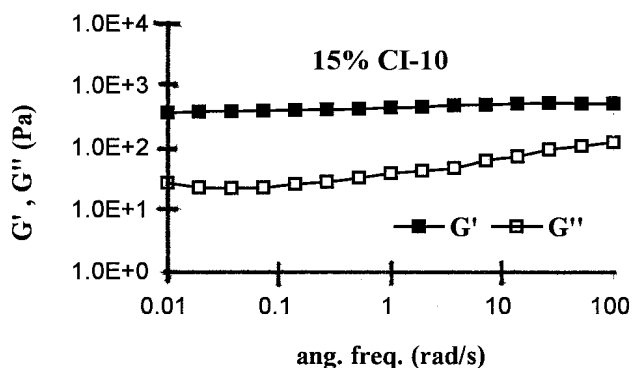
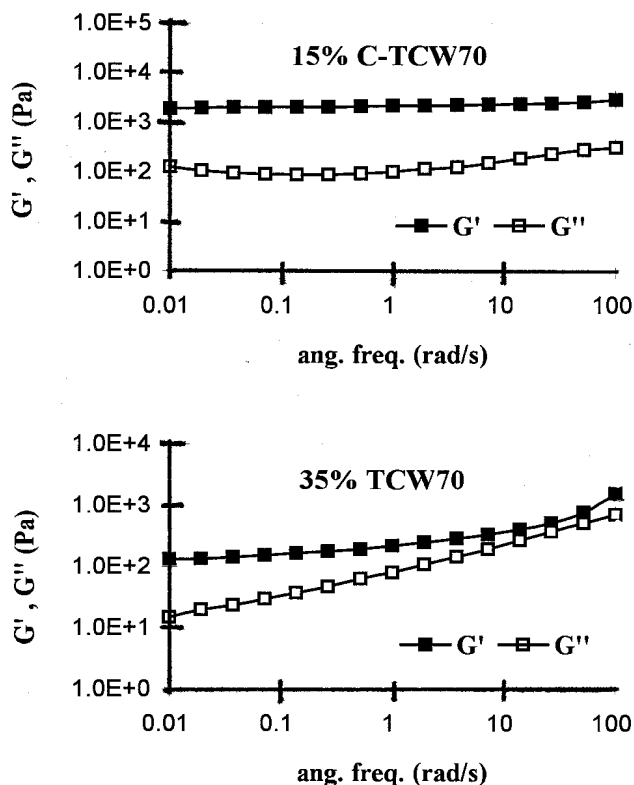


Fig. 9. Frequency dependences of dynamic moduli (G' and G'') of rice and corn starches during aging at 25°C.

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