



Steady and dynamic shear rheology of sweet potato starch–xanthan gum mixtures

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ABSTRACT

The effect of xanthan gum at different concentrations (0.2–0.6% w/w) on the rheological properties of sweet potato starch (SPS) pastes was evaluated under steady and dynamic shear conditions. The presence of xanthan resulted in an increase in the consistency index and vane yield stress of SPS. The effect of temperature on the apparent viscosity of SPS–xanthan mixtures is well described by the Arrhenius equation. Dynamic moduli (G' , G'' , and η^*) values of the mixtures increased with an increase in xanthan concentration while the $\tan \delta$ values decreased. The addition of xanthan appeared to contribute to the elastic properties of the weak network of the SPS pastes. The structure development rate constant (k) of gelation during ageing was strongly influenced by the presence of xanthan. This suggests that the phase separation process caused by the incompatibility phenomena between the amylose component in starch and xanthan can increase the elastic characteristics of the SPS–xanthan mixtures.

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1. Introduction

Sweet potato (*Ipomea batatas* L. Lam), which has been a traditional starch source in Africa and Asia, is mainly consumed in a baked, boiled or steamed form in Korea (Chun & Yoo, 2006). Sweet potato starch (SPS) is widely used in food industries as an ingredient in processed sweet potato products, such as noodles, soups, sauces, snacks, and bread. Previous studies have shown that SPS exhibits wide variation in granule size (3–40 μm) and amylose content (15–30%), has a gelatinisation temperature between 61 and 70 °C, and gives both A- and C-type of X-ray diffraction pattern (Moorthy, 2004). In general, SPS also exhibits a higher viscosity profile and paste clarity compared to corn starch (Jung, Shin, & Choi, 1991; Seog, Park, Nam, Shin, & Kim, 1987).

Although the physicochemical and pasting properties of SPS have been previously reported in numerous studies (Chen, Schols, & Voragen, 2003; Jangchud, Phimolsiripol, & Haruthaithanasan, 2003; Jung et al., 1991; Seog et al., 1987), an interpretation of the rheological properties in terms of its structural properties has not been fully elucidated. It is well known that the addition of gum influences the rheological properties of starch, in particular, the gelation and retrogradation, in a wide variety of starch-based foods. Therefore, it is of considerable practical importance to understand the role of gum interactions on the rheological properties of starch pastes, in order to modify and control the rheological properties of starch–gum mixtures. Xanthan gum is commonly used in food industries as a favourable thickening agent in

starch–gum mixture systems because of its exceptional rheological properties. Although extensive literature is available on the rheology of mixed xanthan gums and various starch pastes, there does not seem to be much information on mixtures of xanthan gum and SPS paste, especially on whether they exhibit synergistic rheological behaviour or not.

Xanthan gum is a high molecular weight extracellular polysaccharide produced by the fermentation of the bacterium *Xanthomonas campestris*. Xanthan is composed of a (1→4) linked β -D-glucan (cellulose) backbone that is substituted on the O-3 position of alternating glucose residues by charged trisaccharide side chains of β -D-mannopyranosyl-(1→4)- β -D-glucuronopyranosyl-(1→2)-6-O-acetyl- β -D-mannopyranosyl. When added to aqueous dispersions it imparts extraordinary stability against heat, acid and alkali conditions, due to its structural rigidity and the extended nature of its molecules due to its linear, cellulosic backbone that is stiffened and shielded by the anionic trisaccharide side-chains (BeMiller & Fennema, 2008). Xanthan gum is known to exhibit peculiar flow properties with pronounced shear-thinning behaviour, due to its unique rigid, rod-like conformation which is more responsive to shear than a random-coil conformation (Urlacher & Noble, 1997). It also produces an unusually high viscosity solution with yield stress even at low concentrations. This rheological behaviour of xanthan gum has led to a wide range of industrial applications.

Yield stress in food systems can be considered to be the minimum stress required to initiate flow and is a measure of the strength of the material network. The yield stress of starch paste has also been analysed in terms of its structural properties because the paste is regarded as a composite material consisting of swollen granules dispersed in a continuous amylose network. In general,

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there are several ways to measure the yield stress of starch pastes indirectly. Indirect methods involve the extrapolation of the shear stress–shear rate curve to zero shear rate by applying flow models, such as the Herschel–Bulkley and Casson models. However, great care is required in obtaining reliable data to calculate the value of the yield stress in this way because the results are largely influenced by the flow model used and the number of data points used, especially at low shear rates (Rao, 2007). As a result of this limitation, only a few researchers (Achayuthakan, Suphantharika, & Rao, 2006; Doublier & Durand, 2008; Genovese & Rao, 2003) have recently begun studying the yield stress of starch dispersions using vane rheometry, a method that was developed by Dzuy and Boger (1983). They found that the vane method was useful for directly measuring the yield stress of starch dispersions. However, a study on the vane yield stress of SPS pastes, especially in the presence of gums, has not been performed.

The objective of this study was to examine the effect of xanthan concentration on the steady and dynamic rheological properties of SPS pastes, and to determine the synergistic effect of xanthan gum on the rheological properties of SPS–xanthan mixtures. The vane yield stress of SPS–xanthan mixtures was also investigated to examine their structural properties.

2. Materials and methods

2.1. Materials and preparation of starch pastes

Sweet potato starch (SPS) (24.4% amylose) and xanthan gum used in this study were purchased from Seoyong Food Co. (Jeju, Korea) and Sigma Co. (St. Louis, MO), respectively. The SPS contained 16.2% moisture, 0.26% protein, 0.29% fat, 0.18% ash, and 83.07% carbohydrate (by difference), which were determined according to AOAC (1984). SPS–xanthan mixtures (5% w/w) were prepared by mixing SPS with distilled water and xanthan gum, to obtain 0%, 0.2%, 0.4%, and 0.6% (weight basis) gum levels. The mixture was allowed to hydrate by stirring for 1 h at room temperature, and then heated at 95 °C in a water bath for 30 min with mild agitation, in order to avoid air entrainment into the mixture. At the end of the heating period, the hot sample mixture was immediately transferred to the rheometer plate for the measurements of the rheological properties.

For the vane yield stress experiments, the SPS–xanthan mixture pastes were also prepared by dispersing SPS and xanthan in distilled water for 1 h at room temperature and heating at 95 °C in a water bath for 30 min with mild agitation provided by a stirrer. The hot paste was quickly cooled in an ice-water bath for 15 min until it reached a temperature of about 30 °C, following the method of Genovese and Rao (2003).

2.2. Flow and dynamic rheological measurements

For measurements of the rheological properties of the SPS–xanthan mixtures, steady and dynamic shear rheological data were obtained with a rheometer (AR 1000, TA Instruments, New Castle, DE) using a parallel plate system (4 cm diameter) with a gap of 500 μm. Each sample was transferred to the rheometer plate at the desired temperature and excess material was wiped off with a spatula. Steady shear (shear stress and shear rate) data were obtained over a shear rate range of 1.0–1000 s⁻¹ at different temperatures (25–70 °C). In order to describe the variation in the rheological properties of samples under steady shear, the data were fitted to the well-known power law model (Eq. (1)), which is used extensively to describe the flow properties of non-Newtonian liquids in theoretical analysis as well as in practical engineering applications (Barnes, Hutton, & Walters, 1989).

$$\sigma = K\dot{\gamma}^n \quad (1)$$

where, σ is the shear stress (Pa), $\dot{\gamma}$ is the shear rate (s⁻¹), K is the consistency index (Pa sⁿ), and n is the flow behaviour index (dimensionless). The apparent viscosity ($\eta_{a,100}$) at 100 s⁻¹ was calculated from the magnitudes of K and n . The effect of temperature (25–70 °C) on apparent viscosity was studied. Dynamic shear data were obtained from frequency sweeps over the range of 0.63–63 rad s⁻¹ at 3% strain. The 3% strain was in the linear viscoelastic region. Frequency sweep tests were also performed at 25 °C. TA rheometer Data Analysis software (version VI. 1.76) was used to obtain the experimental data and to calculate the storage modulus (G'), loss modulus (G''), complex viscosity (η^*), and loss tangent ($\tan \delta = G''/G'$). In order to relax the samples before the steady and dynamic shear rheological measurements were taken, all samples were allowed to rest at the initial temperatures for 5 min. These rheological measurements were performed in triplicate.

For dynamic moduli measurements in the ageing process at 4 °C, each sample was loaded onto the 4 °C platen of the rheometer and the exposed sample edge was covered with a thin layer of light paraffin oil to prevent evaporation during measurements. G' values were monitored for 10 h at 6.28 rad s⁻¹ and 3% strain. The rheological measurements during ageing were conducted in duplicate.

2.3. Vane yield stress

Each sample mixture prepared for the vane yield stress measurements was immediately poured into a jacketed glass vessel (8 cm diameter, 12 cm height) connected to a constant temperature circulator (Model DS50-K10, Haake GmbH, Karlsruhe, Germany) which can provide working temperatures in the range of 0–90 °C (±0.1 °C). Magnitudes of yield stresses were obtained with a Haake VT550 viscometer (Haake Inc., Germany) at 25 °C using a six-blade vane (4 cm diameter, 6 cm height). The vane was gently placed in the sample and allowed to rest for 1 h to recover its structure and reach the measurement temperature. Magnitudes of peak torque values were obtained at the lowest shear rate, 0.01 s⁻¹. The magnitudes of vane yield stress (σ_0) were calculated from the maximum torque value (T_m), the diameter (D), and the height (H) of the vane according to the equation (Eq. (2)):

$$T_m = \frac{\pi D^3}{2} \left(\frac{H}{D} + \frac{1}{3} \right) \sigma_0 \quad (2)$$

3. Results and discussion

3.1. Flow behaviour

The shear stress (σ) versus shear rate ($\dot{\gamma}$) data at 25 °C were well fitted to the simple power law model (Eq. (1)) with high determination coefficients ($r^2 = 0.98$ – 0.99), as shown in Table 1. All samples had high shear-thinning behaviour with values of flow behaviour indices (n) as low as 0.24–0.36. The n values decreased with an increase in xanthan concentration, indicating that the SPS–xanthan mixtures became more pseudoplastic, showing a

Table 1
Effect of xanthan concentration on flow rheological properties of sweet potato starch–xanthan mixtures at 25 °C.

Concentration (%)	Apparent viscosity	Power law		
	$\eta_{a,100}$ (Pa s)	n	K (Pa s ⁿ)	r^2
0 (no gum)	0.92 ± 0.01	0.36 ± 0.00	17.6 ± 0.21	0.99
0.2	0.80 ± 0.01	0.32 ± 0.00	18.3 ± 0.20	0.99
0.4	0.92 ± 0.01	0.28 ± 0.00	25.3 ± 0.21	0.99
0.6	0.97 ± 0.01	0.24 ± 0.00	32.2 ± 0.81	0.98

dependence on xanthan concentration. The magnitudes of the apparent viscosity ($\eta_{a,100}$) and consistency index (K) obtained from the power law model increased with an increase in xanthan concentration from 0.2 to 0.6%. However, the $\eta_{a,100}$ value at a concentration of 0.2% was much lower than that of the control (0% gum), due to the fact that the n values of SPS–xanthan mixtures were lower compared to the control. Such high shear-thinning behaviour of SPS–xanthan mixtures can also be attributed to the unique rigid, rod-like conformation and high molecular weight of xanthan gum (Urlacher & Noble, 1997). From these results, it was found that the SPS–xanthan mixtures had high shear-thinning behaviour with yield stress and their steady shear properties were apparently influenced by the concentration of xanthan gum.

3.2. Effect of temperature on apparent viscosity

The effect of temperature (25–70 °C) on the apparent viscosity of starch pastes mixed with gums at a specified shear rate can be determined using an Arrhenius model (Eq. (3)), in which the apparent viscosity ($\eta_{a,100}$) decreases exponentially with temperature:

$$\eta_{a,100} = A \cdot \exp(E_a/RT) \quad (3)$$

where $\eta_{a,100}$ is the apparent viscosity (Pa s) at 100 s^{-1} , A is a constant (Pa s), T is the absolute temperature (K), R is the gas constant ($8.3144 \text{ J mol}^{-1} \text{ K}^{-1}$), and E_a is the activation energy (kJ mol^{-1}). The magnitudes of E_a were determined at each xanthan gum concentration from regression analysis of $1/T$ versus $\ln \eta_{a,100}$. The calculated E_a values at 0%, 0.2%, 0.4%, and 0.6% xanthan concentrations were 18.1, 12.6, 10.6, and 8.29 kJ mol^{-1} , respectively, with high determination coefficients ($r^2 = 0.90\text{--}0.97$). E_a decreased with an increase in xanthan concentration. The decrease in apparent viscosity with temperature is more pronounced at lower xanthan concentration. This is in good agreement with our previous study of rice starch–xanthan mixtures (Kim & Yoo, 2006). The E_a values (8.29–12.6 kJ mol^{-1}) of the SPS–xanthan mixtures in the gum concentration range of 0.2–0.6% were relatively higher than those (2.46–7.98 kJ mol^{-1}) of the rice starch–xanthan mixtures, which were measured under the same experimental conditions in our laboratory. This indicates that the viscosity of SPS–xanthan mixtures is more responsive to temperature changes in comparison with the rice starch–xanthan mixtures. The differences of E_a values between SPS–xanthan and rice starch–xanthan mixture samples appear to be due to differences in the chemical structure of starch. In addition, the E_a values (8.29–18.1 kJ mol^{-1}) of SPS–xanthan mixtures changed greatly with the increase in xanthan concentration from 0 to 0.6%, showing lower E_a values than those (17.5–23.7 kJ mol^{-1}) of previously described SPS–galactomannan mixtures (Choi & Yoo, 2008). Marcotte, Hoshahili, and Ramaswamy (2001) reported that xanthan gum solutions exhibited small viscosity changes with increasing temperature in comparison to other gums and that the temperature effect decreased with increasing gum concentration. The lower E_a values in the presence of xanthan gum may be related to its lower flow behaviour index (n) (Table 1), i.e., the more pseudoplastic the products, the lower the temperature effects on their apparent viscosity (Van Wazer, Lyons, Kim, & Colwell, 1964).

3.3. Dynamic shear properties

Plots of frequency (ω) versus storage modulus (G') and loss modulus (G'') for SPS–xanthan mixtures at 25 °C (Fig. 1) showed that the magnitudes of G' and G'' increased with an increase in ω , and G' was much greater than G'' at all values of ω showing a slight frequency dependency. In general, the dynamic rheological data of $\log(G', G'')$ versus $\log \omega$ were subjected to linear regression, and Table 2 provides the magnitudes of the slopes (n' and n''), intercepts (K' and K'') and r^2 in the following equations (Eqs. (4) and (5)):

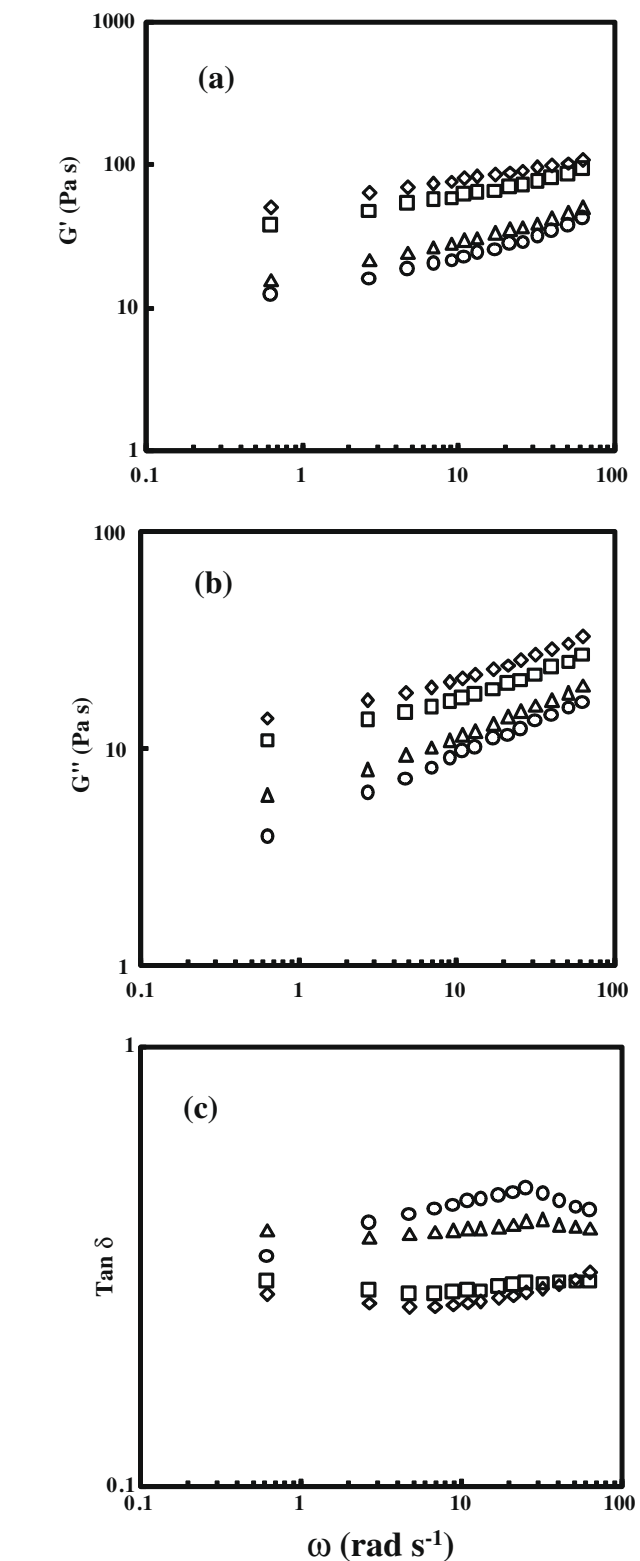


Fig. 1. Plot of $\log G'$ and $\log G''$ versus $\log \omega$ of sweet potato starch–xanthan mixtures at 25 °C: (○) 0% (control), (△) 0.2%, (□) 0.4%, (◇) 0.6%.

$$G' = K'(\omega)^{n'} \quad (4)$$

$$G'' = K''(\omega)^{n''} \quad (5)$$

The magnitudes of K' and K'' increased with an increase in xanthan concentration and K' values (11.7–54.5 Pa s) were much larger than those (4.66–13.2 Pa s) of K'' . There was a substantial

Table 2Effect of xanthan concentration on n' , n'' , K' , and K'' parameters at 25 °C as determined from Eqs. (4) and (5).

Concentration (%)	G'			G''		
	n'	K' (Pa s)	r^2	n''	K'' (Pa s)	r^2
0 (no gum)	0.30 ± 0.01	11.7 ± 0.15	0.97	0.33 ± 0.00	4.66 ± 0.20	0.99
0.2	0.26 ± 0.02	16.1 ± 0.48	0.99	0.27 ± 0.00	6.19 ± 0.04	0.99
0.4	0.19 ± 0.01	38.8 ± 0.66	0.99	0.22 ± 0.01	10.5 ± 0.35	0.98
0.6	0.16 ± 0.01	54.5 ± 0.36	0.99	0.21 ± 0.00	13.2 ± 0.17	0.97

difference between the K' values of the mixtures and the control as compared to the K'' values. The slopes of SPS–xanthan mixtures with n' (0.16–0.26 Pa s) lower than n'' (0.21–0.27 Pa s) decreased with an increase in xanthan concentration, and were also relatively lower than those ($n' = 0.30$ Pa s; $n'' = 0.33$ Pa s) of the control. These observed results indicate that the elastic properties of SPS pastes may be increased by the presence of xanthan gum. Such elastic properties of SPS–xanthan mixtures can merely be related to the associations of ordered chain segments of xanthan gum, resulting in a weak three-dimensional network, as described by Doublier and Cuvelier (1996). For all samples, $\tan \delta$ values were in the range of 0.24–0.40, indicating that the elastic nature prevailed over the viscous nature. The $\tan \delta$ values (0.24–0.38) of the SPS–xanthan mixtures were lower than those (0.40) of the control (Fig. 1), meaning that they are more structured and more elastic gel-like compared to the control. They also decreased with increasing xanthan concentration, indicating an increase in the elastic characteristics of SPS–xanthan mixtures. From these observations, it was found that the SPS–xanthan mixtures showed more solid-like behaviour than the control, indicating that xanthan gum can reinforce the network structure of the starch pastes. Therefore, the addition of xanthan gum appears to contribute synergistically to the rheological properties of SPS–xanthan mixtures.

Many researchers have investigated the synergistic effect of starch and gums. The synergistic effect of gums on the rheological properties of starch pastes has been explained by various mechanisms, which are an interaction between starch exudates and the gum, an increase of the gum concentration in the continuous phase of the medium, and the effect of the gum on the physical properties of the starch granules, such as the size, shape, rigidity, integrity, and adhesive interactions among the granules, as well as the amount of exudates from the starch granules (Mandala & Bayas, 2004; Ross-Murphy, 1984). Based on a similar mechanism, the synergistic effect of xanthan gum on the rheological properties of SPS pastes can be interpreted as an increase in the elastic properties of xanthan gum, due to the increase in its local concentration in the continuous phase. This is because the volume of the phase accessible to xanthan gum is reduced, due to swelling of the starch granules during gelatinisation (Alloncle & Doublier, 1991). This mechanism can be explained by phase separation processes in relation to the incompatibility phenomena existing between unlike polysaccharides, resulting from the preferential interactions between like polysaccharides over interactions between unlike polysaccharides (amylose and xanthan gum in the continuous phase). Recently, microscopic observations of starch granules in starch–xanthan mixture systems also clearly demonstrated the evidence of a phase separation between starch amylose and xanthan, indicating that the increase in the local concentration of xanthan gum in the continuous phase is due to the excluded volume effect of the starch granules (Mandala & Bayas, 2004). The same mechanism was observed earlier in other studies of starch–xanthan mixtures (Alloncle & Doublier, 1991; Kim & Yoo, 2006; Sikora, Kowalski, & Tomasiak, 2008).

3.4. Vane yield stress

Fig. 2 illustrates yield stress *versus* time curves and vane yield stress values (σ_0) of SPS–xanthan mixtures at different gum concentrations. These curves exhibited an initial linear increase in stress that represents the elastic response of the material due to stretching of network bonds. Following a peak stress where the material yielded, there is a stress decay that is related to the gradual structural breakdown (James, Williams, & Williams, 1987). The yield stress values of SPS–xanthan mixtures increased with an increase in xanthan concentration. The synergistic effect of xanthan

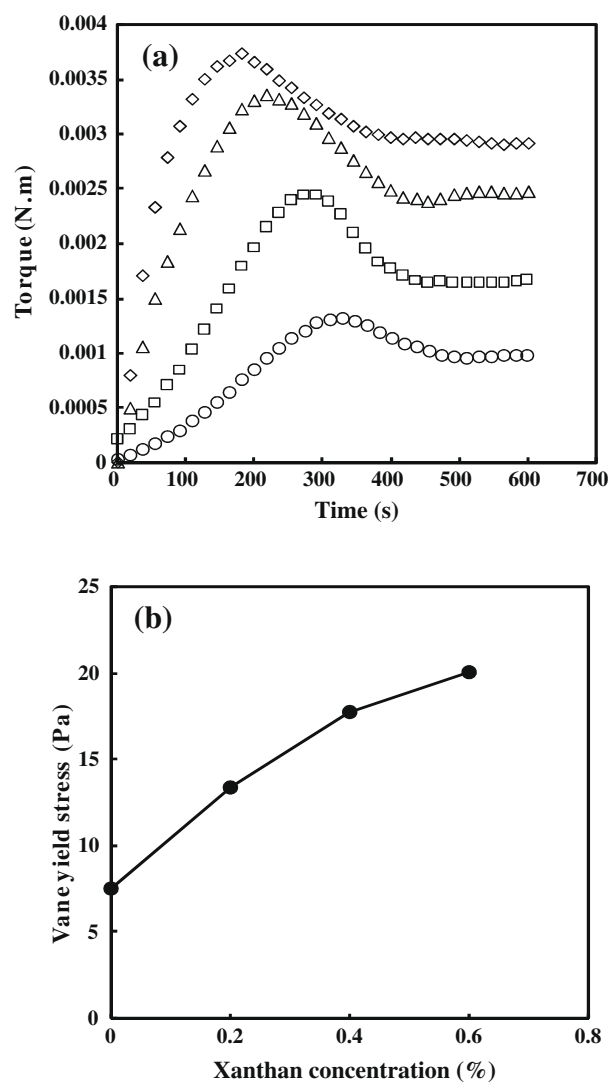


Fig. 2. Yield stress–time curves (a) and vane yield stress values (b) of sweet potato starch–xanthan mixtures at different gum concentrations at 25 °C: (○) 0%, (△) 0.2%, (□) 0.4%, (◇) 0.6%.

gum in the SPS–xanthan mixture system is evident in the higher values of yield stress compared to the control (0% gum). The initial slope of the yield stress *versus* time curves also increased with increasing xanthan concentration, indicating that the elastic properties of SPS were strongly influenced by the addition of xanthan gum. Such higher elastic properties may be related to the rigid conformation of xanthan gum. This rigidity implies a much more limited mobility of the chains and hence much longer relaxation times, resulting in higher elastic properties, as described by Doublier and Couvelier (1996). Choi, Chun, and Yoo (2006) also reported a more pronounced effect of xanthan gum on elastic properties, based on a comparison of the dynamic moduli of xanthan and other gums in the gum solution systems. Such increases in the elastic properties can also be explained by the pronounced effect of xanthan gum on K' values in the SPS–xanthan mixture systems, as described previously (Table 2). Therefore, the increased K' and vane yield stress could be due to the formation of an elastic weak gel network. In colloidal dispersions, several researchers (Buscall, Goodwin, Hawkins, & Ottelwill, 1982; Chen & Zukoski, 1990; Fagan & Zukoski, 1997) have also shown that the yield stress and G' at high frequency are proportional to each other. From these observations, it can be concluded that the vane yield stress is closely related to the elastic behaviour in this system.

3.5. Effect of xanthan concentration on G' during ageing

The gelation phenomenon of starch pastes containing amylose can be detected by measurements of the dynamic mechanical storage modulus (G'), which reflects the elastic property of the sample and has a characteristic pattern as a function of time (Eidam & Kulicke, 1995). Fig. 3 shows changes in storage moduli (G') for SPS–xanthan mixtures with different gum concentrations, as a function of ageing time (10 h at 4 °C). The G' values during a long ageing period increased with increasing gum concentration. The G' values for SPS–xanthan mixtures reached a plateau after a long ageing, whereas the control showed a continuous increase in G' without the plateau region. These results indicate that the addition of xanthan gum led to an increase of the structure development rate with increasing gum concentration. The rapid increase in G' during ageing can be interpreted as a result of the increase in the effective concentration of amylose in starch that is concentrated within the continuous phase, as explained by Alloncle, Lefebvre, Llamas, and Doublier (1989). These results also confirm an earlier observation that the rate of G' increase during ageing was affected by the

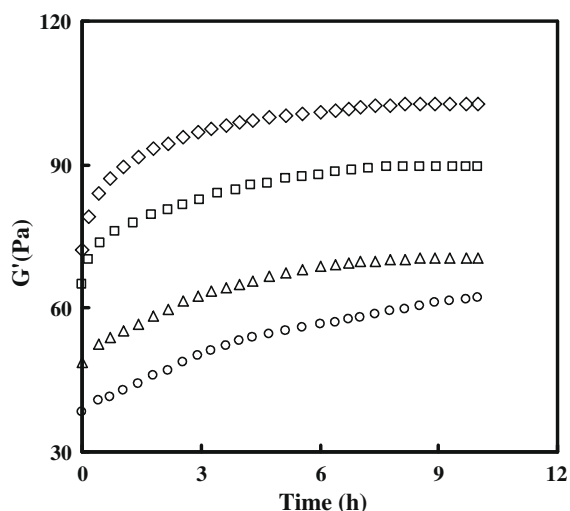


Fig. 3. Changes in G' during ageing at 4 °C for 10 h for sweet potato starch–xanthan mixtures as a function of gum concentration: (○) 0%, (△) 0.2%, (□) 0.4%, (◇) 0.6%.

Table 3

Parameters of the first order kinetics model (Eq. (6)) for sweet potato starch–xanthan mixtures during ageing at 4 °C for 10 h.

Xanthan gum concentration (%)	G'_0 (Pa)	G'_{sat} (Pa)	k ($\times 10^{-4} \text{ s}^{-1}$)	r^2
0 (no gum)	38.4 ± 0.06	61.7 ± 0.66	0.84 ± 0.02	0.89
0.2	48.3 ± 0.50	70.3 ± 1.91	0.88 ± 0.01	0.94
0.4	67.2 ± 1.49	90.5 ± 0.06	1.06 ± 0.01	0.94
0.6	71.9 ± 0.37	102 ± 2.26	1.33 ± 0.02	0.96

presence of xanthan gum and greatly dependent on the xanthan concentration (Kim & Yoo, 2006). In addition, in the starch–gum mixture systems such gel-accelerating effect during ageing may be caused by the thickening effect of the gums, which restrict the mobility of the amylose molecules, resulting in the local interactions between amylose molecules forming more easily and quickly, as described by Eidam and Kulicke (1995). The same effect was observed in previous studies of other starch–gum mixtures (Alloncle & Doublier, 1991; Eidam & Kulicke, 1995; Kim, Lee, & Yoo, 2006; Kim & Yoo, 2006).

If the G' value is linearly related to the development of tertiary structure, the changes in the G' of gelation during ageing can be described by first order kinetics (Grosso & Rao, 1998). The structure development rate (k) of SPS–xanthan mixtures at constant temperature was determined based on an equation of first-order kinetics (Eq. (6)) that is evaluated from semilog plots of unaccomplished structure development *versus* time.

$$\ln \frac{G'_{\text{sat}} - G'_t}{G'_{\text{sat}} - G'_0} = kt \quad (6)$$

where G'_{sat} is the G' value at the plateau of ageing time (10 h), G'_t is the G' value at any time t , G'_0 is the G' value at zero time, and k (s^{-1}) is the structure development rate constant of gelation. Table 3 shows the values of G'_0 , G'_{sat} , and k of the first-order kinetics of SPS–xanthan mixtures during ageing at 4 °C for 10 h. For the control, the structure development rate was not determined because of a continuous increase in G' without a plateau region, even after 10 h, as shown in Fig. 3. The values of k for SPS–xanthan mixtures increased with an increase in xanthan concentration, indicating that the gelation of SPS–xanthan mixtures was promoted by the presence of xanthan gum, as shown in Table 3. The higher k values of the mixtures compared to the control mean that xanthan gum promoted starch retrogradation at the beginning of ageing, and then retarded it slightly during longer storage, as shown in Fig. 3. From these results, it was found that the addition of xanthan gum led to a great increase in the structure development rate with increasing xanthan concentration, indicating that the elastic character of xanthan gum can influence the reinforcement of the overall gel properties, due to the incompatibility phenomena between unlike polysaccharides.

4. Conclusions

In SPS–xanthan mixture systems rheological parameters obtained from the power law model were strongly influenced by xanthan gum concentration. The dynamic rheological data for storage (G') and loss moduli (G'') as a function of frequency (ω) at 25 °C showed that the mixtures displayed weak gel-like behaviour. The Arrhenius temperature relationship seemed to be influenced by the xanthan concentration and the chemical structure of starch. An increase in the elastic characteristics of the SPS–xanthan mixtures can be explained by the decrease in $\tan \delta$ values with increasing gum concentration. Magnitudes of vane yield stress increased with an increase in xanthan concentration, suggesting that the addition of xanthan gum gave rise to a synergistic effect on the yield stress of SPS pastes. Changes in G' values of the SPS–xanthan

mixtures during ageing at 4 °C for 10 h were strongly influenced by the presence of xanthan gum. The structure development rate constant (k) of gelation during ageing, which was described by a first-order kinetic process, increased with an increase in xanthan concentration. The ability of xanthan gum to increase the rate of gelation appeared to be attributed to phase separation processes as a result of incompatibility phenomena between the starch component and the xanthan gum.

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