

Effect of NaCl Addition on Rheological Behaviors of Commercial Gum-Based Food Thickener Used for Dysphagia Diets

Hyun-Moon Cho¹, Whachun Yoo², and Byoungseung Yoo¹

¹Department of Food Science and Biotechnology, Dongguk University, Seoul 100-715, Korea

²Rheosfood Inc., Seoul 100-715, Korea

ABSTRACT: Rheological properties of thickened fluids used for consumption by people with dysphagia (swallowing difficulty) are very sensitive to several factors, such as thickener type, temperature, pH, sugar, protein, and NaCl. In this study, steady and dynamic rheological properties of thickened water samples mixed with five commercial xanthan gum-based food thickeners (A~E) were studied in the presence of NaCl at different concentrations (0.3%, 0.6%, 0.9%, and 1.2%). The magnitudes of apparent viscosity ($\eta_{a,50}$), consistency index (K), yield stress (σ_{oc}), and dynamic moduli (G' and G'') showed significant differences in rheological behaviors between thickened samples with various NaCl concentrations. Dynamic moduli values of all thickened samples, except for samples with thickener C, were much higher than those of the control (0% NaCl). All rheological parameter values (K, G' , and G'') in a thickener A were much higher than those in other thickeners. These results suggest that rheological properties of thickened samples containing NaCl are strongly affected by xanthan gum-NaCl interaction and depended on the type of thickener.

Keywords: food thickener, NaCl, viscosity, xanthan gum, rheological property

INTRODUCTION

Dysphagia, swallowing difficulty, is mainly caused by stroke, cancer, and neuromuscular disorders, and it may lead to aspiration pneumonia, dehydration, and malnutrition. Therefore, diet modifications, such as diets with thickened fluids, are sometimes recommended for patients with dysphagia to help maintain their nutritional needs (1) and also to reduce the risk of aspiration pneumonia resulting from the intake of thin fluids (2,3). Recently, various commercial food thickeners have been widely used as additives in beverages and thin soups to produce thickened fluids with desirable rheological properties for patients with dysphagia because of ease of preparation, convenience, reasonable cost, and the suspending ability and volume stability of the thickened liquids (4,5). Food thickeners generally have modified starch and gum as their base materials (6). In the present study, xanthan gum (XG)-based food thickeners were investigated for preparing thickened fluids because they are commonly used in diet modifications for patients with dysphagia in Korea due to their palatability and smooth texture when compared to starch-based thickeners (3,7).

Many researchers have studied the rheological properties of thickened fluids containing commercial food thickeners (3,6,8,9). They have reported that the rheological properties of thickened fluids are greatly influenced by the type of thickener, thickener concentration, and dispersing medium. In particular, they also found that the gums in the thickeners interacted differently with the constituents of the dispersing media, resulting in different rheological behaviors depending on the type of dispersing medium. However, there is limited information on thickened fluids with salt (NaCl) such as Korean traditional thin soups. It is known that adding NaCl improves taste and masks off-flavor notes, and also enhances mouthfeel, and most importantly, enhances flavor balance and overall flavor intensity (10). Addition of NaCl may also affect the rheological properties of thickened fluids prepared with food thickeners used for dysphagia patients. Therefore, understanding the rheological properties of various thickened fluids containing different NaCl concentrations may help patients with dysphagia to safely swallow fluids because the correct rheological properties are very important for treating dysphagia. Although extensive literature is available on the rheological properties of thickened fluids with food

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Correspondence to Byoungseung Yoo, Tel: +82-2-2260-3368, E-mail: bsyoo@dongguk.edu

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thickeners, no attempt has been made to study the rheological properties of thickened fluids with commercial XG-based food thickeners as affected by NaCl at different concentrations. Thus, the objective of this study was to investigate the effects of NaCl addition on steady and dynamic rheological properties of thickened water samples prepared with various XG-based food thickeners marketed in Korea. Understanding the effects of NaCl on the rheological properties of thickened water prepared with XG-based thickener will lead to improving the structure stability of XG-based thickeners in the presence of NaCl.

MATERIALS AND METHODS

Materials and sample preparation

Five commercially available instant food thickeners (thickeners A, B, C, D, and E) were provided by a Korean market: thickener A [composite of xanthan gum (XG), guar gum (GG), and dextrin], thickener B, (composite of XG and dextrin), thickener C (composite of XG, carboxymethyl cellulose, GG, and dextrin), thickener D (composite of XG and dextrin), and thickener E (composite of XG and dextrin). All food thickeners were obtained from the following manufacturers: Rheosfood Inc., Seoul, Korea; Sankyo Co., Shizuoka, Japan; Tsuruya chemical industries, Ltd., Yamanashi, Japan; Natural F & P, Inc., Chungbuk, Korea. Sodium chloride (NaCl) was purchased from Sigma Co. (St. Louis, MO, USA). Bottled water (JPDC, Jeju, Korea) was used as the dispersing medium. The NaCl solutions containing 0%, 0.3%, 0.6%, 0.9%, and 1.2% (weight basis) NaCl were prepared with bottled water and stirred for 5 min at room temperature. Subsequently, the thickened water was prepared by mixing the food thickener at a 3% concentration with the NaCl solution at room temperature with moderate stirring for 1 min using a magnetic stirrer. The thickened water sample was immediately transferred to the rheometer plate at 25°C to measure the rheological properties.

Rheological behavior measurements

Flow properties of thickener dispersions were measured with a Carri-Med CSL² 100 rheometer (TA Instruments, New Castle, DE, USA) with a measuring system having a plate-plate geometry (4 cm dia.) at a gap of 500 μm. Steady shear (shear stress and shear rate) data were obtained over the shear rate in the range of 1.0~100 s⁻¹. The data were fitted to the power law (Eq. 1) and Casson (Eq. 2) models in order to determine the steady shear rheological properties of the samples, which are as follows:

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

$$\sigma^{0.5} = K_{oc} + K_C\dot{\gamma}^{0.5} \quad (2)$$

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 behavior index (dimensionless). Casson yield stress (σ_{oc}) was determined as the square of the intercept (K_{oc}) obtained from the linear regression of the square roots of shear rate-shear stress data. Using the magnitudes of K and n , the apparent viscosity ($\eta_{a,50}$) at 50 s⁻¹, a reference shear rate for swallowing, was calculated. Dynamic shear data were obtained from the frequency sweeps over the range of 0.63~62.8 rad/s at the 2% strain, which was in the linear viscoelastic region. Frequency sweep tests were also conducted at 25°C. The TA rheometer Data Analysis software (ver. VI. 1.76, TA Instruments) was used to calculate the storage modulus (G'), loss modulus (G''), and loss tangent ($\tan \delta = G''/G'$). All samples were allowed to equilibrate for 5 min at their initial temperatures prior to the steady and dynamic shear rheological measurements. All rheological measurements were performed in triplicate.

Statistical analysis

The results are reported as the mean with a standard deviation of triplicate measurements for each sample. Analysis of variance (ANOVA) followed by Duncan's multiple range test were used to establish the significance of differences among the mean values at the 0.05 significance level. Statistical analyses were performed using the Statistical Analysis System program (version 9.2) (SAS Institute, Cary, NC, USA).

RESULTS AND DISCUSSION

Flow behavior

The experimental results of the shear stress (σ) vs. $\dot{\gamma}$ data for thickened water samples with different NaCl concentrations at 25°C were well fitted to the power law model (Eq. 1) and Casson model (Eq. 2) with high determination coefficients ($R^2 = 0.97 - 0.99$) (Table 1). All thickened samples with different thickeners had high shear-thinning behaviors with low n values (0.11~0.41), which could possibly be due to the presence of XG in the food thickeners (3,7,11). It is known that the shear-thinning character of XG is due to the formation of high-molecular-weight aggregates of stiff rod molecules (12). Thickened samples without NaCl (the control) ($n = 0.11 \sim 0.16$) were much thinner compared to those with NaCl ($n = 0.14 \sim 0.41$), and furthermore, significant differences were observed in the n values among all of the thickened samples with NaCl, indicating that

Table 1. Steady shear rheological properties of thickened water samples with different thickeners

Thickener type	NaCl concentration (%)	Apparent viscosity $\eta_{a,50}$ (Pa·s)	Power law		Yield stress σ_{oc} (Pa)
			n (–)	K (Pa·s ⁿ)	
A	0	0.82±0.01 ^{e1)}	0.11±0.00 ^e	27.0±0.20 ^d	31.1±0.32 ^d
	0.3	1.89±0.01 ^a	0.14±0.00 ^d	55.2±0.16 ^a	64.2±0.47 ^a
	0.6	1.75±0.00 ^b	0.17±0.00 ^c	44.5±0.48 ^b	52.1±1.33 ^b
	0.9	1.60±0.01 ^c	0.20±0.00 ^b	36.8±0.06 ^c	44.1±1.19 ^c
	1.2	1.29±0.02 ^d	0.25±0.00 ^a	24.3±0.16 ^e	30.9±1.10 ^d
B	0	1.40±0.01 ^c	0.16±0.00 ^d	36.9±0.51 ^b	50.9±0.63 ^b
	0.3	2.00±0.00 ^a	0.17±0.00 ^d	52.0±0.41 ^a	65.5±0.60 ^a
	0.6	1.69±0.08 ^b	0.22±0.01 ^c	35.7±0.21 ^c	39.6±0.80 ^c
	0.9	1.33±0.04 ^c	0.33±0.01 ^b	18.3±0.10 ^d	24.7±0.22 ^d
	1.2	1.07±0.05 ^d	0.41±0.01 ^a	11.0±0.15 ^e	16.9±0.23 ^e
C	0	0.96±0.01 ^c	0.14±0.00 ^d	27.3±0.23 ^b	32.5±0.51 ^b
	0.3	1.20±0.01 ^a	0.14±0.00 ^d	34.5±0.68 ^a	39.6±1.42 ^a
	0.6	1.01±0.01 ^b	0.21±0.00 ^c	22.3±0.29 ^c	28.9±0.80 ^c
	0.9	0.78±0.01 ^d	0.24±0.01 ^b	15.0±0.04 ^d	18.8±0.27 ^d
	1.2	0.71±0.01 ^e	0.28±0.00 ^a	11.7±0.02 ^e	15.4±0.49 ^e
D	0	0.90±0.01 ^b	0.15±0.00 ^c	25.0±0.31 ^b	24.6±0.24 ^b
	0.3	0.98±0.01 ^a	0.15±0.00 ^c	26.9±0.44 ^a	30.0±0.63 ^a
	0.6	0.72±0.05 ^c	0.23±0.00 ^b	14.4±0.65 ^c	17.8±0.95 ^c
	0.9	0.51±0.02 ^d	0.28±0.01 ^a	8.51±0.03 ^d	11.2±1.80 ^d
	1.2	0.41±0.02 ^e	0.28±0.01 ^a	6.81±0.02 ^e	8.32±1.11 ^e
E	0	1.05±0.02 ^b	0.15±0.00 ^d	29.2±0.19 ^a	39.4±0.42 ^a
	0.3	1.14±0.03 ^a	0.19±0.00 ^c	27.3±0.59 ^b	32.8±1.04 ^b
	0.6	0.81±0.01 ^c	0.25±0.00 ^b	15.3±0.29 ^c	18.8±0.34 ^c
	0.9	0.61±0.02 ^d	0.32±0.01 ^a	8.74±0.12 ^d	11.7±1.15 ^d
	1.2	0.51±0.02 ^e	0.32±0.01 ^a	7.21±0.03 ^e	8.44±1.18 ^e

¹⁾Mean of three measurements±standard deviation values in the same thickener type with different letters (a-e) are significantly different ($P<0.05$).

the NaCl concentration in the thickened water systems had an effect on the n values. In general, the n values increased with an increase in the NaCl concentration. However, no significant change in n values of thickened samples, except for thickener A and E, was observed when the concentration of NaCl was increased from 0% to 0.3%. This suggests that the addition of NaCl at high concentrations (0.6%~1.2%) reduced the shear-thinning of XG-based thickeners. The n value of the thickened sample is very important because a high n value results in a slimy mouthfeel, as described by Szczesniak and Farkas (13). In contrast, the thickened samples with low n values appear to thin on mastication and give a pleasant, light mouthfeel (12). Therefore, the addition of NaCl to XG-based thickeners may improve the organoleptic sliminess due to a low degree of shear-thinning (a high n value). Among the food thickeners (thickener A~E) examined, the thickener A at various NaCl concentrations had lower n values ($n=0.11\sim 0.25$) compared to other thickeners ($n=0.14\sim 0.41$), indicating that the thickener A was less slimy and had better mouthfeel than other thickeners in the presence of NaCl (Table 1).

In general, it is known that steady-shear viscosity is a dominant parameter for the flow velocity of a food bo-

lus, and yield stress is also a rheological parameter involved in the perceived ease of swallowing, as noted by Funami (14) and Steele et al. (15). The K, $\eta_{a,50}$, and σ_{oc} of the thickened samples, which were obtained from the power law and Casson models, decreased as the NaCl concentration increased from 0.3% to 1.2% (Table 1), suggesting that the higher NaCl addition resulted in less resistance to flow. There was an essential change in K and σ_{oc} values between concentrations of NaCl when compared to the $\eta_{a,100}$ values. This result indicates that the K and σ_{oc} values are reliable indicators of rheological parameters for estimating flow properties of thickened samples as a function of NaCl concentration. In general, the thickened water samples with XG-based thickeners showed a large increase in K, $\eta_{a,100}$, and σ_{oc} with the addition of NaCl at 0.3% concentration, indicating the synergistic effect of NaCl on XG-based thickeners, except for thickener E. However, the decrease in rheological parameter values of thickened samples at higher concentrations ($>0.3\%$) can be due to the conformation change in the XG in the presence of NaCl (16). Sereno et al. (17) suggested that the addition of NaCl is responsible for shielding the ionic groups on XG side chains, resulting in a reduction of individual molecular volume occupancy, leading to a decrease in viscosity. In addition, the

thickeners A and B showed much higher rheological parameter values (K , $\eta_{a,50}$, and σ_{oc}) when compared to other thickeners. Thus, it can be concluded that the thickened samples in the presence of NaCl at 0.3% concentration could have higher rheological parameter values compared to the control (0% NaCl). Moreover, the steady shear properties of thickened samples were dependent on the type of thickener and were strongly influenced by the addition of NaCl as well as the NaCl

concentration. Therefore, the manufacturer's guidelines for preparing thickened fluids containing NaCl from XG-based thickeners need to be better specified as to the NaCl concentration.

Dynamic shear properties

Plots of frequency (ω) versus G' and G'' for the thickened water samples with different thickeners at a 0.6% NaCl concentration (Fig. 1) revealed that the magnitudes of G'

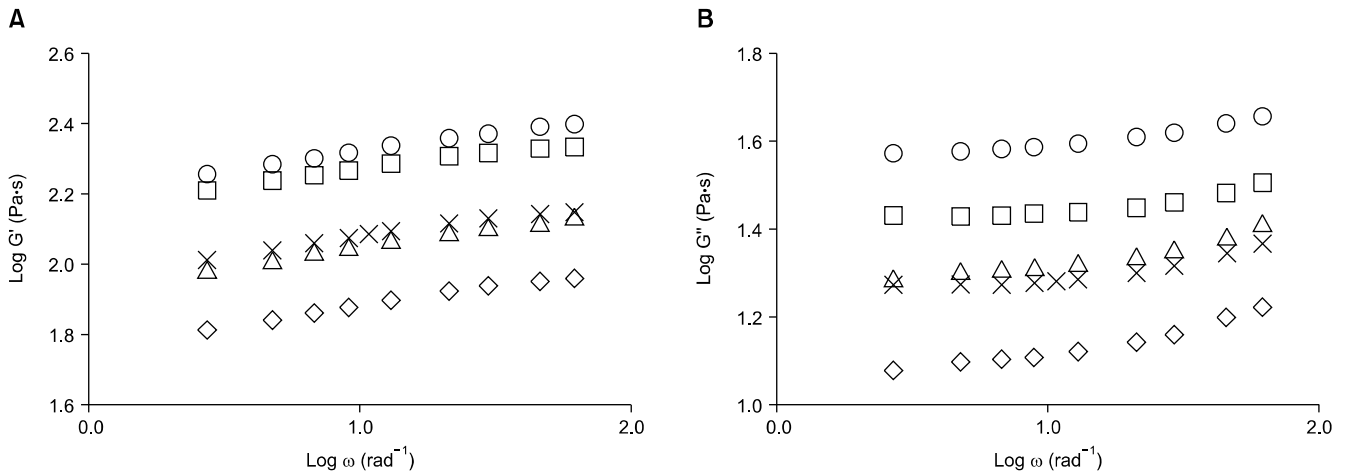


Fig. 1. Plots of G' and G'' versus low ω for thickened water samples with various thickeners at 0.6% NaCl. (A) G' , (B) G'' . \circ , thickener A; \square , thickener B; \triangle , thickener C; \diamond , thickener D; \times , thickener E.

Table 2. Storage modulus (G') and loss modulus (G'') at 6.28 rad·s⁻¹ for thickened water samples with different thickeners

Thickener type	NaCl concentration (%)	G' (Pa)	G'' (Pa)	$\tan \delta$
A	0	57.0±0.36 ^{e1)}	16.1±0.01 ^e	0.28±0.00 ^a
	0.3	187±2.63 ^d	33.7±0.52 ^d	0.18±0.00 ^c
	0.6	202±2.16 ^c	36.4±0.35 ^c	0.18±0.00 ^c
	0.9	210±0.14 ^b	39.1±0.08 ^b	0.19±0.00 ^b
	1.2	219±2.23 ^a	41.2±0.64 ^a	0.19±0.00 ^b
B	0	103±3.22 ^c	15.7±0.34 ^d	0.15±0.00 ^a
	0.3	170±0.92 ^b	21.9±0.15 ^c	0.13±0.00 ^b
	0.6	184±0.87 ^a	24.6±0.41 ^b	0.13±0.00 ^b
	0.9	182±0.17 ^a	25.8±0.20 ^a	0.14±0.00 ^a
	1.2	166±2.27 ^b	24.4±0.29 ^b	0.15±0.01 ^a
C	0	101±1.13 ^c	21.2±0.15 ^a	0.21±0.00 ^a
	0.3	121±2.92 ^a	20.5±0.39 ^a	0.17±0.00 ^c
	0.6	110±1.73 ^b	19.1±0.04 ^b	0.17±0.00 ^c
	0.9	98.0±0.13 ^{cd}	17.3±0.27 ^c	0.18±0.00 ^b
	1.2	94.4±3.40 ^d	17.2±0.39 ^c	0.18±0.00 ^b
D	0	60.0±2.45 ^d	10.8±0.21 ^c	0.18±0.01 ^a
	0.3	79.4±0.68 ^a	11.5±0.36 ^b	0.14±0.00 ^c
	0.6	73.3±1.25 ^b	11.4±0.03 ^b	0.16±0.00 ^b
	0.9	68.6±0.07 ^c	12.1±0.11 ^a	0.18±0.00 ^a
	1.2	67.7±0.31 ^c	12.2±0.01 ^a	0.18±0.00 ^a
E	0	79.5±1.52 ^c	13.3±0.13 ^c	0.17±0.00 ^a
	0.3	113±1.81 ^a	14.3±1.58 ^c	0.13±0.01 ^b
	0.6	112±2.99 ^a	17.0±0.25 ^a	0.15±0.01 ^c
	0.9	96.1±0.58 ^b	16.4±0.18 ^a	0.17±0.00 ^a
	1.2	84.5±0.85 ^c	14.7±0.19 ^b	0.17±0.00 ^a

¹⁾Mean of three measurements±standard deviation values in the same thickener type with different letters (a-e) are significantly different ($P<0.05$).

and G'' increased with an increase in ω and G' was much higher than G'' at all values of ω with frequency dependency. This exhibited a weak gel-like behavior. All thickened samples in the presence of NaCl, except for thickener C, showed higher dynamic moduli values than the control, indicating that the addition of NaCl enhanced the viscoelastic properties of thickened water samples. Addition of NaCl slightly changed the G' values when compared to G'' values. In particular, there were larger differences in G' values between NaCl concentrations of 0% and 0.3% when compared to G'' . This indicates that the addition of NaCl at a low concentration stabilized the thickened water samples by contributing to a higher solid-like component. Meyer et al. (18) reported that the dynamic moduli (G' and G'') of XG in the presence of NaCl could increase due to the salt-induced self-aggregation of XG molecules. Wyatt and Liberatore (19) also noted that the addition of NaCl enhanced the intermolecular interaction of XG molecules due to the charge screening effect, which causes a reduction in the hydrodynamic size of the molecule, thereby promoting a network formation. This network formation can result in an increase of the elastic properties of thickened samples with NaCl, evidenced by the higher G' compared to G'' , as shown in Table 2. Therefore, it is obvious that the addition of NaCl greatly influences the synergistic effect of the elastic properties of XG in the XG-based thickeners, resulting in a significant increase in the G' values of the thickened water samples. Based on the above observations, it was found that such higher dynamic moduli (G' and G'') of thickened samples with thickeners, except for a thickener C, in the presence of NaCl might be attributed to the synergistic effect of NaCl. Changes in the dynamic moduli values of the thickened samples with different NaCl concentrations were more pronounced with thickener A in comparison to the other thickeners. The G' values of thickener A increased with increased NaCl concentration from 0.3% to 1.2%, whereas those of thickener C, D, and E decreased, indicating that NaCl in thickened water samples has different effects depending on the type of thickener. In addition, changes in G'' in thickened samples with thickener A at different NaCl concentrations followed patterns similar to those observed for G' , but other thickeners generally showed different patterns. These observations lead to the conclusion that the addition of NaCl has a great and variable effect on the dynamic rheological properties of thickened water samples with XG-based thickeners.

The $\tan \delta$ values of all samples were within the range of 0.13~0.28 (Table 2), which are much smaller than the unity, indicating that all the samples are predominantly elastic. The $\tan \delta$ values (0.13~0.19) of thickened samples in the presence of NaCl were lower than

those (0.15~0.28) of the control, indicating that they are more structured and more elastic gel-like compared to those of the control. In particular, a significant change in $\tan \delta$ was observed between 0% and lower concentrations (0.3% and 0.6%), suggesting that the elastic properties of thickened samples can be more pronounced at lower NaCl concentrations. Such significant changes in the $\tan \delta$ in the presence of NaCl suggest that a different structural product type is being presented to dysphagia patients despite the fact that the thickened samples have the same viscosity, as noted by Payne et al. (20). Therefore, it could be concluded that a large decrease in $\tan \delta$ values of the thickened samples in the presence of NaCl was found at lower NaCl concentrations (0.3% and 0.6%), and it appeared to be due to the salt induced self-aggregation of XG molecules in the thickeners.

From these observations, we found that the addition of NaCl has a great and variable effect on the rheological properties of thickened water samples prepared with XG-based thickeners. The results of this study will provide valuable information for setting the guidelines for preparing thickened fluid products with the appropriate concentrations of NaCl for patients with dysphagia. Addition of NaCl results in different rheological properties of thickened fluids, depending on the type of thickener and the NaCl concentration. Bottled water was used as the dispersing medium for thickened samples with NaCl in this study. Therefore, additional studies are needed to investigate various fluids, such as sodium soups, to extend the results of this work.

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AUTHOR DISCLOSURE STATEMENT

The authors declare no conflict of interest.

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