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Note

Comparison of Rheological and Tribological Properties of Cold Thickened Beverages for Dysphagia Management

Won Hyeong Cho, Juneha Bak, and Byoungseung Yoo

Department of Food Science and Biotechnology, Dongguk University-Seoul, Gyeonggi 10326, Korea

ABSTRACT: This study investigated the rheological and tribological properties of cold beverages [bottled water (BW), sports drink (SD), orange juice (OJ), and whole milk (WM)] thickened with various concentrations (1%, 2%, and 3%, w/w) of xanthan gum-based food thickeners. All thickened beverages exhibited high pseudoplastic behavior, with increasing thickener concentration leading to higher viscosity and viscoelastic moduli and a lower flow behavior index. Thickened BW, SD, and WM exhibited typical Stribeck curves covering the boundary, mixed, and hydrodynamic lubrication regimes. However, thickened OJ displayed a different curve pattern comprising five regimes because of the presence of small pulp and gel particles. As the thickener concentration was increased, the maximum friction coefficient (μ) values of thickened BW, SD, and OJ decreased, whereas that of thickened WM increased because of the depletion flocculation of emulsion particles. The maximum μ values of thickened beverages, except for thickened WM, were positively correlated with *n* and tan δ values with increasing thickener concentration. Thus, the tribological characteristics of cold thickened beverages had a good relationship with their rheological properties, which were greatly influenced by the thickener concentration and beverage type.

Keywords: deglutition disorders, rheology, thickened beverage, tribology, xanthan gum-based thickener

INTRODUCTION

Dysphagia, which is characterized by difficulty in swallowing, can arise from stroke, cancer, or neuromuscular disorders and increases the risk of aspiration pneumonia and other respiratory complications (Matta et al., 2006). For patients with dysphagia, food thickeners are often used to modify the rheological properties of beverages, making them safer to consume.

Compared with starch-based thickeners, commercially available xanthan gum (XG)-based thickeners are generally preferred because they have superior thickening characteristics, better palatability and viscosity stability, and smoother texture (Cho and Yoo, 2015). Achieving the desired viscosity of beverages is undoubtedly important for dysphagic patients. Thus, many studies have explored the rheological properties of cold thickened beverages with XG-based thickeners (Cho et al., 2012; Seo and Yoo, 2013; Cho and Yoo, 2015; Kim and Yoo, 2018). In particular, the apparent viscosity at 50 s^{-1} ($\eta_{a,50}$), which is regarded as the reference viscosity characteristic for swallowing for dysphagic patients (Zhu et al., 2014), and the flow behavior index (*n*) have an inverse relationship with organoleptic sliminess (Cho and Yoo, 2015; Kim and Yoo, 2015).

Recently, tribology, which is the study of the lubrication and friction behaviors of interacting surfaces in relative motion, has attracted increasing interest in food science (Araiza-Calahorra et al., 2023). Although the friction coefficient (μ) obtained from tribological analysis can significantly vary with food properties (e.g., viscosity), its magnitude also depends on the nature and characteristics of the chosen surface (Stokes et al., 2011; Upadhyay and Chen, 2019). The μ value obtained from tribological measurements is an effective indication of the lubricating properties between two surfaces at a given moving speed. In particular, soft tribological properties determined using polydimethylsiloxane (PDMS)-based tribopairs, which exhibit similar wettability and deformability to the human tongue, are known for their relevance to food texture and mouthfeel (Rudge et al., 2019). Tribology has been used as a tool to understand polymer solutions' lubrication ability (Stokes et al., 2011; Bak and Yoo, 2024b; Yoon et al., 2024). However, research on the oral tribological properties of cold thickened beverages prepared with XG-based thickeners for dysphagic

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Correspondence to Juneha Bak, E-mail: wnsgk4251@dongguk.edu, Byoungseung Yoo, E-mail: bsyoo@dongguk.edu

patients remains limited compared with studies on their flow and dynamic rheological characteristics. Consequently, the relationships between the rheological and tribological properties of cold thickened beverages for dysphagia management remain unclear. Therefore, in the present study, we compared the rheological and oral tribological properties of various cold thickened beverages [bottled water (BW), orange juice (OJ), sports drink (SD), and whole milk (WM)] prepared with various concentrations of XG-based thickeners to evaluate the relationship between their rheological and tribological characteristics.

MATERIALS AND METHODS

Materials and preparation of thickened beverage

We purchased four commercially available beverages [BW (Jeju Samdasoo), SD (Donga-Otsuka Co., Ltd.), OJ (Coca-Cola Beverage Co.), and WM (Seoul Dairy Co., Ltd.)] from a local market. All beverages were thickened with a commercial XG-based thickener (Visco-up®, Rheosfood Inc.) in accordance with the manufacturer's instructions. The appropriate amount of thickener was added to each beverage and dissolved using a magnetic stirrer for 1 h to achieve concentrations of 1%, 2%, or 3% (w/w). Then, the mixtures were stored overnight in a refrigerator at 4°C to ensure complete hydration.

Rheological measurements

The rheological properties of thickened beverages were determined using the Haake RheoStress 1 Rheometer (Haake GmbH) equipped with a plate-plate geometry (diameter of 35 mm and gap of 500 μm). The sample solution was placed onto the rheometer plate and stabilized for 5 min prior to measurement. The shear stress (σ) was measured in a shear rate ($\dot{\gamma}$) range of 0.1 to 100 s^{-1} at 25°C. A power law equation was used to calculate the consistency index (K) and flow behavior index (n):

$$\sigma = K \cdot \dot{\gamma}^n$$

The K and n values were used to determine the apparent viscosity at 50 s^{-1} ($\eta_{a,50}$), which is the reference shear rate for swallowing (Jo et al., 2018).

The dynamic viscoelastic moduli of all samples were measured using a small amplitude oscillatory rheological measurement. Frequency sweep tests were performed in the range of 0.63 to 62.8 rad·s^{-1} under a strain of 2% within a linear viscoelastic region. All measurements were performed at 25°C. The slope and intercept values for the elastic (G') and viscous (G") moduli were determined from the log-log plots of viscoelastic moduli vs. frequency. The tan δ values (G"/G') at 6.28 rad·s^{-1} were used to compare the weak gel-like properties of samples. All measurements were performed in triplicate.

Measurement of the friction coefficient (μ)

The friction coefficient (μ) was measured using the Haake MARS II Rheometer (Thermo Fisher Scientific) equipped with a steel ball-on-three-PDMS-plate geometry in accordance with the method of Bak and Yoo (2024a). The friction was measured at entrainment speeds ranging from 0.05 mm·s^{-1} to 500 mm·s^{-1} under a constant normal force (0.5 N) for 5 min at 25°C. μ is defined as the ratio of friction to normal forces. All measurements were performed at least three times.

Statistical analysis

The results are expressed as the mean±standard deviation. Statistical differences among samples were analyzed using analysis of variance with Duncan's multiple range tests. All analyses were performed using SPSS (version 27.0, SPSS Institute Inc.), and statistical significance was considered at $P<0.05$.

RESULTS AND DISCUSSION

Steady and dynamic rheological properties

The flow behavior of samples was determined using the power law model, as indicated by the high determination coefficient values ($R^2 \geq 0.96$). The flow parameter values (K, n, and $\eta_{a,50}$) are summarized in Table 1. The n values of all thickened beverages were lower than 1, indicating pseudoplastic behavior. Moreover, their n values decreased with increasing XG-based thickener concentration, indicating less resistance to flow (strong pseudoplastic behavior). This decrease was likely related to a reduction in organoleptic sliminess, as observed in previous studies (Cho and Yoo, 2015; Yoon and Yoo, 2017). By contrast, their K and $\eta_{a,50}$ values increased with increasing XG-based thickener concentration. Compared with thickened BW, thickened SD, OJ, and WM exhibited higher K and $\eta_{a,50}$ values, regardless of thickener concentration. A similar result was reported by Cho et al. (2012), where BW with XG-based thickener was significantly thinner than other thickened beverages (OJ, WM, and apple juice). This was because of interactions between macromolecules and beverage components, including cations, sugars, and proteins (Cho and Yoo, 2015; Kim and Yoo, 2015).

The intercept and slope values from the viscoelastic moduli plots for thickened beverages are shown in Table 2. For all samples, the intercept values for G' were higher than those for G" (tan δ<1), and the slope values for G' were lower than 1, indicating weak gel-like properties. Moreover, for all beverages, the slope values decreased,

Table 1. Steady shear rheological characteristics of beverages prepared with various concentrations of xanthan gum-based thickeners determined using the power law model

Beverage	Thickener conc. (%)	$\eta_{a,50}$ (Pa·s)	*n* (–)	*K* (Pa·s^n)	R^2
Bottled water	1	0.24±0.00^c	0.15±0.00^a	6.76±0.05^c	0.99
	2	0.76±0.02^b	0.11±0.00^b	25.12±0.56^b	0.97
	3	1.48±0.01^a	0.11±0.00^b	47.37±0.45^a	0.99
Sports drink	1	0.29±0.00^c	0.19±0.00^a	6.98±0.09^c	0.99
	2	1.01±0.01^b	0.11±0.00^b	32.35±0.12^b	0.97
	3	1.98±0.01^a	0.11±0.00^b	63.34±0.28^a	0.96
Orange juice	1	0.33±0.01^c	0.18±0.00^a	8.05±0.07^c	0.99
	2	1.12±0.01^b	0.12±0.00^b	35.02±0.45^b	0.96
	3	2.21±0.01^a	0.11±0.00^c	72.18±0.20^a	0.96
Whole milk	1	0.41±0.01^c	0.20±0.00^a	9.44±0.26^c	0.99
	2	1.22±0.01^b	0.13±0.00^b	37.42±0.22^b	0.99
	3	2.68±0.01^a	0.11±0.00^c	86.29±0.72^a	0.96

All data are expressed as the mean±standard deviation obtained from triplicate tests.
Different lowercase letters in the same column for each beverage indicate statistically significant differences at $P<0.05$.
Conc., concentration.

Table 2. Dynamic rheological properties (at 6.28 rad·s^{-1}) of beverages prepared with various concentrations of xanthan gum-based thickeners

Beverage	Thickener conc. (%)	G′			G″			tan δ
		Intercept (Pa)	Slope (–)	R^2	Intercept (Pa)	Slope (–)	R^2	
Bottled water	1	7.53±0.06^c	0.20±0.01^a	0.97	3.14±0.03^c	0.17±0.00^a	0.97	0.42±0.00^a
	2	35.11±0.30^b	0.16±0.00^b	0.99	9.84±0.06^b	0.14±0.00^b	0.99	0.28±0.00^b
	3	73.14±0.09^a	0.15±0.00^b	0.99	18.35±0.11^a	0.12±0.00^c	0.96	0.25±0.00^c
Sports drink	1	8.05±0.02^c	0.23±0.01^a	0.96	3.44±0.02^c	0.17±0.00^a	0.97	0.43±0.00^a
	2	37.39±0.25^b	0.15±0.00^b	0.99	9.93±0.09^b	0.12±0.00^b	0.98	0.27±0.00^b
	3	80.15±0.51^a	0.14±0.00^c	0.99	18.30±0.15^a	0.09±0.00^c	0.95	0.23±0.00^c
Orange juice	1	9.41±0.13^c	0.23±0.01^a	0.95	3.87±0.04^c	0.18±0.00^a	0.97	0.41±0.00^a
	2	40.68±0.21^b	0.15±0.00^b	0.99	10.84±0.03^b	0.13±0.00^b	0.98	0.27±0.00^b
	3	87.42±0.16^a	0.14±0.00^b	0.99	20.08±0.13^a	0.10±0.00^c	0.96	0.23±0.00^c
Whole milk	1	18.13±0.27^c	0.22±0.00^a	0.98	7.08±0.07^c	0.21±0.00^a	0.99	0.39±0.00^a
	2	80.15±1.06^b	0.15±0.00^b	0.99	19.80±0.10^b	0.13±0.00^b	0.96	0.25±0.00^b
	3	157.31±1.28^a	0.14±0.00^c	0.99	34.77±0.48^a	0.09±0.00^c	0.96	0.22±0.00^c

All data are expressed as the mean±standard deviation obtained from triplicate tests.
Different lowercase letters in the same column for each beverage indicate statistically significant differences at $P<0.05$.
Conc., concentration.

and the intercept values increased as the thickener concentration increased, suggesting the formation of a stronger viscoelastic network with an increase in thickener concentration (Bak and Yoo, 2024b).

Similar to the results from the steady shear rheological tests, thickened BW attained lower intercept values for G' (7.53–73.14 Pa) and G" (3.14–18.35 Pa) compared with other thickened beverages (8.05–157.31 and 3.44–34.77 Pa, respectively), regardless of the thickener concentration. This was likely because of interactions between the XG-based thickener and beverage components (Cho and Yoo, 2015; Kim and Yoo, 2015). Specifically, the presence of mono- and di-valent cations in beverages can facilitate interactions between anionic polymers (i.e., XG) by mediating indirect/direct crosslinking, leading to increased rheological properties (Sherahi et al., 2018; Bak and Yoo, 2024c). Similar observations were found by Cho et al. (2012) and Park and Yoo (2020). Notably, thickened WM exhibited much higher intercept values for G' (18.13–157.31 Pa) and lower tan δ values (0.22–0.39) compared with other thickened beverages (7.53–87.42 Pa and 0.23–0.43, respectively), indicating the formation of a stronger and more elastic weak gel-like network (Cho et al., 2012; Yoon and Yoo, 2017). This was attributed to the interaction of carboxyl groups in XG with positively charged protein units on the surface of emulsion particles in WM (Liu et al., 2012). These findings suggest that the viscoelastic properties of thickened beverages prepared with XG-based thickener are strongly influenced by the beverage type and thickener concentration.

Tribological properties

Fig. 1 shows the Stribeck curves (μ value vs. entrainment

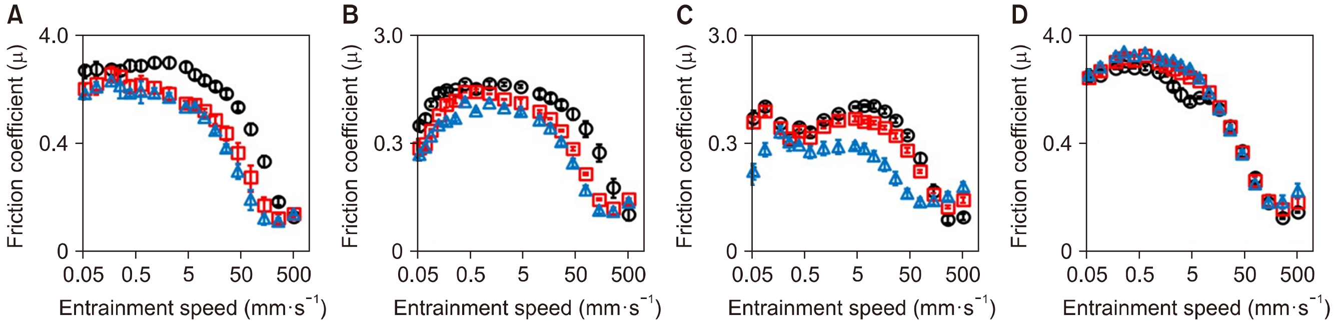

Fig. 1. Stribeck curves of beverages prepared with various concentrations of xanthan gum-based thickeners: 1% (○), 2% (□), and 3% (△). (A) Bottled water, (B) sports drink, (C) orange juice, and (D) whole milk. All data are expressed as the mean±standard deviation obtained from triplicate tests.

speed) for all thickened beverages (1%–3% XG-based thickener). Except for thickened OJ, other beverages exhibited typical Stribeck curves comprising the boundary, mixed, and hydrodynamic lubrication (BL, ML, and HL, respectively) regimes (Stephan et al., 2023). In the BL regime, the tribopair surfaces were in contact, resulting in an increase in the μ value at an initial and slow entrainment speed (Chen and Stokes, 2012). With an increase in the entrainment speed, lubrication transited to the ML regime, and the μ value decreased because of the formation of a thin monolayer lubricant film between the tribopairs (Laguna et al., 2017). However, when the entrainment speed was further increased, the μ value reincreased, suggesting transitioning from the ML to the HL regime (Fox et al., 2021).

By contrast, the frictional curve for thickened OJ comprised five regimes. The μ value increased at a very low speed because of the direct contact of tribopairs. As the speed increased, the μ value decreased because of the formation of a monolayer lubrication film. However, the value subsequently increased because of particulate rolling of the entrained small pulp and gel particles between the tribopairs (Zhang et al., 2017). Nevertheless, as the speed was further increased, these particles were destroyed and formed a lubrication film, leading to a decline in the μ value. Eventually, the lubrication system entered the HL regime, wherein the lubrication characteristics are closely associated with the rheological properties (Rudge et al., 2020). This lubrication behavior was similar to that of beverages containing gel particles, as reported by Gabriele et al. (2010) and Ghebremedhin et al. (2021). Except for thickened WM, the μ value of other beverages decreased as the thickener concentration increased (Fig. 1). This result indicates that the lubrication properties improved with an increase in the thickener concentration, whereas the stickiness of thickened beverages decreased. Interestingly, this finding aligns with results from the steady shear rheological tests, which showed that the *n* value of thickened beverages tended to decrease with an increase in the thickener concentration, thereby suggesting a reduction in organoleptic sliminess (Cho and Yoo, 2015). Similarly, Yoon et al. (2024) and Bak and Yoo (2024a) reported a positive relationship between the μ and *n* values of agglomerated potato starch slurry and gum arabic-based emulsion thickened with guar gum, respectively.

Several studies have also reported an inverse relationship between the μ value of food polymers and the apparent viscosity and elastic modulus (Cassin et al., 2001; Malone et al., 2003; Fernández Farrés and Norton, 2015; Blok et al., 2021). This was likely because of the formation of a lubrication layer with a more ordered and structured network arising from the increased viscoelasticity between tribopairs and effectively separating their surfaces. This is in accordance with our findings of decreases in the maximum μ values of BW, SD, and OJ (1.38–2.23, 0.73–1.06, and 0.28–0.66, respectively) as the thickener concentration was increased (Table 3). Moreover, regardless of the thickener concentration, the order of $\eta_{a,50}$ and G' values was as follows: OJ, SD, BW, respectively (Table 1 and 2). However, their μ values

Table 3. Maximum friction coefficient (μ) values of beverages prepared with various concentrations of xanthan gum-based thickeners

Beverage	Thickener conc. (%)	Maximum μ
Bottled water	1	2.23±0.22^{b}
	2	1.50±0.18^{d}
	3	1.38±0.23^{d}
Sports drink	1	1.06±0.06^{e}
	2	0.96±0.04^{ef}
	3	0.73±0.02^{gh}
Orange juice	1	0.66±0.02^{g}
	2	0.51±0.03^{gh}
	3	0.28±0.02^{h}
Whole milk	1	1.99±0.00^{c}
	2	2.56±0.17^{a}
	3	2.78±0.11^{a}

All data are expressed as the mean±standard deviation obtained from triplicate tests.
Different lowercase letters in the same column for each beverage indicate statistically significant differences at P<0.05.
Conc., concentration.

showed the opposite results: BW, SD, OJ, respectively (Table 3).

Conversely, despite an increase in the $\eta_{a,50}$ and G' values of thickened WM with an increase in thickener concentration, its maximum μ value (1.99 – 2.78) also increased. This is likely attributable to the aggregation and coalescence of emulsion particles in thickened WM (Kongjaroen et al., 2022). Similarly, Nguyen et al. (2017) posited that the higher μ value of skim yogurt prepared with XG than that without was caused by the promotion of flocculation of casein micelles because of depletion interactions with the gum.

In conclusion, the rheological and tribological properties of four different cold beverages thickened with XG-based thickener were investigated. Thickened BW, SD, and WM showed typical Stribeck curves comprising the BL, ML, and HL regimes, but not thickened OJ, which produced a curve comprising five regimes because of the presence of small pulp and gel particles. Thickened BW, SD, and OJ showed maximum μ values, which were positively correlated with the tan δ values as a function of thickener concentration, thereby suggesting the formation of a more structured viscoelastic network exhibiting better lubrication properties. Similarly, their maximum μ and *n* values increased with an increase in the thickener concentration, indicating that the increasing maximum μ value trend is likely correlated to organoleptic sliminess. Conversely, because of the presence of emulsion particles, thickened WM showed the opposite trend, indicating that the lubrication properties of thickened beverages are dependent on the beverage type. These findings suggest that the relationship between the rheological and tribological properties of thickened beverages with an XG-based thickener is greatly influenced by the thickener concentration and beverage type. The findings of the present study demonstrate that the rheological and oral tribological properties of various thickened beverages prepared with XG-based thickener need to be considered for dysphagia management. Moreover, these results will be useful for preparing thickened beverages with desirable tribological and rheological properties for dysphagic patients.

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AUTHOR DISCLOSURE STATEMENT

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Concept and design: BY. Analysis and interpretation: WHC. Data collection: WHC. Investigation: WHC. Validation: WHC. Formal analysis: WHC. Methodology: WHC. Visualization: WHC. Supervision: JB, BY. Project administration: BY. Project administration: BY. Resource: BY. Writing the article: WHC, BY. Critical revision of the article: JB. Final approval of the article: all authors. Statistical analysis: WHC. Obtained funding: BY. Overall responsibility: JB, BY.

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