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Research Note

Non-Newtonian Characteristics of Gochujang and Chogochujang at Different Temperatures

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ABSTRACT: This study was conducted to determine the rheological properties of gochujang and chogochujang at different temperatures (25, 35, and 45°C). Rheological properties of the samples were determined using a rotational rheometer at a shear range of 1 to 40 s^{-1}. Gochujang and chogochujang were found to be non-Newtonian fluids according to the Herschel-Bulkley model. Yield stress and consistency coefficient of gochujang at different temperatures were higher than those of chogochujang, whereas the opposite was observed for flow behavior index. Moreover, all rheological properties of gochujang and chogochujang decreased with increasing temperature. The consistency coefficient was related to temperature using an Arrhenius-type relationship. Gochujang (14.48 kJ/mol) had slightly higher activation energy than chogochujang (14.03 kJ/mol).

Keywords: gochujang, chogochujang, non-Newtonian, Herschel-Bulkley model, activation energy

INTRODUCTION

Gochujang is a fermented traditional Korean hot pepper paste that provides hot, sweet, and savory tastes. Gochujang is made from red pepper powder, soybean powder, and rice flour (1), and its distinctive tastes are originated from digestion of these ingredients. It is indispensable in dishes such as bibimbap (2) and is used as a seasoning or a condiment (3). Gochujang can also be used as a raw material in the food industry to make various products or can be sold directly to consumers. Chogochujang, a combination of vinegar and gochujang, is often enjoyed with rice topped with raw fish, sashimi, or various kinds of vegetables.

Food pastes such as gochujang are generally characterized as shear-thinning non-Newtonian fluids due to the complex interactions among their components. These kinds of fluids are generally described by empirical rheological models, and the most widely used are the Power-Law and Herschel-Bulkley models (4-6). At present, there have been limited studies on the rheological properties of gochujang and none on chogochujang.

Yoo and Choi (7) previously studied the effect of fermentation time (0∼12 weeks) on the rheological properties of gochujang. They reported that dynamic and steady shear viscosities at different fermentation times followed the Cox-Merz superposition rule upon application of the shift factor. The rheological properties of gochujang as influenced by particle size of red pepper powder were reported by Yoo et al. (8). They found that apparent viscosity increased as the average diameter of red pepper powder decreased. Dynamic moduli (storage modulus, loss modulus, and complex viscosity) values of gochujang mixed with gums (9) and acetylated starches (10) were also studied.

The viscosity of gochujang develops as starch is gelatinized through processing (11), and it is important to identify the flow characteristics influencing product yields, efficiency of production facilities, and transportation in the manufacturing process. In addition, the flow behavior of gochujang is important with respect to consumers' preferences; it should be thick enough to stay on solid foods but not so thick as to easily mix with other food materials (7). Therefore, characterization of rheological properties is of interest in practical applications related to handling and quality control. Knowledge of the rheological properties of these products is needed to evaluate their quality and for use in engineering calculations.

The aim of this study was to determine the rheological properties of gochujang and chogochujang at different temperatures (25 to 45°C).

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MATERIALS AND METHODS

Materials

Commercial gochujang (Sajo Industries Co., Ltd., Sunchang, Korea) and chogochujang (Ottogi Co., Eumseong, Korea) were procured from a local market and kept in a chiller (*ca.* 4°C). Samples were at room temperature for 2 h prior to the experiments.

Measurement of physicochemical properties

A sample (5 g) was mixed with 45 mL of distilled water and homogenized for 1 min. The mixture was held at ambient temperature for 1 h in order to separate the solid and liquid phases. The pH of the supernatant was measured using a pH meter (pH/Ion 510, Oakton Instruments, Vernon Hills, IL, USA). Color determination of the samples on a petri dish was measured using a chroma meter (CM-600d, Konica Minolta, Osaka, Japan) set for CIELAB color space, while total soluble solids (TSS) content was measured using a refractometer (PR-301, Atago Co., Tokyo, Japan). Moisture content was obtained by drying a specific amount (5 g) of sample to a constant weight at 105°C in an oven (FOL-2, Jeio Tech Co., Ltd., Daejeon, Korea), and results were reported on a wet basis. Five measurements were obtained for each sample.

Measurement of rheological properties

The rheological properties of the samples were determined using a rotational rheometer (RV1, Thermo Electron Corp., Karlsruhe, Germany). The temperature of the sample during the measurement was controlled using a temperature-controlled recirculating water bath (RW-0525G, Jeio Tech Co., Ltd.). Measurements were conducted at 25, 35, and 45°C. The rheometer was first zero-adjusted before the measurements. About 40 mL of the sample was poured into a tube. The bob (rotor) and the tube containing the sample were attached to the rheometer. Twelve shear rates ranging from 1 to 40 s^{-1} were chosen, and measuring time was 60 s. The TSS content of each sample was kept constant during the measurements. The experiments were replicated three times, and the mean values were compared.

Temperature dependency of rheological properties

The consistency coefficient of a non-Newtonian fluid can be related to temperature using an Arrhenius-type relationship as follows (5):

$$k = k_0 \exp [E_a/(\mathrm{R} \cdot \mathrm{T})] \quad (1)$$

Taking a natural logarithm to obtain,

$$\ln k = \ln k_0 + (E_a/\mathrm{R}) \cdot (1/\mathrm{T}) \quad (2)$$

where k is consistency coefficient (Pa·s), k_0 is pre-exponential constant (Pa·s), E_a is activation energy (J/mol), R is gas constant [8.314 J/(mol·K)], and T is absolute temperature (K).

Data analysis

The shear stress and shear rate data for gochujang and chogochujang at different temperatures were fitted with various linear regression equations using the RheoWin Job Manager software (version 4.61, Thermo Electron Corp.). The regression equations giving the highest coefficient of determination were selected. The yield stress and flow behavior index were also determined using the Power-Law and Herschel-Bulkley models as follows.

$$\log \tau = \log k + n \log \gamma \quad (3)$$

$$\log (\tau - \tau_y) = \log k + n \log \gamma \quad (4)$$

where τ is shear stress (Pa), τ_y is yield stress (Pa), n is flow behavior index, and γ is shear rate (s^{-1}).

The consistency coefficient was related to temperature using Eq. 1. The mean relative percentage error (MRPE) was used to evaluate the adequacy of the derived Herschel-Bulkley equations and Arrhenius-type equations in predicting the shear stress values and consistency coefficients of gochujang and chogochujang at different temperatures, respectively, as outlined in Nooruddin et al. (12).

$$\mathrm{MRPE} = \frac{1}{N} \sum_{i=1}^{N} \frac{(\tau_{exp})_i - (\tau_{pre})_i}{(\tau_{exp})_i} \times 100$$

where N is the number of experiments, τ_{exp} is the measured τ from experiments and τ_{pre} is the calculated τ.

RESULTS AND DISCUSSION

Basic properties of gochujang and chogochujang

The mean pH values of gochujang and chogochujang were 4.58 and 3.51, respectively, confirming acidity. The mean moisture contents and TSS values of the samples were 41.10 and 50.51% and 5.48 and 4.74°Brix, respectively. The mean L^*, a^*, and b^*-values of gochujang and chogochujang were 11.98 and 32.02, 17.23 and 21.04, and 8.79 and 12.51, respectively. The obtained results were comparable to the pH of 4.72 of domestic gochujang analyzed by Lee et al. (13). The results show that chogochujang was slightly more acidic than gochujang due to added vinegar. They also reported a mean moisture content of 46.67% and L^*, a^*, and b^*-values of 4.84, 21.26, and 8.20, respectively. The results suggest that gochujang had more solids than chogochujang as well as higher viscosity.

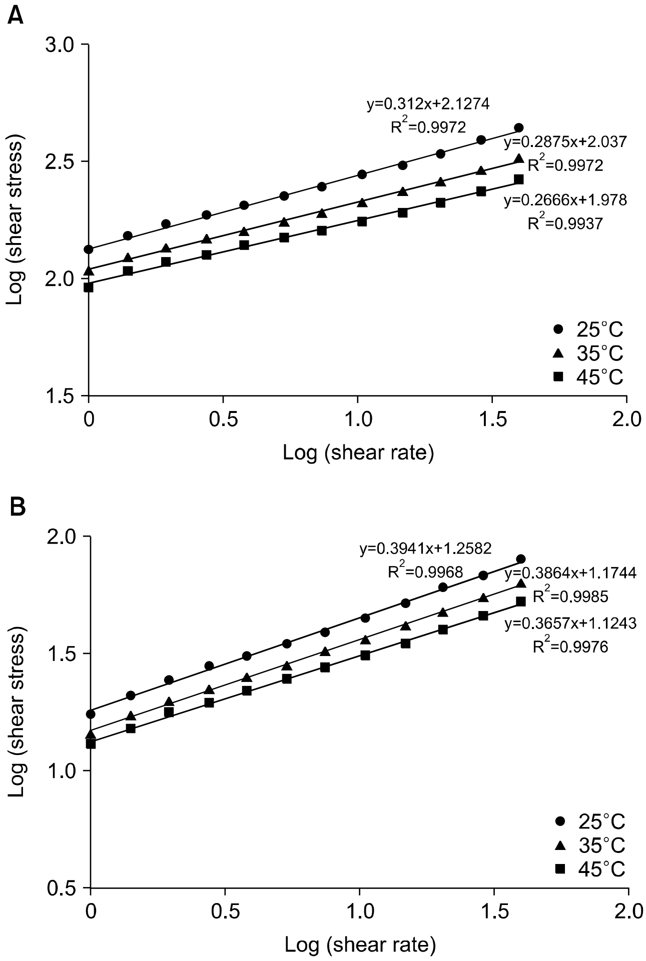


Fig. 1. Representative rheogram of logarithm of shear stress vs. logarithm shear rate for both gochujang (A) and chogochujang (B) at different temperatures.

Table 1. Mean rheological properties and range of coefficient of determination of regression for gochujang and chogochujang at different temperatures (number of replications=3)

Type	Temperature (°C)	τ_y (Pa)	k (Pa·s^n)	n (−)	R^2
Gochujang	25	51.39	86.90	0.4016	0.9996
	35	43.02	68.99	0.3815	0.9993
	45	38.43	60.24	0.3545	0.9982
Chogochujang	25	3.99	14.64	0.4427	0.9992
	35	3.59	11.87	0.4368	0.9995
	45	3.43	10.26	0.4197	0.9990

τ_y, yield stress; k, consistency coefficient; n, flow behavior index; R^2, coefficient of determination.

Rheograms of gochujang and chogochujang

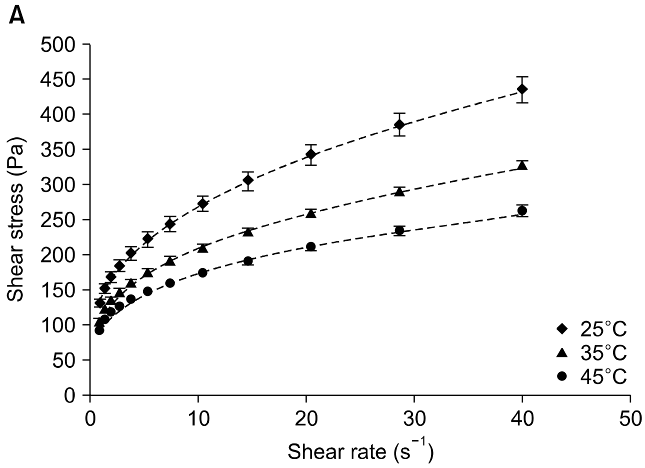
A number of studies have shown that many food pastes and fruit purees behave either as a Power-Law fluid or as a Herschel-Bulkley fluid (14-16). Fig. 1 shows a representative rheogram for gochujang and chogochujang at different temperatures on a logarithmic scale. The data fell on a straight line but did not pass through the origin, which means that the samples were not a Power-Law fluid but behaved as a Herschel-Bulkley fluid at different temperatures. Other food pastes and fruit purees have been fitted with the Herschel-Bulkley model, including fenugreek paste (14), siriguela pulp (15), and malaxed olive paste (16).

Rheological properties of gochujang and chogochujang

The consistency coefficient and flow behavior index values were derived from the slope and intercept of the Herschel-Bulkley regression equation for all data. Table 1 shows the rheological properties and the range of coefficient of determination (R^2) of regression for both gochujang and chogochujang at different temperatures. The results suggest that there were good fits for both data of gochujang and chogochujang at different temperatures, and their R^2 values were above 0.99. The yield stress and consistency coefficient of gochujang at different temperatures were higher than those of chogochujang probably due to the stronger particle bonding of gochujang compared to chogochujang (11).

However, the flow behavior index values of gochujang at different temperatures were higher than those of chogochujang. These rheological properties indicate that gochujang was more viscous than chogochujang, probably due to the higher solids content of gochujang compared with chogochujang as shown previously. In addition, values for yield stress, consistency coefficient, and flow behavior index of both gochujang and chogochujang decreased with increasing temperature. Yield stress and consistency coefficient values of sweet potato puree (17), raspberry jam and strawberry jam (18), and ketchup (19) also behaved in a similar manner. The flow behavior index also decreased with increasing temperature for papaya puree (20), ketchup (19), and sesame paste (21), which is expected due to the general tendency for viscosity to decrease with temperature.

Using the rheological properties in Table 1, the shear stress values for gochujang and chogochujang at different temperatures were predicted using the Herschel-Bulkley equation. Fig. 2 shows the plots of experimental and predicted shear stresses for gochujang and chogochujang at different temperatures, respectively. Generally, the predicted curves for both gochujang and chogochujang encompassed most of the data points. In order to evaluate the goodness of fit of the equation, the MRPE was calculated for both experimental and predicted shear stresses. Table 2 shows the mean percentage error for gochujang and chogochujang at different shear rates at 25°C. The percent error ranged from 0.01∼4.78 and 0.01∼7.43, and MRPE was 1.15 and 1.17 for gochujang and chogochujang at 25°C, respectively. The rest of the data were subjected to the same analyses, and the results show that MRPE ranged from 1.15∼1.73 and 1.58∼1.77 for gochujang and chogochujang, respectively. All MRPE



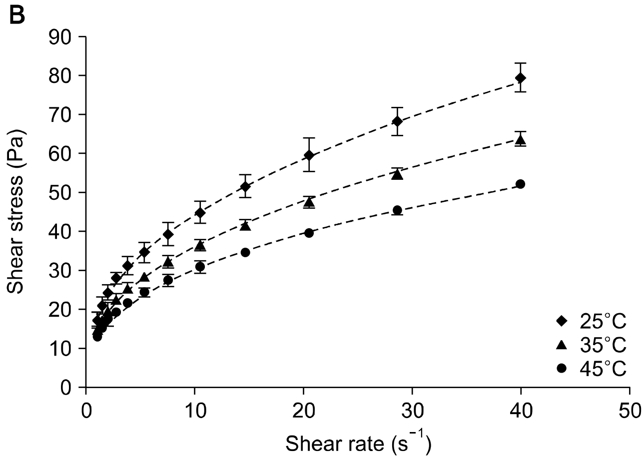


Fig. 2. Rheograms of experimental and predicted shear stresses vs. shear rate for gochujang (A) and chogochujang (B) at different temperatures (symbols represent experimental data while dotted lines for predicted by the Herschel-Bulkley equation).

Table 2. Mean relative percentage error (MRPE) for shear stress values of gochujang and chogochujang at different shear rates at 25°C as predicted by the Herschel-Bulkley equation and using the derived rheological properties

Shear rate (s^{-1})	Gochujang			Chogochujang		
	Shear stress (Pa)		Percent error	Shear stress (Pa)		Percent error
	Experimental	Predicted		Experimental	Predicted	
1.00	131.68	138.29	4.78	17.25	18.63	7.43
1.40	152.65	150.76	1.25	20.95	20.96	0.02
1.96	168.65	165.03	2.19	24.34	23.66	2.88
2.73	184.61	181.34	1.80	28.04	26.78	4.70
3.82	202.43	200.00	1.22	31.23	30.41	2.71
5.35	222.11	221.33	0.35	34.61	34.61	0.01
7.48	244.09	245.73	0.67	39.28	39.47	0.49
10.46	272.85	273.63	0.29	44.84	45.12	0.62
14.63	304.85	305.53	0.22	51.60	51.66	0.11
20.45	342.04	342.01	0.01	59.57	59.23	0.56
28.60	384.78	383.73	0.27	68.17	68.02	0.22
40.00	434.95	431.44	0.81	79.38	78.20	1.51
		MRPE	1.15		MRPE	1.77

values for both samples were far less than 10%, which is still acceptable for most engineering purposes (22).

Temperature dependency of the consistency coefficient

The consistency coefficient was related to temperature using an Arrhenius-type relationship. The pre-exponential constant and the activation energy were obtained from the slope and intercept of the Arrhenius regression, and the results are summarized in Table 3. Gochujang (14.48 kJ/mol) had slightly higher activation energy than chogochujang (14.03 kJ/mol), indicating that the consistency coefficient of gochujang was more temperature-sensitive, and temperature had a greater effect on viscosity. The derived activation energies for gochujang and chogochujang correlatd well with that of peach puree at 9.35 kJ/mol (18), ketchup at 5.49~21.48 kJ/mol (19), and blueberry puree at 9.39 kJ/mol (23).

Table 3. Pre-exponential constants (k_0), activation energies (E_a), and coefficient of determination (R^2) of regression for the consistency coefficients of gochujang and chogochujang

Type	k_0	E_a (kJ/mol)	R^2
Gochujang	0.249	14.48	0.9831
Chogochujang	0.051	14.03	0.9929

CONCLUSION

The rheological properties of gochujang and chogochujang at different temperatures (25, 35, and 45°C) confirmed these two foods to be non-Newtonian fluids according to the Herschel-Bulkley model. The yield stress and consistency coefficient of gochujang at different temperatures were higher than those of chogochujang. However, the flow behavior index values of chogochujang at different temperatures were higher than those of gochujang. In addition, values for yield stress, consistency coefficient, and flow behavior index of gochujang and chogochujang decreased with increasing temperature. The consistency coefficient was related to temperature using an Arrhenius-type relationship. Gochujang (14.48 kJ/mol) had slightly higher activation energy than chogochujang (14.03 kJ/mol).

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AUTHOR DISCLOSURE STATEMENT

The authors declare no conflict of interest.

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