Non-Newtonian Characteristics of Gochujang and Chogochujang at Different Temperatures

Ji Eun Choi and Jun Ho Lee
Department of Food Engineering, Daegu University, Gyeongbuk 38453, Korea

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 to 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).
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). 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 samples 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):

\[ k = k_0 \exp \left( \frac{E_a}{R \cdot T} \right) \]  

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.

\[ \ln k = \ln k_0 + \left( \frac{E_a}{R} \right) \cdot \frac{1}{T} \]  

where \( k \) is shear stress (Pa), \( k_0 \) is yield stress (Pa), \( n \) is flow behavior index, and \( \gamma \) 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).

\[ \text{MRPE} = \frac{1}{N} \sum_{i=1}^{N} \frac{\left( \tau_{\exp,i} - \tau_{\text{pre},i} \right)}{\tau_{\exp,i}} \times 100 \]  

where \( N \) is the number of experiments, \( \tau_{\exp} \) is the measured \( \tau \) from experiments and \( \tau_{\text{pre}} \) is the calculated \( \tau \).

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.
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 to 4.78 and 0.01 to 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 to 1.73 and 1.58 to 1.77 for gochujang and chogochujang, respectively. All MRPE values were less than 0.99. 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 to 4.78 and 0.01 to 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 to 1.73 and 1.58 to 1.77 for gochujang and chogochujang, respectively. All MRPE values were less than 0.99.

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     | 0.4016         | 0.9996 |
|             | 35               | 43.02     | 0.3815         | 0.9993 |
|             | 45               | 38.43     | 0.3545         | 0.9982 |
| Chogochujang| 25               | 3.99      | 0.4427         | 0.9992 |
|             | 35               | 3.59      | 0.4368         | 0.9995 |
|             | 45               | 3.43      | 0.4197         | 0.9990 |

$r_y$, yield stress; $k$, consistency coefficient; $n$, flow behavior index; $R^2$, coefficient of determination.
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 correlated 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 co-
efficient, and flow behavior index of gochujang and cho-
gochujang 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 chogo-
chujang (14.03 kJ/mol).

ACKNOWLEDGEMENTS
This research was supported by the Daegu University Re-
search Grant, 2013.

AUTHOR DISCLOSURE STATEMENT
The authors declare no conflict of interest.

REFERENCES
1. Shin D, Jeong D. 2015. Korean traditional fermented soybean
products: Jang. J Ethnic Foods 2: 2-7.
2. Chung KR, Yang HJ, Jang DJ, Kwon DY. 2015. Historical and
biological aspects of bibimbap, a Korean ethnic food. J Ethnic
Foods 2: 74-83.
3. Jang DJ, Lee AJ, Kang SA, Lee SM, Kwon DY. 2016. Does si-
wonhan-mat represent delicious in Korean foods?. J Ethnic Foods
3: 159-162.
4. Keshani S, Chuah AL, Russly AR. 2012. Effect of tempera-
ture and concentration on rheological properties pomelo
juice concentrates. Int Food Res J 19: 553-562.
5. Lopes AS, Mattietto RA, Menezes HC, Silva LHM, Pena RS.
2013. Rheological behavior of Brazilian cherry (Eugenia uni-
flora L) pulp at pasteurization temperatures. Food Sci Technol
Campinas 33: 26-31.
6. Diamante L, Umemoto M. 2015. Rheological properties of
fruits and vegetables: a review. Int J Food Prop 18: 1191-1210.
7. Yoo B, Choi WS. 1999. Effect of fermentation time on rheol-
gical properties of kochujang in steady and dynamic shear. Food
Sci Biotechnol 8: 300-304.
8. Yoo B, Lee SM, Chang YH. 2001. Rheological properties of
Kochujang as affected by the particle size of red pepper pow-
der. Food Sci Biotechnol 10: 311-314.
9. Choi SJ, Yoo B. 2006. Rheological effect of gum addition to
hot pepper-soybean pastes. Int J Food Sci Technol 41: 56-62.
10. Choi SJ, Chang HG, Yoo B. 2008. Rheological properties of
hot pepper-soybean pastes mixed with acetylated starches.
Food Sci Biotechnol 17: 780-786.
11. Kim YC, Yoo BS. 2000. Rheological properties of traditional
kochujang. Korean J Food Sci Technol 32: 1313-1318.
12. Nooruddin HA, Hossain ME, Al-Yousef H, Okasha T. 2016.
Improvement of permeability models using large mercury in-
jection capillary pressure dataset for Middle East carbonate
reservoirs. J Porous Media 19: 405-422.
13. Lee S, Yoo SM, Park BR, Han HM, Kim HY. 2014. Analysis
of quality state for Gochujang produced by regional rural fami-
ilies. J Korean Soc Food Sci Nutr 43: 1088-1094.
14. Işıklı ND, Karababa E. 2005. Rheological characterization of
ferugreek paste (çemen). J Food Eng 69: 185-190.
15. Augusto PED, Cristiano M, Ibarz A. 2012. Effect of tempera-
ture on dynamic and steady-state shear rheological prop-
erties of siriguela (Spondias purpurea L.) pulp. J Food Eng 108:
283-289.
16. Tamborrino A, Catalano P, Leone A. 2014. Using an in-line
rotating torque transducer to study the rheological aspects of
malaxed olive paste. J Food Eng 126: 65-71.
17. Ahmed J, Ramaswamy HS. 2006. Viscoelastic properties of
sweet potato puree infant food. J Food Eng 74: 376-382.
18. Maceiras R, Alvarezo E, Cancela MA. 2007. Rheological prop-
eerties of fruit purees: effect of cooking. J Food Eng 80: 763-769.
19. Koocheki A, Ghandi A, Razavi SMA, Mortazavi SA, Vasiljevic
T. 2009. The rheological properties of ketchup as a function
of different hydrocolloids and temperature. Int J Food Sci Tech-
nol 44: 596-602.
20. Guerrero SN, Alzamora SM. 1998. Effects of pH, tempera-
ture and glucose addition on flow behaviour of fruit purees:
II. Peach, papaya and mango purées. J Food Eng 37: 77-101.
21. Lokumcu Altay F, Ak MM. 2005. Effects of temperature,
shear rate and constituents on rheological properties of tahin
(sesame paste). J Sci Food Agric 85: 105-111.
22. Pardeshi IL, Arora S, Borker PA. 2009. Thin-layer drying of
green peas and selection of a suitable thin-layer drying mod-
el. Drying Technol 27: 288-295.
23. Antonio GC, Faria FR, Takeiti CY, Park KJ. 2009. Rheological
behavior of blueberry. Ciênc Tecnol Aliment 29: 732-737.