Nonlinear Viscoelastic Behaviors of Different Types of O/W Emulsion-Based Mayonnaises in Several Shear Flow Fields

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ABSTRACT

In this research, the rheological behaviors of different types (normal, non-cholesterol and reduced-fat) of mayonnaises have been investigated and compared both in steady shear and oscillatory shear flow fields.

INTRODUCTION

Mayonnaise is one of the most widely-used condiments made of vegetable oil, egg yolk, vinegar and seasonings. Among these materials, egg yolk contains lipoproteins, lecithin, and other phosphatides, which contribute to its emulsifying capacity, and egg yolk is the only permitted emulsifying agent in mayonnaise[1]. Mayonnaise is an oil-in-water (O/W) emulsion containing droplets of one liquid dispersed through a second liquid termed a continuous phase[2].

Due to the flocculation of adjacent oil droplets to form a network, mayonnaise is essentially a weak gel system. The strength of the interactions between oil droplets depends on the van der Waals attractions, which are balanced to some extent by electrostatic and steric repulsion. The quality of mayonnaise depends on the right balance between these forces : If electrostatic force is too strong, an attraction will pull the droplets together causing the aqueous phase to be squeezed out and promoting coalescence of the droplets. On the other hand, if steric repulsion force is too strong, a repulsion will allow the droplets to slip easily past one another[3].

Commercial mayonnaises can have an extremely multifarious composition based on various manufacturing formulas. Mainly, the quantity, number and amount of spices or other flavoring agents lead to differences in their quality. For this reason, it is difficult to set up the factors on which the quality depends[4].

Nowadays, consumers concern about the adverse health effects associated with overconsumption of certain types of lipids. This has led to a trend within the food industry toward the development of reduced-fat or reduced-cholesterol products[5,6]. The creation of reduced-fat or reduced-cholesterol products with the same quality attributes as the original full-fat products has been a considerable challenge, and the food industry has been trying to produce this kind of products (or substituting materials) for its continuous developments[7].

Rheology of mayonnaise is of great importance and its correct evaluation can provide valuable information that can be used in quality control of commercial production, storage stability, sensory assessments of consistency and texture, design of unit operations, and knowledge of the effects of mechanical processing on the structure of the emulsions[8].

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The main objective of this study is to systematically characterize and compare the rheological properties of different types (normal, non-cholesterol and reduced-fat) of mayonnaises using a rotational rheometry system both in steady shear and periodically small/large amplitude oscillatory shear flow fields.

EXPERIMENTAL SECTION

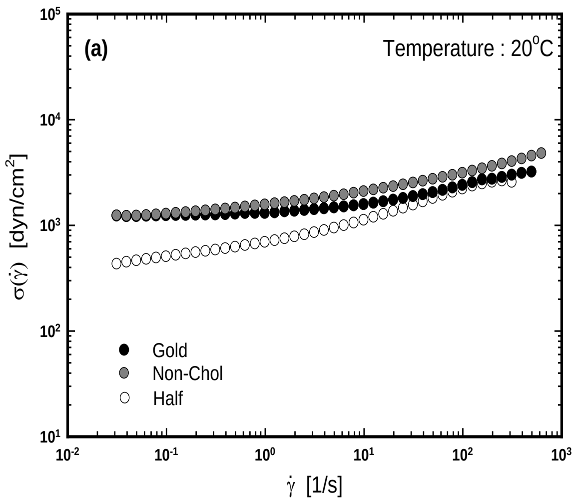
The semi-solid food emulsions selected in this study were three different types (normal, non-cholesterol and low-fat) of commercially available mayonnaises supplied from the Ottogi Food Co. (Korea). The steady shear and the dynamic viscoelastic properties of these mayonnaise samples were measured using a strain-controlled rheometer [Advanced Rheometric Expansion System (ARES), Rheometric Scientific, Piscataway, NJ, USA] equipped with a parallel-plate fixture with a radius of 12.5 mm and a gap size of 1.0 mm or 1.5 mm. All rheological measurements were performed at a fixed temperature of 20 ℃ over a wide range of shear rates, angular frequencies and strain amplitudes.

Before mayonnaise samples were loaded, the two plates were covered with sandpaper in order to eliminate a wall-slip effect between the test material and the plates. In all measurements, a fresh sample was used and rested for 20 min after loading to allow material relaxation and temperature equilibration.

The steady shear flow properties were measured over a wide range of shear rates from 0.025 to 1000 1/s with a logarithmically increasing scale. In order to interpret the relationship between the viscoelastic behavior and the microstructure of mayonnaises, frequency-sweep tests in small amplitude oscillatory shear flow fields were nextly performed over an angular frequency range from 0.025 to 100 rad/s with a logarithmically increasing scale at a fixed strain amplitude of 1 %. In addition, strain-sweep tests were carried out over a strain amplitude range from 0.25 to 500 % with a logarithmically increasing scale at several fixed angular frequencies of 0.05, 0.1, 0.25, 0.5, 1, 2.5, 5, 10, 25 and 50 rad/s in order not only to find out the linear viscoelastic region but also to investigate a nonlinear viscoelastic behavior in large amplitude oscillatory shear flow fields. Finally, sinusoidal shear strains of $\gamma(t) = \gamma_0 \sin \omega t$ at several strain amplitudes of 1, 5, 10, 50, 100, 200, 300, 400, 500 and 600 % with a constant angular frequency of 1 rad/s were imposed to the three kinds of mayonnaise samples.

RESULTS AND DISCUSSION

Fig. 1 (a) and (b) show the shear rate dependence of the shear stress and steady shear viscosity for Gold (Normal type), Non-Chol (Non-Cholesterol type) and Half (Low-Fat type) mayonnaises, respectively. For all types of mayonnaises, the shear stress tends to decrease and then approach a limiting constant value (= yield stress) as a decrease in shear rate toward zero at low range of shear rates. While the Newtonian viscosity region is not observed at low shear rates, the steady shear viscosity demonstrates a pronounced non-Newtonian shear-thinning behavior as an increase in shear rate. It is also



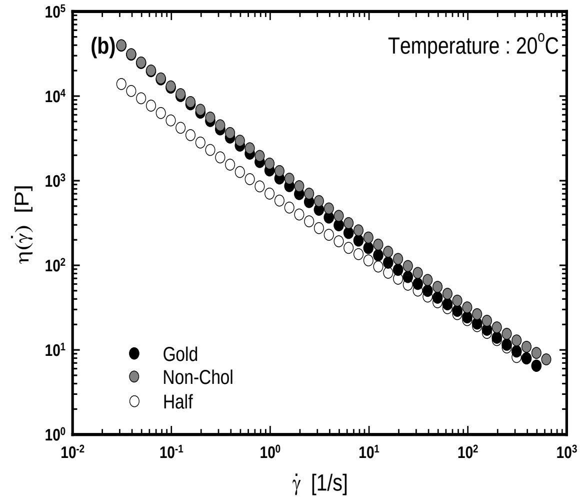


Figure 1. (a) Shear stress and (b) steady shear viscosity versus shear rate for Gold, Non-Chol and Half mayonnaises

found that the normal and non-cholesterol mayonnaises exhibit a quite similar flow behavior.

Fig. 2 (a), (b) and (c) show both the storage modulus and loss modulus as a function of strain amplitude at a fixed angular frequency of 1 rad/s for Gold, Non-Chol and Half mayonnaises, respectively. It is observed that the storage modulus is always greater than the loss modulus within a linear viscoelastic region, indicating that the rheological behavior in this region is in nature dominated by an elastic property rather than a viscous property. In addition, the storage modulus begins to show a nonlinear behavior at a smaller strain amplitude range than does the loss modulus. At sufficiently large strain amplitude range ($\gamma_0 > 80 \sim 100$ %), however, a viscous behavior becomes superior to an elastic behavior because the storage modulus demonstrates a sharper decrease with increasing strain amplitude than does the loss modulus.

Especially, Fig. 2 (a) well represents an exceptional nonlinear behavior at strain amplitude range larger than 15 % where the loss modulus is first increased up to a certain strain amplitude ($\gamma_0 \approx 80$ %), beyond which

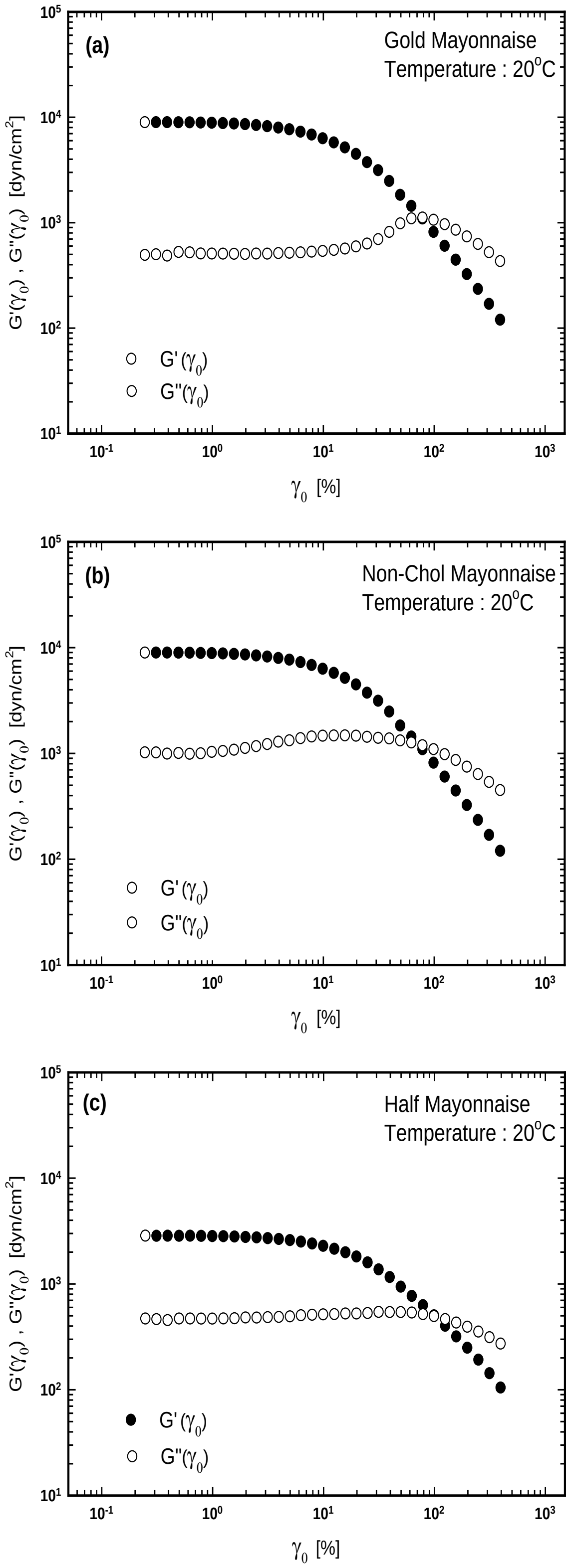


Figure 2. Storage modulus and loss modulus as a function of strain amplitude at a fixed angular frequency of 1rad/s for (a) Gold, (b) Non-Chol and (c) Half mayonnaises.

followed by a decrease in loss modulus with increasing strain amplitude, indicating a strain-overshoot phenomenon.

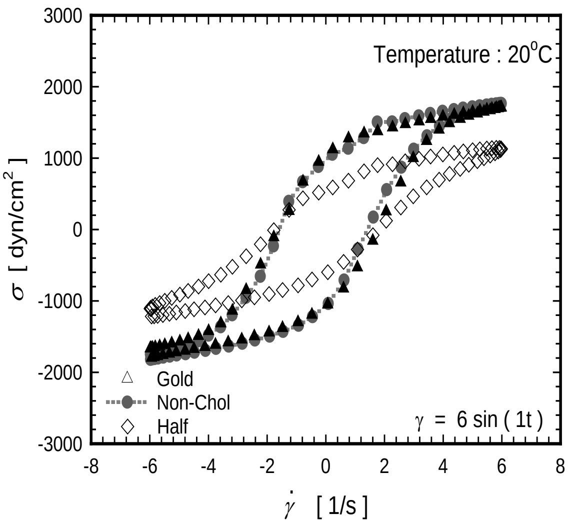


Figure 3. Lissajous curves for Gold, Non-Chol and Half mayonnaises at strain amplitude of 600 %.

Fig. 3 represents the Lissajous curves obtained from the relation between stress and strain rate for Gold (Normal type), Non-Chol (Non-Cholesterol type) and Half (Low-Fat type) mayonnaises, respectively. When large strain amplitude ($\gamma_0 = 600$ %) was imposed, 'S' shaped curves are obtained,

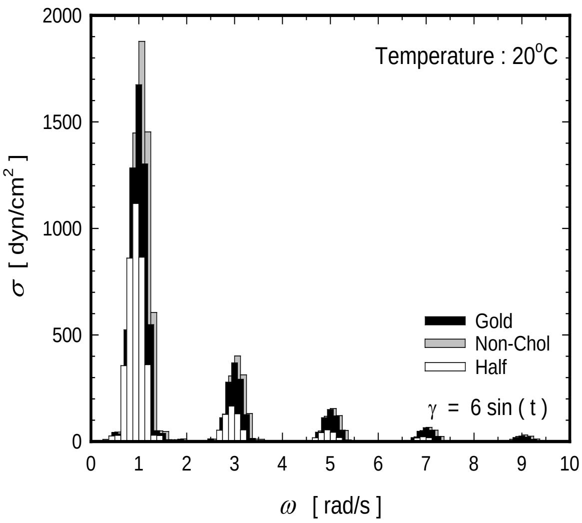


Figure 4. Fourier spectrum of nonsinusodal response for Gold, Non-Chol and Half mayonnaises.

demonstrating a nonlinear viscoelastic behavior[9].

Fig. 4 displays the Fourier spectrum obtained from the FFT of the experimental stress response for Gold, Non-Chol and Half mayonnaises. The Fourier spectrum consists of the first and several higher harmonic terms from the first-harmonic at angular frequency of 1 rad/s to the seventh-harmonic (or the ninth-harmonic) at angular frequency of 7 rad/s (or 9 rad/s). Therefore, the effects of higher harmonic terms should be considered to interpret a nonlinear viscoelastic behavior for these three types of mayonnaises.

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