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Research Note

Effect of Pre-shearing and Temperature on the Yield Stress of Stirred Yogurt

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Abstract

The yield stress of stirred yogurt was measured by the vane viscometer at different pre-shearing conditions, such as pre-shear speed, pre-shear time, and wait time, and temperature (12-38°C). The yield stress ranged from ~17.6 to 10 Pa and from 34.2 to 11.9 Pa, depending on the pre-shearing conditions and temperature, respectively. The pre-shear speed and the wait time significantly affected the yield stress. The temperature dependence of the yield stress was described by the Eyring's kinetic model. The linear function of the temperature on the yield stress was limited at the 22°C, and at the above 22°C, the yield stress was maintained to be a constant (~12.5 Pa).

Key words: yogurt, yield stress, vane viscometer, Eyring's kinetic model

Introduction

The flavor and the unique semi-solid texture are important functionalities of yogurt. Especially, the semi-solid property is important to control the processing conditions as well as the final product qualities. The unique texture properties of yogurt are obtained by the aggregation of the casein molecules when the pH is near the isoelectric point of casein protein (Fox & McSweeny, 1998). Such aggregation between casein molecules generates a weak three-dimensional (3-D) network structure, and due to the network structure, the flow behavior of yogurt greatly differs from the milk or other acidified milk products, such as butter milk. The unique texture of stirred yogurt is due to the 3-D network structure of agglomerates of casein. In stirred yogurts, the 3-D gel structure has been broken, cooled, and packed after coagulation. After packing the product is re-solidified to a nearly solid by hydrocolloid based thickening agents, such as gelatin or carageenan. In this study, the yogurt mainly indicates the stirred yogurt.

When the imposed stress is not high enough to overcome the random thermal motion of molecules, there is a reversible deformation in the system, instead of flowing. The reversible deformation process is known as yield or plastic deformation. The yield stress is important in designing the process system, such as pumping and piping, and in practical usage in many areas, such as sensory perception. (Macosko, 1994; Steffe, 1996; Larson, 1999).

The macroscopic flow is simply described in microscopic movements of molecules by the Eyring's kinetic model (Larson, 1999). The Eyring's kinetic model has been modified to study the reversible flow behavior (i.e. yield stress). According to this theory, the yield stress can have its maximum value at the zero absolute temperature, because the energy barrier to overcome becomes infinitely large at 0K. Then, the yield stress linearly decreases as thermal energy and the collision rate increases. The Eyring's kinetic theory implicitly indicates the effect of processing parameters (i.e., temperature and shear rate) on the yield stress.

For the stirred yogurt, the thermal treatment and shearing are part of important processing units, such as pumping and sterilization. The weakly flocculated particle gel structure of yogurt generates somewhat strange rheological behaviors, such as low yield stress, slip, and shear history dependence (Yoon & McCarthy, 2002). Due to the nature of the shear history dependence, the shear rate and viscosity relation of yogurt may display rheological hysteresis (Fox & McSweeny, 1998). Many literatures have extensively discussed the rheological behavior of yogurt in terms of the viscosity and shear rate relation, including rheological hysteresis (Benezench & Maingonnat, 1993; Yoon & McCarthy, 2002; Guggisberg et al., 2009). However, the effects of these

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processing parameters (i.e., temperature and shearing) on the yield stress have not been deeply discussed.

The flow behavior of stirred yogurt is significantly affected by shearing during processing or handling, because the weak interactions between casein agglomerates are dissociated by shearing, and the structure is reformed as the external convection force is equilibrated. Since the structure of yogurt is sensibly changed with the convection force and temperature, measuring changes in yield stress is a good index to estimate the structural changes of yogurt due to shearing and thermal treatment.

The vane viscometer is specially designed to measure the yield stress. Because a vane inserted into a fluid will create far less disturbance than any solid bob, the rotation motion of the vane fixture can directly measure the torque required to flow. The vane viscometer has been widely used to measure the yield stress of the paste or semi-solid food products (Steffe, 1996).

The objectives of this study were to: 1) measure the yield stress of yogurt by the vane viscometer, 2) to investigate effects of pre-shearing on the yield stress, and 3) to analyze the temperature dependence of yogurt based on the Eyring's kinetic model.

Materials and Methods

The test fluid was a commercial whole milk yogurt used in the study of Yoon & Mc Carthy (2002) (Mountain High plain yogurt, Meadow Gold Dairies, Inc., Englewood, CO, USA). The approximate composition of the commercial stirred yogurt is fat (3.5%), protein (3.5%), and carbohydrate (4.4%).

A vane viscometer (YR-1 Yield stress rheometer) was provided from the Brookfield Engineering Labs. Inc. (Middleboro, MA, USA). To study the effect of external shearing on the yield stress, the measuring conditions, such as measuring speed, pre-shear speed, pre-shear time, and wait-time (Table 1), were varied at 25°C. To study the effect of temperature on the yield stress, the measuring temperature was varied from 12 to 38°C under constant measuring condition (i.e. measuring speed = 0.1 rpm, pre-shearing speed = 0.05 rpm, pre-shear time = 60 sec, and wait time = 0 sec). The measuring conditions were close to the processing conditions applied in the fluid dynamic studies with the MRI viscometer (Yoon and McCarthy, 2002). All experiments are duplicated, and the averaged values were represented in this paper.

Table 1. Effect of the pre-shear time on the yield stress of yogurt (pre-shear speed = 0.05 rpm, wait time = 0 and 20 sec, and run speed = 0.1 rpm)

Pre-shear time (sec)	Yield stress (Pa) wait time = 20 sec	Yield stress (Pa) wait time = 0 sec
0	15.78 (±0.75)	15.78 (±0.75)
30	15.68 (±0.71)	12.50 (±0.76)
60	15.01 (±0.88)	12.97 (±1.36)
120	15.17 (±0.83)	12.62 (v0.99)

*ANOVA results showed the insignificant effect of pre-shear time for both wait-time conditions (p = 0.73 at wait-time 20 sec, p=0.08 at wait-time 0sec).

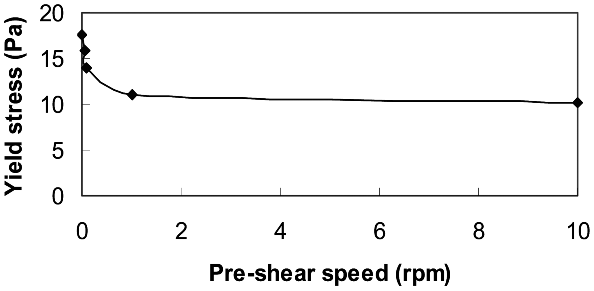

Fig. 1. Effect of pre-shear speed on the yield stress of yogurt (pre-shear time = 120 sec, wait time = 20 sec, and run speed = 0.1 rpm).

Results and Discussion

Effects of pre-shearing on the yield stress

Yogurt sample was pre-sheared with controlled pre-shearing speeds for 120 sec, then equilibrated for 20 sec before measuring the yield stress. The yield stress of yogurt logarithmically decreased from 17.6 to 10.1 Pa as the pre-shear speed increased (Fig. 1). It implies that increasing pre-shear speed significantly breaks the casein agglomerate before measuring the yield stress.

Effect of the time for pre-shearing (i.e., pre-shear time) on the yield stress was studied by applying varied pre-shearing time from 0 to 120 sec at two wait-times (0 and 20 sec) before measuring yield stress (Table 1). As described in Table 1, the yield stress is not affected by the pre-shear time for both cases (i.e., 20 and 0 wait-time). In both cases, pre-shearing lowered the yield stress, but the pre-shear time on the yield stress did not affect. It should be noted here that the yield stress measured after pre-shearing is significantly dependent on the wait time between pre-shearing and measuring yield stress. The yield stress values measured immediately after applying pre-shearing showed significantly lower than those measured after 20 seconds of wait time (ANOVA, $p < 0.01$). To study effect of the wait time on the yield stress, the wait time was varied from 0 to 20 sec after pre-shearing for 60 and 120 sec (Fig. 2). In both cases, the yield stress increased as the wait

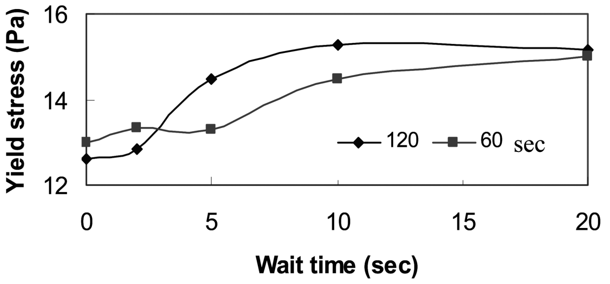

Fig. 2. Effect of wait time on the yield stress of yogurt (pre-shear speed = 0.05 rpm, pre-shear time = 60 and 120 sec, and run speed = 0.1 rpm).

time increased. It may imply that there may be a re-association of pre-sheared casein agglomerates during wait time. The results clearly showed that breaking of structure of stirred yogurt is affected by shearing speed rather than shearing time, and the broken structure is kinetically re-structured during waiting period.

Fig. 2 shows an interesting relation between structure and yield stress. The yield stress values after pre-shear time for 120 sec increased more rapidly and showed higher at wait time for 5 and 10 sec than those after pre-shear time for 60 sec. It might be because the higher shearing time makes the smaller casein particles and the smaller casein particles make more re-association of casein agglomerates during wait time.

Effect of shear rate on the yield stress:

To determine the shear rate dependence of the yield stress, the rotational speed of the spindle was varied from 0.1 to 50 rpm. Theoretically, the shear rate represents the effect of convection on the rate of collision of molecules (Larson, 1999). According to the Eyring's kinetic model, the collision rate of molecules in the flow depends on two physical quantities, such as thermal energy and shear rate, and the yield stress is simply described as (Crist, 1993; Larson, 1999):

$$\sigma_y = \sigma_0 + \frac{k_B T}{v^*} \text{In}\left(\frac{2\dot{\gamma}}{\Omega_0}\right) \qquad (1)$$

where, σ_y = the yield stress, σ_0 = the yield stress at zero temperature, v* = the activation volume, Ω_0 = the typical molecular collision rate (10^{13} sec^{-1}), $\dot{\gamma}$ = the shear rate, k_B = the Boltzman constant, T = temperature (K). The eqn. 1 indicates that the yield stress is a linear function of either thermal energy or shear rate. Since the $\dot{\gamma}$ applied experimentally is much smaller than the Ω_0 ($\dot{\gamma} << \Omega_0$), the yield stress is decreasing with increasing temperature, but increases with increasing shear rate. Since the shear rate is proportional to the rotational speed of the vane (Ω), the shear rate is defined as (4):

$$\dot{\gamma} = k'\Omega \qquad (2)$$

where, k' = mixer viscometry constant. The k' is empirically determined by comparison the angular velocity of vane and bob. In our study, the k' was not determined, however, the effect of shear rate was relatively compared by controlling the rotational speed of vane, since the k' is a constant in the same material. As Ω increased to 0.1, 0.5, and 1.2 rpm, the yield stress at 18.5°C decreased to 20.32 (±0.89), 20.06 (±0.81), and 19.16 (±0.65) Pa, respectively, but statistically insignificant (ANOVA, p = 0.38) (Table 2).

Table 2. Effect of the rotational speed on the yield stress of stirred yogurt at 18.5°C.

Rotational speed (rpm)	Yield stress (Pa) wait time = 20 sec
0.1	20.32 (±0.89)
0.5	20.06 (±0.81)
1.2	19.16 (±0.65)

* ANOVA results showed the insignificant effect of pre-shear time for both wait-time conditions (p =0.38).

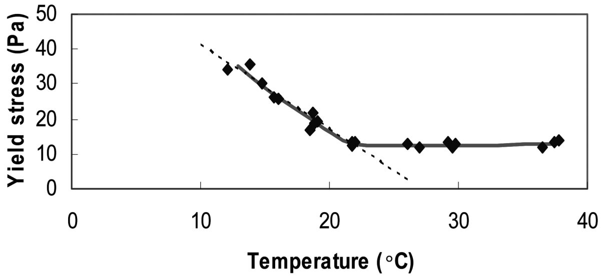

Fig. 3. The temperature dependence of the yield stress of yogurt (the dotted line = the yield stress from the Eyring's kinetic model).

Effects of temperature on the yield stress

The yield stress was measured in the temperature range from 12 to 38°C (Fig. 3). As shown in Fig. 3, the yield stress linearly decreased as temperature increased up to 22°C. The temperature dependence of yield stress of yogurt was in agreement with the theoretical kinetic behavior up to 22°C, however the yield stress was maintained as a constant (~12.5 Pa) above 22°C. This may imply that there is a limit of the Eyring kinetic model to describe the temperature dependence of yield stress of yogurt. A hypothesis can be introduced to explain this limit. If the activation volume (v*) of yogurt at the above 22°C increases with the same rate as the temperature increase, the yield stress may be maintained as a constant.

Conclusion

Effect of temperature and pre-shearing on the yield stress of stirred yogurt were studied by the vane viscometer. Applying pre-shearing clearly showed that the yield stress of stirred yogurt depends on the structure of casein agglomerates. In addition, the pre-shearing speed and wait time showed significant impact on breaking and reforming the casein agglomerate structures. The Eyring's kinetic model partially described the temperature dependence of the yield stress. The yield stress showed a weak dependence on the shear rate, while strong dependence on temperature.

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