Influence of whipping temperature on the whipping properties and rheological characteristics of whipped cream

K. Ihara,*¹ K. Habara,† Y. Ozaki,‡ K. Nakamura,† H. Ochi,* H. Saito,* H. Asaoka,† M. Uozumi,‡ N. Ichihashi,† and K. Iwatsuki§

*Food Science & Technology Institute,

†Food Research & Development Institute,

‡Product Evaluation Center, and

§Research & Development, Morinaga Milk Industry Co. Ltd., 1-83, 5-Chome Higashihara, Zama, Kanagawa 252-8583, Japan

ABSTRACT

The effects of whipping temperature (5 to 15°C) on the whipping (whipping time and overrun) and rheological properties of whipped cream were studied. Fat globule aggregation (aggregation ratio of fat globules and serum viscosity) and air bubble factors (overrun, diameter, and surface area) were measured to investigate the mechanism of whipping. Whipping time, overrun, and bubble diameters decreased with increasing temperature, with the exception of bubble size at 15°C. The aggregation ratio of fat globules tended to increase with increasing temperature. Changes in hardness and bubble size during storage were relatively small at higher temperatures (12.5 and 15°C). Changes in overrun during storage were relatively small in the middle temperature range (7.5 to 12.5°C). From the results, the temperature range of 7.5 to 12.5°C is recommended for making whipped creams with a good texture, and a specific temperature should be decided when taking into account the preferred overrun. The correlation between the whipped cream strain hardness and serum viscosity was high ($R^2 = 0.906$) and persisted throughout the temperature range tested (5 to 15°C). A similar result was obtained at a different whipping speed (140 rpm). The multiple regression analysis in the range of 5 to 12.5°C indicated a high correlation ($R^2 = 0.946$) in which a dependent variable was the storage modulus of whipped cream and independent variables were bubble surface area and serum viscosity. Therefore, fat aggregation and air bubble properties are important factors in the development of cream hardness. The results of this study suggest that whipping temperature influences fat globule aggregation and the properties of air bubbles in whipped cream, which alters its rheological properties.

Key words: whipping temperature, whipping property, cream, rheology

INTRODUCTION

The whipping of cream introduces air bubbles and aggregates fat globules, which constructs a bubbles and fat globules aggregation network and makes the cream hard, ultimately becoming a whipped cream (Noda and Shiinoki, 1986; Van Aken, 2001; Hotrum et al., 2005). Whipped creams are unstable, and it is difficult to control their physical properties that affect characteristics such as mouth feeling, flavor, and appearance. It has been reported that liquid drainage from whipped cream and Ostwald ripening is responsible for the changes (Walstra et al., 2006).

Hotrum et al. (2005) defined a whipping process of 3 stages: 1) air bubbles are introduced and proteins are simultaneously adsorbed into their surfaces, 2) fat globules are adsorbed into the surface and accumulated, and 3) a network of fat globule aggregates is formed. Noda and Shiinoki (1986) defined a process of 4 stages and investigated the influences of demulsification and bubble introduction at each stage on the hardness of cream. Jakubczyk and Niranjan (2006) reported that the introduction of air bubbles influences the hardness of whipped cream. These reports indicate the importance of controlling fat globule aggregation and bubble introduction on the physical properties of whipped cream.

Murray et al. (2007) reported that air bubbles become stable when small particles are adsorbed onto their surface and structures of a protein network are formed. It was pointed out that fat globules and their aggregations contribute to the stability of bubbles in a whipped cream and that controlling these factors is important to the production of good whipped creams. It is known empirically that these factors can be controlled by altering the whipping conditions.

Ihara et al. (2005, 2007) studied the influence of whipping speed on the physical characteristics of whipped creams. They showed that creams that are whipped at a lower speed are relatively stable during storage and suggested that the stability of the air bubble surface

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¹Corresponding author: k_ihara@morinagamilk

influences the total stability of whipped creams. Different cream compositions and processing conditions have been tested to control the aggregation of fat globules and the physical properties of the air bubbles. Van Lent et al. (2008) compared creams reconstituted from buttermilk powder and skim milk powder and showed that fat globules formed with buttermilk powder were small and had a low viscosity. They also showed that the whipping properties varied with the whipping time, overrun (**OR**), and whey release at thawing. Cream processing sometimes needs low molecular weight emulsifiers, which simulate protein desorption from the surface of fat globules (Wilde and Clark, 1993; Cornec et al., 1998), lower the stability of fat globules against shear (Cornec et al., 1998), and accelerate fat globule aggregation during whipping (Hotrum et al., 2005). This mechanism is applied in ice cream production to control fat globule aggregation.

Smith et al. (2000) investigated how heating conditions and stabilizers influenced the structure and physical characteristics of whipped cream and reported that a whipped cream with stabilizer that is pasteurized using the UHT method is more stable than one pasteurized with the HTST method in terms of changes in air bubble diameter and storage modulus (**G'**). They concluded that a more solid serum phase of the UHT-treated cream caused this stability. Bolling et al. (2005) studied the influences of cream production methods and reported that cream pasteurized with the HTST method had better emulsion stability than that pasteurized with the UHT method. The stability of emulsion influences the state of fat aggregation during whipping. Proper emulsion stability is needed for the production of stable whipped cream.

The state of fat crystals, which varies with temperature (Sugimoto et al., 2001), affects the stability of emulsions (Rousseau, 2000). Fat crystals near the interface of fat globules penetrate the fat globule membrane to destabilize them (Van Voekel and Walstra, 1981). The solid fat content varies with temperature (Darling, 1982), and therefore the speed of demulsification is influenced by temperature; thus, temperature is very important for controlling the physical characteristics of cream. Kamath et al. (2008) studied the foaming of milk and reported relationships between temperatures and foaming properties that showed that cream exhibits a high foaming property at 5°C and no foaming at 25°C. They suggested that globule membrane disruption, which occurs as a result of the coexistence of liquid and crystal fat, is the mechanism underlying this phenomenon and that liquid oil adsorption to the bubble surfaces makes those surfaces unstable.

Drelon et al. (2006) investigated the influence of storage temperature and reported that the **OR** of whipped cream decreases at 4°C, that the **OR** and hardness of whipped cream tempered at 25°C is stable, and that this phenomenon is attributable to the progression of demulsification and reinforcement of fat globule networks caused by the tempering treatment. The viscosity and surface tension of cream decreases with increasing temperature (Kristensen et al., 1997); therefore, temperature is thought to affect the introduction of air bubbles.

Cream temperatures affect the physical properties of whipped cream immediately after whipping and during storage, but the temperature of cream varies during whipping. Precise evaluations of the influences of temperature have thus rarely been conducted. The main purpose of this research was therefore to precisely evaluate the effects of temperature on whipping cream. The whipping mechanism is also discussed here.

MATERIALS AND METHODS

Materials and Whipping Conditions

A 45% fat dairy cream (Morinaga Milk Industry, Tokyo, Japan) was used, with 80 g of sucrose added to 1 kg of cream for whipping. The whipping temperatures tested were 5, 7.5, 10, 12.5, and 15°C. The room temperature was controlled to the same temperature of cream to avoid changes in cream temperature during beating. A batch mixer (Kenwood Mixer Major, Kenwood, Hertfordshire, UK) was used for beating, and the whipping speed was 180 rpm. The end point of whipping was defined as when the cone penetration depth (**PD**), which is described in the next section, reached 21.5 ± 1.0 mm. At this end point, the whipped cream showed a good texture for cake making. The whipped creams were stored at 5°C, except the part used for the experiment, which was used immediately. Whipping tests finished at 85, 95, and 97.5% of the whipping end point were conducted to study whipping processes and evaluate the mechanisms of whipping. Thus, 4 independent tests were conducted in total at each temperature condition in the range from 5 to 12.5°C, and it was thought to be possible to evaluate repeatability indirectly. In the series of 15°C experiments, whipping was finished at 85 and 90% of the whipping end point. In the series of 10°C experiments, 3 replications were conducted to evaluate repeatability precisely.

Cone-Penetration Test

A cone penetrometer equipped with a cone (front edge angle: 40°; weight: 12 g; upper diameter: 24 mm;

length: 33 mm) was used to measure cream hardness. Cream hardness was defined as the cone PD 5 s after dropping as a result of its own weight from the whipped cream surface.

OR

Overrun was calculated using the following equation:

$$\text{OR (\%)} = (\rho_0 - \rho_w) / \rho_w \times 100, \quad [1]$$

where ρ_0 is the density of unwhipped cream and ρ_w is the density of whipped cream. The density was obtained using a weighing cup filled with 100 mL of the sample.

Dynamic Viscoelasticity

Storage modulus was measured using a dynamic viscoelasticity measuring instrument (Rheometric Dynamic Analyzer ARES, TA Instruments, New Castle, DE). The conditions were 2-mm sample thickness, 5°C, 0.1% strain, and 5 Hz. Storage modulus was used as an indicator of hardness. The results were the average of 3 measurements.

Strain Hardness

The Rheometric Dynamic Analyzer ARES (TA Instruments) was used to measure strain hardness (**SH**). The strain of whipped cream was measured for a 2-mm-thick sample at 5°C and a stress sweep from 0 to 200 Pa in 2 min. Strain hardness was defined as the stress measured when the whipped cream strain reached 10%, and this was used as an indicator of hardness. The results were the average of 3 measurements.

Aggregation Ratios of Fat Globules

Aggregation ratios (**AR**) of fat globules were measured using the method of Kokubo et al. (1994). The particle size distributions of unwhipped and whipped creams were measured by a laser-scattering particle size analyzer (LA-950V2, Horiba, Tokyo, Japan). Aggregation ratios were calculated using the following equation:

$$\text{AR (\%)} = (V_{wp} - 10) / 90 \times 100, \quad [2]$$

where V_{wp} (%) is the accumulated volume percentage of whipped cream larger than the diameter of a 90% accumulated volume percentage before whipping (D_{90}). The refractive index of the milk fat and the imaginary part of the refractive index (due to adsorption) were

determined to be 1.46 and 0.001, respectively (Martinet et al., 2005). These values indicate the ratio of fat globules in whipped creams with accumulated volume diameters of larger than D_{90} to smaller than D_{90} . The results were the average of 3 measurements.

Serum Viscosity

Serum viscosities were measured using a method based on that described by Noda and Shiinoki (1986). A 3-g sample of whipped cream was defoamed using a vacuum pump at 10 Pa and a serum sample was prepared. Its viscosity was measured by a cone-plate rotational viscometer (HAAKE RotoVisco 1, Thermo Electron, Karlsruhe, Germany) at a shear rate of 300/s. The results were the average of 3 measurements.

Diameter and Surface Area of Air Bubbles

Samples were frozen with liquid nitrogen and then observed with the aid of a scanning electron microscope equipped with a cryo stage (Gatan C1002, Oxford Instruments, Oxfordshire, UK). The stage temperature was −100°C. The projected diameter of air bubbles was measured from the scanning electron microscope images using image processing software (Image Pro Plus, Media Cybernetics, Bethesda, MD). Two images were measured for each sample and the count number of air bubbles was 500 to 800. The Sauter mean diameter (D_{32}) was calculated. Because D_{32} has the same specific surface area of the parent sample population, the surface area of air bubbles in 100 mL of whipped cream (A_b) can be calculated using D_{32} and OR as follows. First, the volume of air bubbles per 100 mL of whipped cream (V_b ; m³) is expressed as

$$V_b = 100 \times 10^{-6} \times \text{OR} / (1 + \text{OR}). \quad [3]$$

The specific surface area (A_{SP}) of air bubbles that have mean diameter D_{32} (μm) is

$$A_{SP} \text{ (m}^2\text{/m}^3\text{)} = 6 \times 10^6 / D_{32}. \quad [4]$$

Therefore, the surface area of air bubbles per 100 mL of whipped cream, A_b (m²), is

$$A_b = V_b / A_{SP} = 600 \times \text{OR} / (1 + \text{OR}) / D_{32}. \quad [5]$$

Dynamic Surface Tension

Dynamic surface tension was measured using a dynamic surface measuring system (Bubble Pressure Tensionmeter BP2, Kruss Hamburg, Germany). The bubble age ranged between 10 and 10,000 ms, and the

Table 1. Measured temperature of the room and creams

Condition (°C)	Room temperature (°C)	Cream temperature (°C)	
		Before whipping	At end point of whipping
5.0	4.8	5.1	4.8
7.5	7.3	7.5	7.5
10.0	9.7	10.0	10.0
12.5	12.7	12.5	12.6
15.0	14.9	15.1	14.9

difference in surface tension was calculated using the data for 10 and 1,000 ms. According to Gibbs' adsorption isotherm equation, the amount of adsorption onto the surface of air bubbles increases with decreasing surface tension:

$$\Gamma = -c/RT \times d\gamma/d[\ln(C_i)], \quad [6]$$

where Γ is the amount of adsorbed substance, R is the gas constant, T is the absolute temperature, γ is surface tension, C_i is the concentration of the solution, and c is a constant.

The degree of adsorption onto the surface increases as the surface tension decreases and the surface age increases, which makes it possible to evaluate the adsorption speed by calculating the differences in surface tension between bubble ages of 0.01 and 1 s. Therefore, this difference was used as an indicator of the speed of fat globule adsorption to the bubble surface.

Statistical Analysis

Regression analysis and multiple regression analysis were conducted using SPSS software (version 9, SPSS Inc., Chicago, IL). P -values less than 0.05 were determined as statistically significant.

RESULTS AND DISCUSSION

Temperature Dependence of the Physical Properties of Whipped Cream

As shown in Table 1, the temperature of cream did not change during whipping and hence these experiments are carried out at constant temperature. Whipping time shortened and OR decreased with increasing whipping temperature (Figure 1a and b). Overrun showed a high dependence on the whipping time in this temperature range; therefore, the temperature effect might be only shortening the whipping time. The solid fat content decreases and there is a high degree of fat globule aggregation at relatively high temperatures in this range. The shear rate sweep measurement using a cone plate rotational viscometer revealed a large viscos-

ity increase at around 15°C (data not shown), which supports the whipping properties found in this study. Bubble mean diameters decreased as the temperature increased from 7.5 to 12.5°C (Figure 1c), which was attributed to a decrease in the surface tension. Additional temperature increases from 12.5 to 15°C caused excess demulsification and an increase in the amount of liquid fat adsorbed to bubble surfaces; therefore, it appears that the adsorption of free fat to bubble surfaces causes bubble disruption and an increase in bubble size.

Adsorption of fat globules to an air-liquid interface makes air bubbles stable (Goff, 1997), and hence the adsorption speed of fat globules is likely to be important for air bubble stability. Diluted cream dynamic surface tensions of 5% fat were measured and the adsorption speed of fat globules were evaluated. As shown in Figure 2, the difference in surface tension between 10- and 1,000-ms-old bubbles exhibited a local maximum at 12.5°C. The difference between data obtained at 10 and 1,000 ms represents an index of adsorption speed, and so the adsorption speed of fat globules or proteins or both appears to be maximal at around 12.5°C. The results for skim milk (0% fat) showed a much lower temperature dependence. Thus, it seems that mainly fat globules are adsorbed at around 12.5°C. This finding indicates that the speed of fat globule adsorption to air bubbles could affect the size of the air bubbles.

As shown in Figure 3, the serum viscosity at the end of whipping was almost 1,000 mPas, which is in accordance with the result of Noda and Shiinoki (1986). The aggregation ratio of fat globules tended to increase with temperature (Figure 3a), whereas the serum viscosities were not affected by temperature (Figure 3b). This could be attributable to the hardness of the creams being kept constant ($PD = 21.5 \pm 1.0$ mm).

Changes in Hardness During Storage

Whipped cream stored at 5°C tended to soften (Figure 4a) and the SH rates tended to decrease up to 10°C. The changes in SH at 12.5 and 15°C were relatively small (Figure 4b), and the change in G' did not appear to be dependent on temperature (Figure 4c). Three different types of hardness (PD, SH, and G') were measured in

Figure 1. a) Whipping time, b) overrun, and c) air bubble mean diameter as functions of whipping temperature.

Figure 2. Temperature dependence of dynamic surface tension of cream with various fat contents.

this study; these findings thus reflect the properties of these differences.

Temperature Dependence of the Physical Properties of Foam During Storage

The OR of cream stored at 5°C decreased, and was constant in all other samples (Figure 5a). The reduction in OR at a lower temperature was consistent with the results of Drelon et al. (2006). A change in OR could be one of the reasons for the change in PD. The bubble mean diameters after 1 d tended to increase at lower temperatures. The D_{32} of air bubbles tended to increase with decreasing temperature; it was therefore considered that the smaller change in D_{32} of bubbles at higher temperature caused the SH to be maintained.

Influence of Serum Viscosity on the Development of Whipped Cream Hardness

Strain hardness was correlated with serum viscosity; this relationship was not affected by temperature (Figure 6b). This finding is in accordance with that of Noda and Shinoki (1986), who reported that elasticity increased with the serum viscosity. The PD data showed the same results; however, the influence of serum viscosity on G' was not clear (data not shown). The application of power regression analysis to serum viscosity and SH data revealed a correlation ($R^2 = 0.786$, $P < 0.01$; Figure 6b). Power regression analysis at 10°C and a whipping speed of 140 rpm showed a similar result to the result at 180 rpm (Figure 6c). This shows that the

Figure 3. Temperature dependence of a) the aggregation ratio of fat globules and b) serum viscosity.

relationship between serum viscosity and SH is largely independent of whipping speed in this range. On the other hand, the coefficient of determination value of a multiple regression analysis including bubble surface area was not higher than the value without the surface area. The serum viscosity thus greatly affected the SH, indicating that serum viscosity is important in the development of SH. Development of a network of fat globules in the serum phase caused the hardness against strain.

Influence of Bubble Surface Area on the Development of Whipped Cream Hardness

Storage modulus increased with bubble surface area (Figure 7a). There was no dependence on temperature in the range from 5 to 12.5°C (Figure 7b), which shows that the surface area of bubbles influences the hardness

Figure 4. Temperature dependence of a) differences in penetration depth (PD) during storage, b) strain hardness (SH), and c) storage modulus (G').

Figure 5. Temperature dependence of a) difference in overrun (OR) values and b) air bubble diameter after 1 d of storage.

directly within this temperature range. Jakubczyk and Niranjana (2006) reported that G' remained constant after the OR reached its maximum value and suggested that the amount of air bubbles contributed to the construction of stable structures. Our findings are in accordance with those of Jakubczyk and Niranjana (2006). On the other hand, the result at 15°C differed from those at the other temperatures, indicating a different underlying whipping mechanism, which may be attributable to excess fat globule aggregation.

Storage modulus should also be affected by the network of fat globules. Therefore, a multiple regression analysis was conducted in which the surface area of bubbles and serum viscosity were independent variables. The following multiple regression equation was obtained:

$$G' = 0.236 \times A^{2.06} \times \eta^{1.15}, \quad [7]$$

Figure 6. Influence of serum viscosity on strain hardness (SH) during whipping. a) Data for individual temperatures; b) correlation including all temperature data (i.e., 5 to 15°C); c) correlation of data at 10°C with a whipping speed of 140 rpm.

Figure 7. Influence of air bubble surface area on storage modulus (G') during whipping. a) Data for individual temperatures; b) correlation including all temperature data (i.e., 5 to 12.5°C).

where A is the surface area of the bubbles (in m²/100 mL of whipped cream) and η is the serum viscosity (mPas). This multiple regression equation was highly significant ($P < 0.01$) and gave a high correlation ($R^2 = 0.895$). The variance inflation factor was 2.53 (i.e., less than 10). It was thus considered that the collinearity between the surface area of bubbles and serum viscosity was not a problem. Equation 7 indicated that there was a relationship among the surface area of bubbles, serum viscosity, and G' , which was reasonable considering the friction between bubble and serum. Friction force increases with increasing air bubble surface area and serum viscosity, which causes the development of hardness. However, other effects are thought to exist and, hence, further study is needed.

CONCLUSIONS

Temperature changes within the range reported herein significantly affected whipping, fat globule aggregation, air bubbles, and the rheological properties of whipped cream: whipping time and OR decreased, and the AR increased with increasing temperature. The increase of temperature promoted fat globule aggregation more, reducing the time to reach the same hardness. Air bubble diameters decreased at temperatures up to 12.5°C. It was thought that the effect of decreasing viscosity and surface tension dominated up to 12.5°C and that excess fat globule aggregation made bubble surfaces unstable at 15°C. Therefore, the temperature range of 7.5 to 12.5°C is recommended for making whipped creams with a good texture, and a specific temperature should be decided when taking into account the preferred OR. Strain hardness and serum viscosity were highly correlated at all temperatures tested in this study. This relationship was also obtained at a different whipping speed (140 rpm). These results suggest that serum viscosity is one of the most important factors affecting the hardness of whipped cream. Storage modulus was correlated with serum viscosity and air bubble surface area in the temperature range of 5 to 12.5°C. The results of multiple regression suggest that the friction between fat globules and serum phase plays an important role in the G' of whipped creams. However, other factors could also affect this parameter, and these should be investigated in future studies.

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