10 Load- and Velocity-Dependent Friction Behavior of Cow Milk Fat AQ1

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10.1 INTRODUCTION

Oral cavity is subjected to severe chemical and mechanical perturbations throughout the day during the consumption of food and beverage products. The food components that constitute flavor and texture interact with the tongue, palate, and teeth to alter the oral sensory perception. Sensory perception is vital to the food transport process in the oral cavity. For example, the friction response of the taste buds, which are the sensory receptors on the tongue, helps in facilitating bolus formation for swallowing [1]. Also, friction of the taste buds is useful in differentiating food products based on creaminess [2], smoothness, and moistness [3]. Therefore, friction is an important factor in sensory perception of food products.

Milk is an important component of dairy food products, and its fat content can influence the oral sensory perception. For example, an increase in the fat content in milk has been related to an increase in the creaminess perception [2]. Furthermore, friction measurements on different milk fat samples, under sliding–rolling testing condition, showed that friction was lower for high-fat content (4%)

compared with low-fat content (0.3%). In another friction study on milk fat, under pure sliding condition, it was observed that the friction of 3.5% and 1.5% fat milk was the same [4]. This study is in contrast with the understanding that high-fat milk gives lower friction compared with low-fat milk. Moreover, it seems that the friction response of milk fat can be influenced by the type of sliding motion at the rubbing surfaces.

In this study, a pin-on-disk instrument with sliding hydrophobic surfaces is used to determine the friction coefficient of 0.3% and 3.5% fat milk. The friction coefficient is measured at different loads and velocity decay rates (λ), where λ is a constant. Friction coefficient maps are developed and used to investigate the role of fat content in the friction mechanism of milk.

10.2 EXPERIMENTAL SECTION

10.2.1 Materials

10.2.1.1 Milk Samples

Low-fat cow milk (0.3% fat) and high-fat milk (3.5% fat) were commercial products purchased from the local supermarket. These samples were from the same manufacturer or supplier. Note that the protein contents were the same for the low- and the high-fat milk. Demineralized water was used as control in all the experiments.

10.2.1.2 Pin-and-Disk Specimens

Polydimethylsiloxane (PDMS) pins and disks were used in friction measurements. They were prepared from a silicon elastomer kit (Sylgard 184, Dow corning, Midland, MI). The base and the curing agent were mixed in a ratio (w/w) of 10:1 and transferred into the molds of pins and disks. Overnight curing was conducted at 65°C in an oven. A mold with polystyrene hemispherical wells was used to prepare a hemispherical pin of 6 mm diameter and a polystyrene circular plate was used to prepare a disk of 60 mm diameter. The roughness of the PDMS disks and pins was measured by contact-mode atomic force microscopy. The average roughness was measured to be 3 and 5 nm for the disks and pins, respectively.

10.2.2 Methods

10.2.2.1 Preparation of the Pin-and-Disk Specimens for Friction Test

PDMS specimens were cleaned before friction measurements. Refer to the illustrations in Figure 10.1 for a detailed description of the cleaning steps.

10.2.2.2 Friction Coefficient Measurements

Friction coefficient (μ) was determined using a pin-on-disk instrument (TR 20, Ducom Instruments Pvt. Ltd., Bengaluru, India). This instrument can operate under a normal load range of 1.5–40 N and a speed range of 1–1000 rpm. Winducom software (Ducom Instruments Pvt. Ltd., India) was used to determine the friction

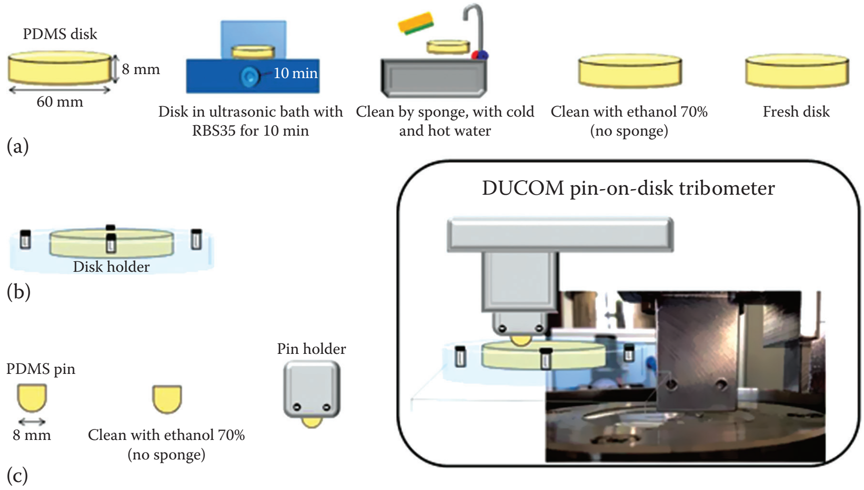

FIGURE 10.1 Cleaning and mounting of pin-and-disk specimens for friction measurements of cow milk fat: (a) disk cleaning (left to right), (b) disk mounting, and (c) pin mounting (left to right).

coefficient as the disk sliding velocity was continuously decreased with time from 80 to 2 mm/s at an exponential rate as follows:

$$V_f = V_i \cdot e^{-\lambda t}$$

where

V_f and V_i are the initial and final velocity (mm/s), respectively
the constant λ represents the velocity decay rate
t represents the duration in seconds

The velocity exponential decay profile at a decay rate (λ) of 0.003, as acquired by the pin-on-disk instrument, is reproduced in Figure 10.2.

The velocity decay rate was fixed at 0.003 for three loading conditions, that is, 1.5, 6.5, and 11.5 N. In another set of experiments, the load was fixed at 1.5 N for three different decay rate conditions, that is, 0.003, 0.005, and 0.009. Note that as λ is increased, the velocity sweep is quicker, which can influence the rate of recovery of perturbed surface layers. In all the experiments, the total volume of milk and demineralized water (control) was 4 mL. Note that demineralized water is deionized water without any minerals.

10.3 RESULTS

The friction coefficient at different loads was used to differentiate between 0.3% fat milk, 3.5% fat milk, and water (Figure 10.3). At 1.5 N load, during the start of the test (high sliding velocity), the friction coefficient of 0.3% fat milk was 0.01, that is, 100 times lower than that of water and five times lower than that

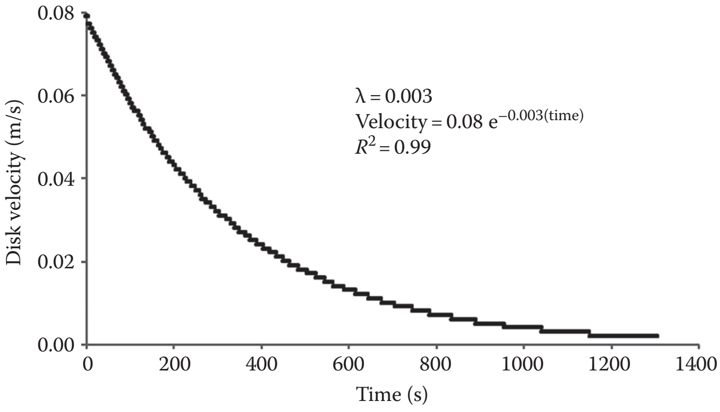

FIGURE 10.2 Exponential decay of disk sliding velocity as a function of time. The decay rate (λ) was 0.003, and initial and final disk velocities were kept at 80 and 2 mm/s, respectively.

of 3.5% fat milk (Figure 10.3a). As the velocity decreases, the low friction coefficient transits into its higher value, and this transition was delayed for 0.3% fat milk compared with 3.5% fat milk and water. At the lowest sliding velocity, the friction coefficient of 0.3% fat milk was still lower than those of 3.5% fat milk and water (Figure 10.4). At 6.5 N load and high sliding velocity, the friction coefficient was the same for 0.3% and 3.5% fat milk (Figure 10.3b). And at low sliding velocity, the friction coefficient of 0.3% fat milk was almost two times higher than that of 3.5% fat milk (Figure 10.4). At 11.5 N load, the friction coefficient trend for the 0.3% and 3.5% fat milk samples was similar and there was no difference in the friction coefficient at low sliding velocity (Figures 10.3c and 10.4). In general, the friction coefficient of 0.3% fat milk and 3.5% fat milk was lower than that of water at all loads applied in this study (Figure 10.4).

Friction coefficients at different velocity decay rates (λ) were used to differenti-
AQ2 ate 0.3% fat milk, 3.5% fat milk, and water (Figure 10.5). At 0.003 decay rate, two important trends were observed: (1) during high and low sliding velocities, the friction coefficient of 0.3% fat milk was lower than that of 3.5% fat milk, and (2) the transition point, that is, increase in the friction coefficient, was delayed for 0.3% fat milk compared with 3.5% fat milk (Figure 10.5a). As the decay rate is increased to 0.005, friction for 0.3% and 3.5% fat milk remains the same (Figures 10.5b and 10.6). Further increase in the decay rate to 0.009 will only partially reinstate the trends observed at 0.003 decay rate (Figure 10.5c). In general, the friction coefficient of water increases from 0.003 to 0.005 or 0.009 decay rate (Figure 10.6). At all decay rates, the friction coefficient of milk was lower than that of water.

10.4 DISCUSSION

The friction coefficient of PDMS surfaces decreases due to an increase in the normal load. Such a behavior is expected for low-modulus (or soft) hydrophobic surfaces due to the dominant adhesion forces arising from the interlocking

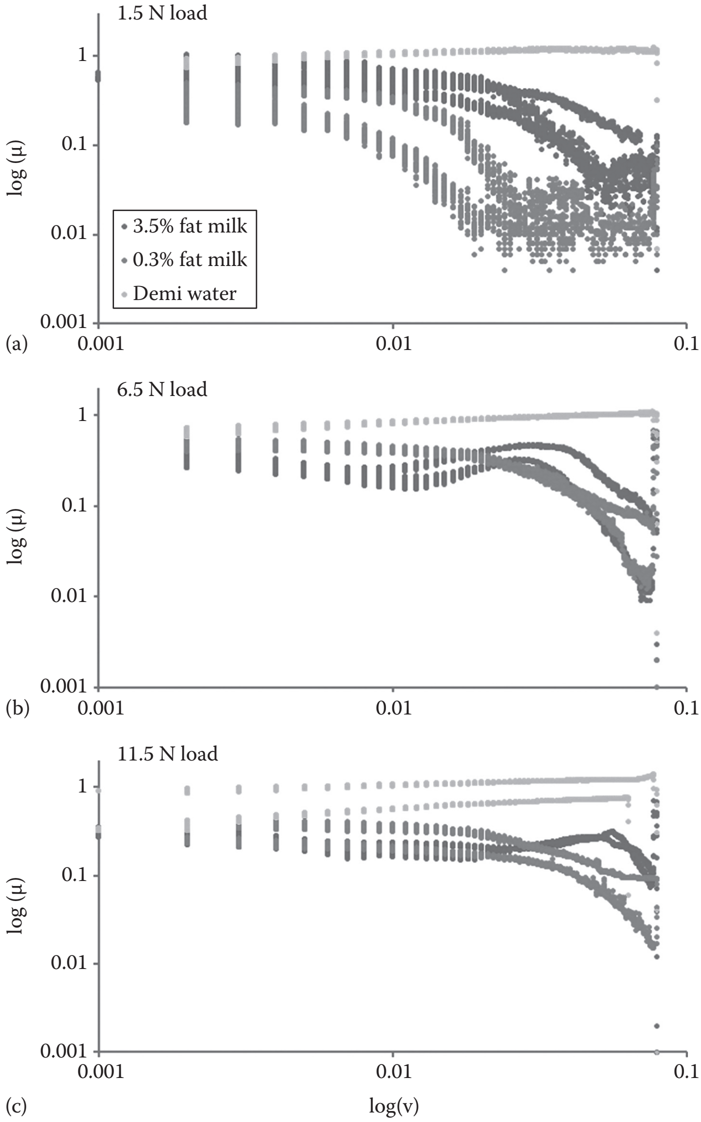

FIGURE 10.3 Change in the friction coefficient (μ) as a function of disk velocity for 3.5% fat milk, 0.3% fat milk, and control (water) at normal load of 1.5 N (a), 6.5 N (b), and 11.5 N (c). Data presented include two repetitions per load. The velocity decay rate (λ) was fixed at 0.003.

of asperities [5,6]. Furthermore, the friction coefficient is strongly influenced by the velocity decay rate (λ). An increase in λ decreased the rate of recovery of the sheared asperities, which will increase their deformation and increase the friction. The above mechanism is derived from friction studies on a water medium and it is not applicable to the milk medium. Therefore, we suspect the role of

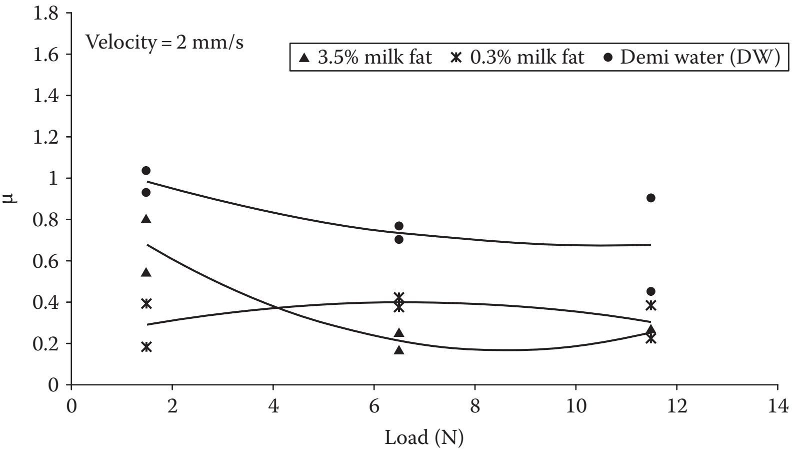

FIGURE 10.4 Relationship between the friction coefficient at low velocity (2 mm/s) and normal load for 3.5% fat milk, 0.3% fat milk, and control (water). Data presented include two repetitions per load.

milk components being dominant over the substrate effect. Milk is a mixture of proteins and fat molecules that can readily adsorb on hydrophobic surfaces and reduce friction better than water.

Casein forms 80% of milk proteins and occurs in the form of micelles, which stabilize the fat molecules in milk [7]. This stability arises from its hydrophobic interaction with the fat molecules and electrostatic repulsion between the micelles. The stability is disrupted by process parameters such as heat, pressure, and shear [7,8]. These process parameters decrease the hydrophobic interaction between casein and fat molecules. This phenomenon is observed in our friction experiments. The friction force induces shear thinning of low- and high-fat milk. We use the term shear thinning because of the increase in the friction as the sliding velocity decreases, which is related to the decrease in film thickness [9]. Later, we hypothesize that shear thinning of milk will produce two different surface active layers on the PDMS, depending on the fat content (Figure 10.7). The friction force will separate casein (hydrophobic head and hydrophilic tail)
AQ3 from the fat molecules, and then they adsorb on the PDMS surface via hydrophobic interaction. The surface layer in low-fat milk (0.3%) will have more casein than fat molecules (Figure 10.7a), whereas in high-fat milk (3.5%), there will be more fat molecules than casein (Figure 10.7b). Casein with its hydrophilic tail attracts water molecules; that is, more water molecules could be bound to the surface layer in low-fat milk. At low load (1.5 N), the shear plane runs through the hydrophilic tail with water molecules, and more water-bound hydrophilic tails are responsible for low friction, as determined for low-fat milk. However, at high load (6.5 N), the shear plane is pushed below the hydrophilic tail and runs through fat molecules. Here, more fat molecules on the surface are responsible for low friction, as shown for high-fat milk. An increase in the rate of decay (from 0.003 to 0.005) shows that more hydrophilic tails contribute to the quick

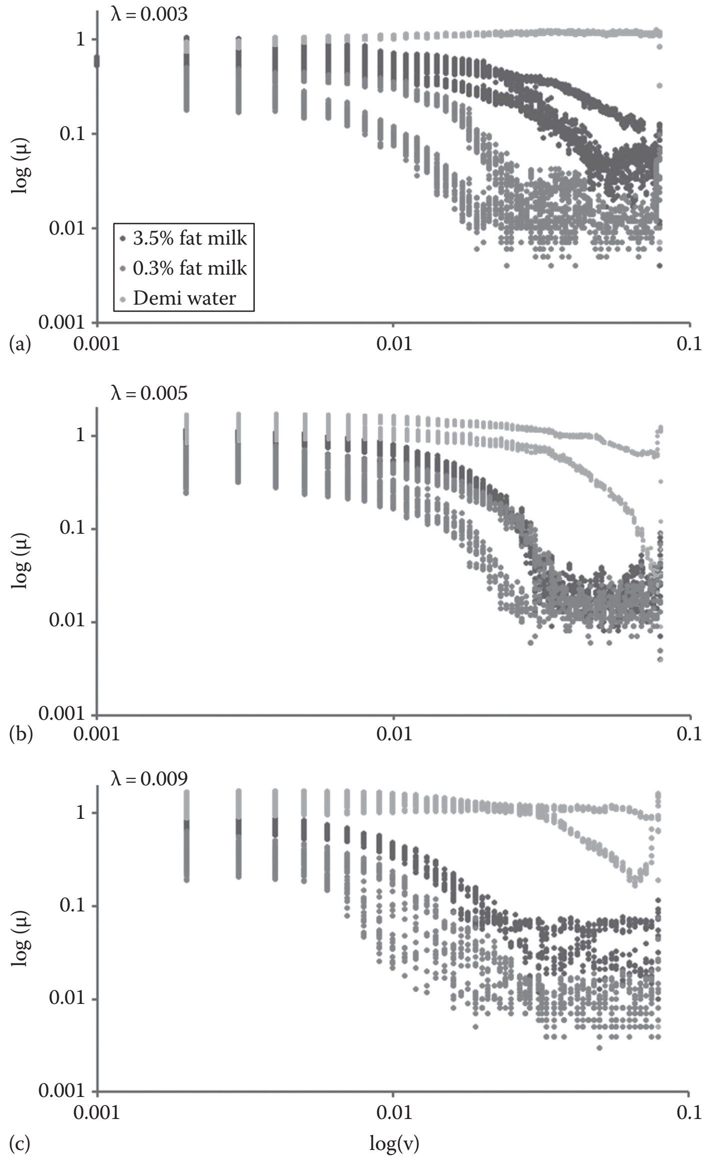

FIGURE 10.5 Change in the friction coefficient as a function of disk velocity for 3.5% fat milk, 0.3% fat milk, and control (water) at a velocity decay rate of 0.003 (a), 0.005 (b), and 0.009 (c). The normal load was fixed at 1.5 N. Data presented include two repetitions per decay rate.

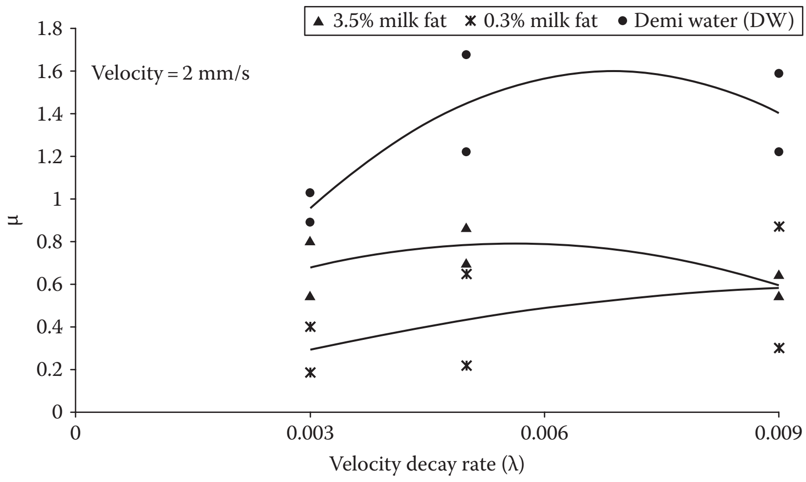

FIGURE 10.6 Relationship between the friction coefficient at low velocity (2 mm/s) and
AQ4 velocity decay rates for 3.5% fat milk, 0.3% fat milk, and control (water). Data presented include two repetitions per decay rate.

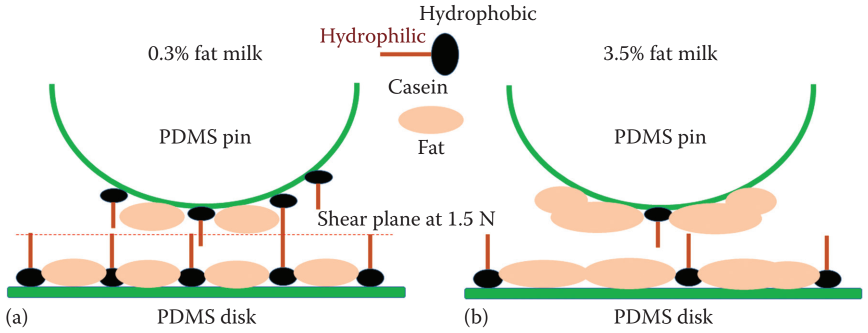

FIGURE 10.7 Schematic of the surface layer composed of casein and fat molecules, adsorbed on PDMS surfaces after shear thinning, for 0.3% fat milk (a) and 3.5% fat milk (b).

recovery and replenishment of water at the shear plane, as low-fat milk maintains a low friction coefficient compared with high-fat milk. More experiments need to be conducted to verify this hypothesis.

10.5 CONCLUSION

Milk components reduce friction compared with water at all loads and velocities used in this study. Low-fat milk has more casein and high-fat milk has more fat molecules in the surface layer formed after shear thinning. Casein with its hydrophilic tail dominates the low friction behavior at low load, and fat molecules dominate the low friction behavior at high load. Moreover, hydrophilic tails are useful in quick replenishment of water molecules, which reduce friction compared with fat molecules on the surface. Overall, this study can be useful in investigating the role of friction in the sensory perception of dairy food products.

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Author Queries

[AQ1] Please check if author name "Cristina Bignardi" in the chapter author group is correct.

[AQ2] Please check if edit to the sentence starting "At 0.003 decay rate..." is correct.

[AQ3] What are 'they' here: 'and then they adsorb on the PDMS surface via hydrophobic interaction'? Fat molecules?

[AQ4] Is this intended: [Figure 6. Relationship between the friction coefficient at low velocity (2 mm/s) and **different** velocity decay rates ...]