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The Effect of Overrun, Fat Destabilization, and Ice Cream Mix Viscosity on Entire Meltdown Behavior

Biqing Wu, Dieyckson O Freire, and Richard W. Hartel

Abstract: This study aims at exploring ice cream meltdown behavior by changing the levels of stabilizer (ST), polysorbate 80 (PS80), and overrun (OR). By adjusting the formulation of ice cream, the degree of fat destabilization (FD), mix viscosity (MV), and overrun can be controlled within a certain range, which in turn presents different meltdown behaviors for study. In addition to the drip-through test, the shape of ice cream as it melts was recorded as height change to further investigate ice cream meltdown. Mix viscosity (at 50 s^{-1}) and fat destabilization were found to have a significant effect not only on drip-through rate, but also the induction time, final weight of the drip-through part, height-change rate, and final height of melted ice cream. On the other side, overrun was found only to have an effect on meltdown when no stabilizers were added. These results indicate serum phase viscosity (mix viscosity) and fat destabilization are important parameters to describe ice cream meltdown. Besides, the entire ice cream meltdown curve and height collapse curve provide important information on ice cream meltdown behavior.

Keywords: fat destabilization, ice cream, meltdown, microstructure, viscosity

Practical application: A new direction of analysis of ice cream meltdown behavior is provided in this study. The induction time, the final drip-through weight, and the height change during the meltdown process were found to be the indicators on the influence of microstructure on ice cream meltdown behavior for the future study.

Introduction

Meltdown is one of the most important properties of ice cream for not only consumption and transportation, but also research study (Goff & Hartel, 2013). It is used as a research tool to observe and predict some physical properties, such as melting rate and shape retention, or to compare the effect of various formulation and processing condition on microstructure. By performing ice cream meltdown test for research, a slice of ice cream is placed on a wire mesh and given sufficient time for meltdown. The meltdown process can be divided into three phases: the lag phase, the fast-melting phase, and the stationary phase. In the lag phase, heat penetrates into the ice cream, and ice crystals start melting and dilute the serum phase, which decreases its viscosity. With decreasing viscosity and increasing flowability of diluted serum phase, ice cream meltdown reaches the second stage, fast-melting phase, where ice cream starts dripping through the wire mesh by the driving force of gravity to reach the maximum meltdown rate (Goff & Hartel, 2013). During this phase, ice cream collapses at a rate and to an extent, depending on the remaining structures including air cells and fat clusters/globules. If there are numerous fat clusters around the air cells, they collide with each other and jam as the serum drains to form a three-dimensional network with air cells, so that meltdown gradually slows and comes to the stationary phase. If there are few fat clusters, ice cream is able to totally drip through without leaving foam on the mesh. Generally, the maximum slope is defined as ice cream meltdown rate (Koxholt et al., 2001).

Numerous factors affect meltdown. Overrun, stabilizer level and type, ice crystal content as well as emulsifier level and type influence ice cream meltdown behavior by modifying ice cream microstructure. Sakurai et al. (1996), Sofjan and Hartel (2004), and Warren and Hartel (2018) found that overrun has an important effect on ice cream meltdown rate because air is an excellent insulator and prevents heat penetrating into the ice cream during the meltdown process (Goff & Hartel, 2013). Increasing overrun significantly decreased meltdown rate, giving ice cream with better melting resistance.

Changing emulsifier types and levels contributes to different levels of fat destabilization, which in turn influences ice cream meltdown rate. Muse and Hartel (2004) and Bolliger et al. (2000) found that increasing the amount of polysorbate 80 (PS80) decreased melt rate significantly, while increasing amount of mono- and diglycerides also decreased melt rate, but to a less extent (Cropper et al., 2013). An increased fat destabilization was seen with the increasing level of emulsifiers added in ice cream (Bolliger et al., 2000). A higher extent of fat destabilization in the ice cream improved melting resistance during the meltdown process and caused a lower melt rate (Warren, 2015). Also, Koxholt et al. (2001) found that larger fat particles contribute to a lower maximum meltdown rate.

Although various studies on ice cream have used ice cream meltdown rate as an indicator to differentiate ice cream structure, few studies have analyzed the whole meltdown curve or combined the shape change with ice cream meltdown behavior. An understanding of the influence of microstructure on three stages of ice cream meltdown will provide a better understanding of the complex phenomena that occur during the ice cream meltdown process.

Materials and Methods

Materials

Cream, sugar (United Sugars, Edina, MN, USA), and nonfat dry milk (Dairy America, Fresno, CA, USA) were purchased from the

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dairy plant at the Univ. of Wisconsin—Madison (Madison, WI, USA). Germantown Premium I.C blended stabilizers with the components of locust bean gum, guar gum, and carrageenan as well as Grinsted® mono- and diglyceride (MDG) were acquired from Danisco USA (New Century, KS, USA). Avapol™ 80K Sorbitan Ester (Polysorbate 80/PS80) was acquired from Avatar® (University Park, IL, USA).

Ice cream formulation design

Ice cream mix was made with 12% milkfat, 16.9% sucrose, 11.3% milk solids nonfat, and 0.15% MDG consistently throughout different formulas. A 3 × 3 × 3 factorial design (27 formulas in total) was conducted on three different levels of blended stabilizer (0%, 0.2%, and 0.4%), polysorbate 80 (0%, 0.015%, and 0.03%), and overrun (50%, 75%, and 100%). Stabilizer and polysorbate 80 were simply added to the base mix at these two levels. Ice cream mix had approximately 41% total solids and the freezing point depression was −2.76 ± 0.06 °C.

Ice cream making process

Dry ingredients and liquid ingredients were mixed, blended, and heated to 85 °C in a batch-jacketed pasteurization system, Stephan Mixer (Stephan Food Processing Machinery, Hamelin, Germany), followed by the homogenization process. Pasteurized mix went through a two-stage homogenizer (Manton-Gaulin MFG, Co. Inc., Everett, MA, USA) at 17.2 MPa (13.8 MPa first stage and 3.4 MPa second stage). Homogenized ice cream mix was then transferred back to the Stephan Mixer and cooled to 10 °C. Ice cream mix was aged at 4 °C for 24 hr.

Ice cream mix was frozen on the Hoyer Frigus KF 80 F continuous freezer (Tetra Pak Hoyer Inc., Aarhus, Denmark). The Hoyer freezer was manipulated in the manual mode to control the desired parameters for the experimental design. The pump ratio was set to 1 in order to have the same residence time in the barrel for all ice cream mix, and the air system was set to 2, 3, and 4 gal/hr to reach the target overruns of 50%, 75%, and 100%, respectively. The dasher speed was set at 500 RPM and draw temperature target was −6.0 °C. Ice cream was collected into 473.2 mL containers, placed in a small blast freezer at −29 °C for 1 hr and then transferred to a walk-in freezer at −29 °C for further storage. Ice cream samples were made in duplicate and all sample mixes were made and frozen in random order.

Analyses

Overrun. The method of overrun measurement involves separately weighing the ice cream mix and ice cream in a fixed volume container (around 177.4 mL). For each batch, the overrun was taken every other sample throughout the ice cream production, controlling the error within ±3%. Overrun measurement was carried out in triplicate.

Meltdown test. The method of ice cream meltdown test was described by Bolliger et al. (2000) and the method of drip through rate calculation was described by Koxholt et al. (2001). Ice cream containers were placed in the −20 °C freezer to temper for 24 hr before conducting meltdown test at ambient temperature (22 ± 1 °C). An 80 g slice of ice cream (with approximately 8.0 cm diameter) was cut at the middle of the pint-size container and placed on a wire mesh (3 holes/cm). Samples with higher overrun had increased volume due to the lower density. A 1 L beaker was placed on a scale underneath the ice cream to collect drip-through part. The time when the first drop dripped was recorded as induction time. The weight of drip-through part was recorded every 5 min for 360 min in Microsoft Excel with a computer connected to the scale. Height (cm) was recorded by ruler every 5 min in the first 120 min and at the end of the meltdown test. Meltdown test was carried out in triplicate.

Partially coalesced fat size distribution. Fat particle size distribution was measured by Malvern Mastersizer 2000 (Malvern Instruments Ltd., Worcestershire, United Kingdom), which uses light scattering to determine the relative volume in each size increment. Samples of melted ice cream and ice cream mix were stored at 4 °C before measurement by the Mastersizer. Two to four drops of sample were added to the chamber for dilution and measurement. Milkfat was the dispersed phase with refractive index set to 1.47 and absorbance set to 0.01. Deionized water was used as dispersant with 1.33 refractive index, and the measurement was conducted within the range of 13% to 15% obscuration values. The size distribution of ice cream mix was used to compare with melted ice cream curve to determine the extent of partial coalescence, which was calculated as the ratio of third peak volume in melted ice cream to the initial emulsion peak (the second peak) in the ice cream mix (Warren & Hartel, 2018). In addition, images were taken through optical microcopy to further confirm fat destabilization extent (images were not shown). Fat destabilization measurement was carried out in triplicate.

Mix viscosity. Ice cream mix viscosity was measured by a Discovery DHR-2 hybrid rheometer (TA Instrument, New Castle, DE, USA) with cup and bob geometry as described by Amador et al. (2017). Ice cream mix was loaded in the temperature-controllable cell to equilibrate to 0 °C. Flow sweep was used from 100 to 1 s^{-1} shear rate and the apparent viscosity at 50 s^{-1} shear rate in the curve was used as mix viscosity. The flow sweep (and the calculated apparent viscosity at 50 s^{-1}) was carried out in triplicate.

Ice crystal size distribution. A refrigerated glove box was used for ice crystal size analysis as described by Donhowe et al. (1991). A light microscope (model FX-35DX, Nikon, Inc., Garden City, NY, USA) was set inside the glove box at −15 °C for taking photographs. After samples were tempered to equilibrate at −15 °C, a thin slice of ice cream was loaded on a chilled glass slide. One or two drops of 1:1 kerosene:pentanol organic solvent were applied to disperse the sample, covered by the chilled cover slide. Ice crystals were spread out by gently tapping the cover slide with chilled tweezers. Ice crystal images were taken at 40× magnification to acquire 300 to 400 ice crystals per container and traced using Microsoft Softonic Paintbrush. The traced images were analyzed by using Image Pro Plus software (Version 7.0, Media Cybernetics, Inc., Rockville, MD, USA) and results were gathered in the Microsoft Excel software. Ice crystal size measurement was carried out in triplicate.

Air cell size distribution. A method of measuring air cell size by using the same refrigerated glove box mentioned above was described by Chang and Hartel (2002). The ice cream sample was placed in the glove box for 30 min for tempering at −15 °C. To analyze, a small ice cream slice was scooped from the center of the sample by a chilled metal spatula and loaded on a glass slide. The ice cream slice was placed in a well (roughly 100 to 200 μm depth) created by two glued cover slides (25 mm × 25 mm). Then, temperature was adjusted to −6 °C to allow the air cells to rise to the top of the slice as some ice crystals melted. Approximately six images were captured by the light microscope at 40× magnification to obtain 300 to 400 air cells per container. The air cells were traced manually, sizes were calculated by Image Pro Plus software, and results were gathered in the

Microsoft Excel software. Air cell size measurement was carried out in triplicate.

Statistical analyses. Data analysis was performed on JMP Pro 13.0 software (SAS, Cary, NC, USA). The effects of the respective variables on the ice cream meltdown responses were determined by performing one-way ANOVA and Tukey's HSD tests ($\alpha < 0.05$). The correlations between the variables and responses were determined by performing multivariate analysis.

Results and Discussion

The effects of ingredients (including overrun, polysorbate 80, and stabilizer levels) on the entire meltdown process were studied. Both the drip-through test and the height change of melted ice cream were used to demonstrate the influence of ingredients and structure on meltdown.

Ice cream microstructure

Mean ice crystal size. The mean ice crystal size fell in a narrow range from 28.5 to 38.2 μm regardless of various formulas as shown in Table 1. Although the mean size of ice crystal varied slightly from one formula to another, no specific trend was seen regardless of different stabilizer, polysorbate 80, and overrun levels, which agrees with previous findings (Amador et al., 2017; Warren & Hartel, 2018).

Mean air cell size. The mean air cell size ranged from 11.8 to 30.1 μm across different formulas as shown in Table 1. Sofjan and Hartel (2004) and Warren and Hartel (2018) found that increasing overrun decreased the mean air cell size within the range from 17 to 29 μm. A similar trend was seen in this study, in general. An increase in overrun provided a high shear stress when incorporating with the ice cream mix and breaking down the air cell.

A strong negative correlation that increasing fat destabilization extent decreased mean air cell size was seen in ice cream with 0% ($r = -0.8978$, $P = 0.0010$) and 0.4% stabilizer ($r = -0.8611$, $P = 0.0029$). For the 0.2% stabilizer ice cream, there was no significant correlation between fat destabilization and mean air cell size ($r = -0.6345$, $P = 0.0664$). Warren and Hartel (2018) also found a negative relationship between fat destabilization extent and mean air cell size. This relationship is mainly because shear stress in the barrel not only induced fat destabilization, but also helped to break down air cells.

Amador et al. (2017) found that adding stabilizers decreased mean air cell size at −3 °C draw temperature due to high shear stress in the freezer breaking down the air cells, whereas no specific trend was seen in this study at −6 °C draw temperature. Even though some statistical differences were found in mean air cell size, the differences were very slight. Further study is needed to better understand the influence of processing conditions and stabilizer level on air cells.

Fat destabilization. Ice cream samples with different levels of stabilizer, polysorbate 80, and overrun had various fat destabilization contents, ranging from 8.8% to 73.2% as shown in Table 1. Ice cream with the highest overrun level (100%), polysorbate 80 level (0.03%), and stabilizer level (0.4%) had the highest fat destabilization, whereas ice cream with the lowest overrun (50%) and no polysorbate 80 or stabilizer added had the lowest fat destabilization. In general, with increasing overrun, fat destabilization increased, though this trend was not seen in the ice cream samples with 0.4% stabilizer and 0.015% polysorbate 80. Increased stabilizer level enhanced fat destabilization throughout all samples. When there was no stabilizer added, increasing polysorbate 80 increased fat destabilization. As stabilizers were added (to 0.2%), the lowest fat destabilization occurred when polysorbate 80 was 0.015%. With stabilizer added at 0.4% level, generally additional polysorbate 80 enhanced fat destabilization, but this trend was not seen in 100% overrun samples. The trend of increasing overrun causing increased fat destabilization has been reported previously (Warren & Hartel, 2018). The narrow lamellae between the air cells in the high overrun ice cream could increase the possibility of fat globules/clusters collision and adsorption to the air cells surface and promote partial coalescence.

The trend of increasing stabilizer content causing increased fat destabilization was seen throughout all samples. When no stabilizer was added, ice cream had lowest fat destabilization compared to ice cream with 0.2% and 0.4% stabilizer, which agrees with previous findings by Amador (2016) and Goff and Spagnuolo (2001). Stabilizers increase the apparent viscosity of ice cream mix, further increasing the shear stress during freezing and promoting shear interactions among fat globules (Goff & Spagnuolo, 2001, Stanley et al., 1996).

Using Tukey's HSD test, when ice cream had 0% and 0.2% stabilizer, 0% and 0.015% levels of polysorbate 80 did not show a statistical difference on fat destabilization extent as compared to 0.03% level. In general, increasing polysorbate 80 also increased fat destabilization level across all overruns when no stabilizer was added, which agrees with the previous finding by Tharp et al. (1998). Added polysorbate 80 increased the displacement of protein on the fat globule surface, accelerating fat destabilization (Goff & Hartel, 2013). However, when the apparent mix viscosity (at 50 s^{-1} shear rate) was higher than 0.25 Pa·s due to the addition of stabilizers, the change of fat destabilization level did not follow the same trend. Increasing mix viscosity (at 50 s^{-1} shear rate) caused shear force increase during freezing, promoting fat globule interactions and destabilization. The shear stress from viscous mix appears to be the dominant factor affecting fat destabilization level in this study, more so even than additional polysorbate 80. Therefore, added 0.015% or 0.03% polysorbate 80 did not significantly influence fat destabilization level in ice creams with 0.4% stabilizer.

Meltdown

The ice cream meltdown curve was usually seen as a sigmoid curve with lag phase, fast-melting phase, and plateau phase, which represented three stages of ice cream meltdown. Lag phase ended when the first drop dripped through the screen, as represented by induction time. The slope of the fast-melting phase was defined as ice cream meltdown rate (Koxholt et al., 2001). Plateau phase was when the meltdown slowed and came to a static state, as represented by the percentage of final weight after 6-hr meltdown.

The shape of ice cream meltdown curve was dependent on the composition, as shown in Figure 1. Here, three different curves were selected to show the range of behaviors observed. Ice cream with 50% overrun, 0% stabilizer, and polysorbate 80 had the weakest structure among all samples prepared, with the lowest fat destabilization; it melted completely within 1 to 2 hr. Ice cream with 100% overrun, 0.4% stabilizer, and 0.03% polysorbate 80 had the most intricate structure among all samples, with the highest fat destabilization; a relatively high amount of foam was retained on the screen after the meltdown test, retaining nearly 85% of the original mass in the remnant foam. An ice cream meltdown curve with structure between these two samples was seen for condition of 75% overrun, 0.2% stabilizer, and 0.015% polysorbate 80.

Table 1–Means and standard deviation of ice cream ice crystal size, air cell size, fat destabilization extent (FD), and mix viscosity (MV) with three levels of stabilizer, polysorbate 80 (PS80), and overrun (OR).

Stabilizer	OR	PS80	Mean ice crystal size (μm)	Mean air cell size (μm)	FD (%)	MV (Pa·s)
0%	50%	0%	$28.5 \pm 2.9^{x,X,A}$	$22.4 \pm 1.9^{xy,X,A}$	$8.8 \pm 5.0^{x,X,A}$	$0.0220 \pm 0.0007^{x,A}$
		0.015%	$33.9 \pm 0.3^{y,X,A}$	$24.3 \pm 2.5^{x,X,A}$	$11.8 \pm 5.0^{x,X,A}$	$0.0244 \pm 0.0013^{x,A}$
		0.03%	$32.3 \pm 0.8^{xy,X,A}$	$18.1 \pm 1.7^{y,X,A}$	$22.3 \pm 4.8^{y,X,A}$	$0.0217 \pm 0.0019^{x,A}$
	75%	0%	$31.6 \pm 0.9^{x,X,A}$	$18.3 \pm 2.7^{x,XY,A}$	$18.7 \pm 3.0^{x,Y,A}$	$0.0220 \pm 0.0007^{x,A}$
		0.015%	$35.8 \pm 0.1^{y,Y,A}$	$20.1 \pm 1.9^{x,XY,A}$	$22.7 \pm 4.6^{x,Y,A}$	$0.0244 \pm 0.0013^{x,A}$
		0.03%	$35.4 \pm 1.0^{y,Y,A}$	$16.1 \pm 0.9^{x,XY,A}$	$46.2 \pm 8.1^{y,Y,A}$	$0.0217 \pm 0.0019^{x,A}$
	100%	0%	$31.0 \pm 0.5^{xy,X,A}$	$16.0 \pm 1.7^{x,Y,A}$	$30.0 \pm 2.9^{x,Z,A}$	$0.0220 \pm 0.0007^{x,A}$
		0.015%	$33.4 \pm 1.1^{x,X,A}$	$16.2 \pm 1.9^{x,Y,A}$	$29.1 \pm 6.2^{x,Y,A}$	$0.0244 \pm 0.0013^{x,A}$
		0.03%	$29.8 \pm 1.7^{y,X,A}$	$11.8 \pm 2.9^{x,Y,A}$	$58.0 \pm 9.2^{y,Z,A}$	$0.0217 \pm 0.0019^{x,A}$
0.2%	50%	0%	$31.9 \pm 0.9^{x,X,A}$	$30.1 \pm 0.4^{x,X,B}$	$20.3 \pm 3.4^{x,X,B}$	$0.0886 \pm 0.0084^{x,B}$
		0.015%	$37.7 \pm 1.3^{y,X,B}$	$24.8 \pm 0.5^{y,X,A}$	$15.1 \pm 8.7^{x,X,A}$	$0.0957 \pm 0.0023^{x,B}$
		0.03%	$33.1 \pm 0.9^{x,X,A}$	$24.4 \pm 0.5^{y,X,B}$	$46.6 \pm 14.5^{y,X,B}$	$0.0894 \pm 0.0112^{x,B}$
	75%	0%	$32.6 \pm 1.9^{x,X,A}$	$24.6 \pm 0.6^{x,Y,B}$	$34.8 \pm 11.9^{x,X,B}$	$0.0886 \pm 0.0084^{x,B}$
		0.015%	$38.2 \pm 0.4^{y,X,B}$	$20.5 \pm 1.2^{y,Y,A}$	$24.0 \pm 11.6^{x,X,A}$	$0.0957 \pm 0.0023^{x,B}$
		0.03%	$33.2 \pm 1.8^{x,X,A}$	$18.8 \pm 1.2^{y,Y,B}$	$57.2 \pm 8.4^{y,XY,AB}$	$0.0894 \pm 0.0112^{x,B}$
	100%	0%	$32.1 \pm 0.9^{x,X,A}$	$26.9 \pm 0.7^{x,Z,B}$	$51.6 \pm 12.6^{x,Y,B}$	$0.0886 \pm 0.0084^{x,B}$
		0.015%	$33.0 \pm 1.2^{x,Y,A}$	$18.3 \pm 1.7^{y,Y,A}$	$45.5 \pm 8.8^{x,Y,B}$	$0.0957 \pm 0.0023^{x,B}$
		0.03%	$33.4 \pm 0.4^{x,X,AB}$	$13.9 \pm 1.1^{z,Z,A}$	$69.5 \pm 7.2^{y,Y,B}$	$0.0894 \pm 0.0112^{x,B}$
0.4%	50%	0%	$32.9 \pm 0.3^{x,X,A}$	$26.8 \pm 0.8^{x,X,C}$	$39.8 \pm 7.7^{x,X,C}$	$0.2642 \pm 0.0130^{x,C}$
		0.015%	$31.9 \pm 0.4^{x,X,A}$	$25.3 \pm 1.2^{x,X,A}$	$49.4 \pm 5.7^{xy,X,B}$	$0.2904 \pm 0.0051^{y,C}$
		0.03%	$37.1 \pm 1.5^{y,X,B}$	$25.3 \pm 1.2^{x,X,B}$	$56.8 \pm 10.8^{y,X,B}$	$0.2882 \pm 0.0035^{y,C}$
	75%	0%	$30.7 \pm 0.6^{x,Y,A}$	$23.2 \pm 0.7^{x,Y,B}$	$55.4 \pm 5.0^{x,Y,C}$	$0.2642 \pm 0.0130^{x,C}$
		0.015%	$29.5 \pm 0.7^{x,Y,C}$	$22.8 \pm 0.7^{x,Y,A}$	$57.0 \pm 4.2^{x,X,B}$	$0.2904 \pm 0.0051^{y,C}$
		0.03%	$35.3 \pm 1.2^{y,X,A}$	$23.0 \pm 0.9^{x,X,C}$	$63.2 \pm 8.7^{x,XY,B}$	$0.2882 \pm 0.0035^{y,C}$
	100%	0%	$32.0 \pm 0.6^{x,X,A}$	$21.1 \pm 0.7^{x,Z,C}$	$68.5 \pm 4.6^{x,Z,C}$	$0.2642 \pm 0.0130^{x,C}$
		0.015%	$37.0 \pm 0.4^{y,Z,B}$	$24.4 \pm 0.5^{y,XY,B}$	$55.9 \pm 8.7^{y,X,B}$	$0.2904 \pm 0.0051^{y,C}$
		0.03%	$36.6 \pm 2.3^{y,X,B}$	$22.4 \pm 1.7^{xy,X,B}$	$73.2 \pm 4.3^{x,Y,B}$	$0.2882 \pm 0.0035^{y,C}$

Note. Stabilizer is a mixture of locust bean gum, guar gum, and carrageenan. Tukey's HSD test was performed for significant difference at $P < 0.05$. Superscripts x, y, and z denote significant difference among ice cream with different polysorbate 80 levels; X, Y, and Z denote significant difference among ice cream with different overrun levels; A, B, and C denote significant difference among ice cream with different stabilizer levels.

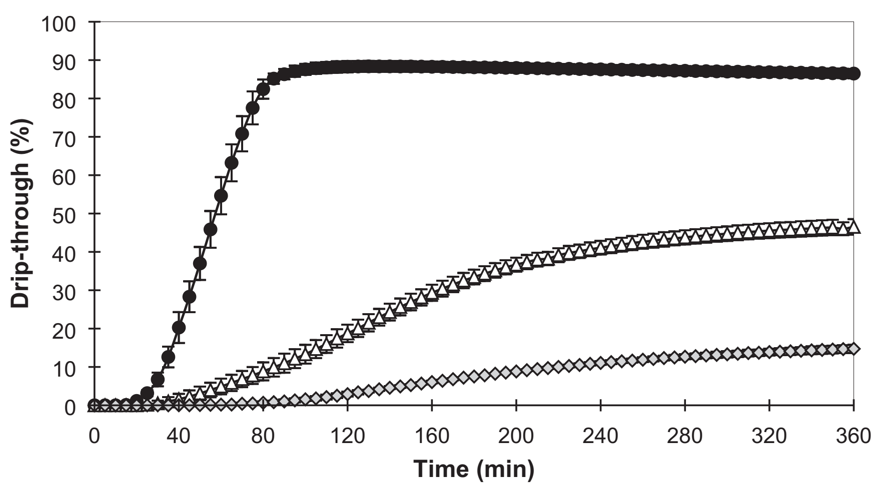

Figure 1–Example ice cream meltdown curves. The error bars stand for standard deviation of mean values among six samples. Circle, ice cream with 0% stabilizer (ST), 0% polysorbate 80 (PS80), and 50% overrun (OR); triangle, ice cream with 0.2% ST, 0.015% PS80, and 75% OR; diamond, ice cream with 0.4% ST, 0.03% PS80, and 100% OR.

Ice cream height change during the meltdown test provides additional information on structure collapse. As there are two types of meltdown behavior after a certain time, total drip-through and remnant foam, height changes are completely different. For those that totally dripped through, height change had a sharp reduction over a short time, whereas for those that left a remnant foam structure, ice cream height gradually decreased and remained at a certain height with only a slight change after 6 hr. Figure 2 shows the height change curves for the same representative samples as in Figure 1. Various structural parameters were found to correlate with the various measures of meltdown, and details can be found in Supporting Information.

The effect of ice cream microstructure on meltdown has been discussed in recent years. The modification of structure by adjusting ice cream formulas provides different meltdown behaviors. Fat destabilization extent, mix viscosity, and overrun were found to influence meltdown (Amador et al., 2017; Daw & Hartel, 2015; Muse & Hartel, 2004; Sakurai et al., 1996; Sofjan & Hartel, 2004; Warren & Hartel, 2018). By adding polysorbate 80, proteins desorb from the fat globule surfaces and the reduction of steric

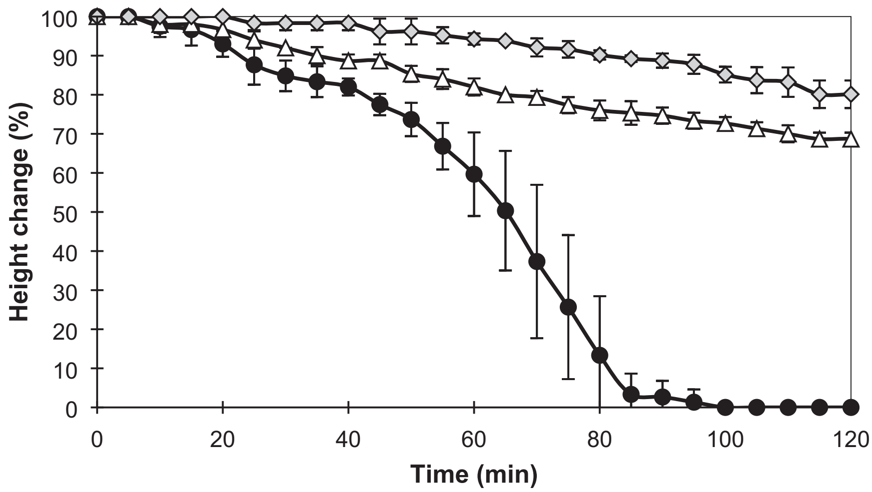

Figure 2–Example ice cream height change curves. The error bars stand for standard deviation of mean values among six samples. Circle, ice cream with 0% stabilizer (ST), 0% polysorbate 80 (PS80), and 50% overrun (OR); triangle, ice cream with 0.2% ST, 0.015% PS80, and 75% OR; diamond, ice cream with 0.4% ST, 0.03% PS80, and 100% OR.

stabilization promotes fat destabilization extent (Goff & Hartel, 2013). As a result, during the meltdown, large fat clusters collide and jam with each other to prevent further drainage (Muse & Hartel, 2004; Warren & Hartel, 2018). Adding stabilizers increases the serum phase viscosity. As ice crystals melt, water dilutes the serum phase and the melted ice cream drains governed by the gravitational force. When the serum phase is viscous, the drainage process slows and leads to a low meltdown rate (Amador et al., 2017; Muse & Hartel, 2004). Meanwhile, the amount of air affects heat conduction and thus further affects ice cream meltdown rate because air is an insulator to prevent heat penetration (Sakurai et al., 1996; Sofjan & Hartel, 2004; Warren & Hartel, 2018). The effect of three structure elements on meltdown will be discussed in detail below.

Fat destabilization. Multivariate analysis on all the data showed a positive correlation between fat destabilization and induction time ($r = 0.7726$, $P < 0.0001$). Increasing fat destabilization increased the induction time to the first drop. Ice cream with high extent of fat destabilization promoted a high yield stress, which increased the resistance of water to flow against gravitational force.

Overall, an inverse correlation was found between fat destabilization and drip-through rate ($r = -0.6851$, $P < 0.0001$), corresponding with previous findings (Bolliger et al., 2000; Muse & Hartel, 2004; Tharp et al., 1998; Warren & Hartel, 2014, 2018). However, the effect was more pronounced at certain conditions, specifically at low stabilizer levels. As shown in Figure 3, an increase in fat destabilization extent in ice cream without stabilizer significantly decreased drip-through rate. Ice cream with 0.03% polysorbate 80 significantly decreased the drip-through rate compared to 0% and 0.015% polysorbate 80 levels because of the higher extent of fat destabilization. For ice creams with 0.2% and 0.4% stabilizer, the change of drip-through rate was not affected by the change of fat destabilization (Figure 3). The increased fat destabilization did not significantly decrease the drip-through rate when the mix viscosity (at 50 s^{-1} shear rate) was high. Mostly, ice cream drip-through rate fell in the narrow ranges of 0.19 to 0.25 g/min for 0.2% stabilizer and 0.07 to 0.14 g/min for 0.4% stabilizer. Without stabilizer, drip-through rate greatly depended on how the large fat clusters collided with each other and resisted the drainage of serum phase. On the other hand, ice cream with high mix viscosity (at 50 s^{-1} shear rate) had a high yield stress for serum phase to flow and drip through. Thus, when increasing mix viscosity (at 50 s^{-1} shear rate) to a certain degree, it became the dominant factor in the drip-through rate instead of fat destabilization extent.

Tharp et al. (1998) found that with an increasing fat destabilization, the drainage of melted ice cream was reduced. Similar relationship was found at 0% stabilizer in this study as shown in Figure 4. A strong inverse correlation was found between fat destabilization and final drip-through weight at 0% stabilizer ($r = -0.9815$, $P < 0.0001$). Interestingly, for ice cream with 0.2% or 0.4% stabilizer, the degree of fat destabilization did not affect the amount of melted ice cream dripping through as shown in Figure 4 (0.2% stabilizer: $r = -0.5250$, $P = 0.1467$; 0.4% stabilizer: $r = 0.0146$, $P = 0.9703$). When the apparent viscosity of serum phase was low, fat clusters could readily collide with each other during the drainage and maintained the foam structure on the mesh. However, when the mix viscosity (at 50 s^{-1} shear rate) increased to 0.09 Pa·s or even 0.28 Pa·s, the mobility of fat clusters was restricted by the viscous serum phase. Thus, even though fat destabilization extent covered a broad range (0.2% stabilizer: 15.1% to 69.5%; 0.4% stabilizer: 39.8% to 73.2%), the change of final drip-through weight at each stabilizer level was limited (0.2% stabilizer: 44.5% to 53.5%; 0.4% stabilizer: 14.9% to 33.7%).

Overall, a negative correlation was found between fat destabilization and height-change rate ($r = -0.7572$, $P < 0.0001$); however, this was also influenced by stabilizer level. Figure 5 displays a strong negative correlation between fat destabilization and height-change rate at 0% stabilizer level ($r = -0.8187$, $P = 0.0070$). However, this correlation was not seen in ice creams with 0.2% ($r = -0.5055$, $P = 0.1650$) or 0.4% stabilizer ($r = -0.2841$, $P = 0.4588$) limited by the narrow range of the height-change rate (0.007% to 0.017% and 0.007% to 0.011%, respectively). When ice cream contained a higher degree of fat destabilization at 0% stabilizer level, the foam structure was held by the network of fat clusters and air cells, and resulted in less variation in height. Still, the effect of stabilizer on height-change rate was remarkable. With the presence of stabilizers, the melted ice cream structure collapsed slowly due to the low mobility of serum phase, which led to slow change in height.

Effect of fat destabilization extent on shape retention has been suggested by Bolliger et al. (2000), Tharp et al. (1998), and Warren and Hartel (2018). In this study, a positive correlation was found

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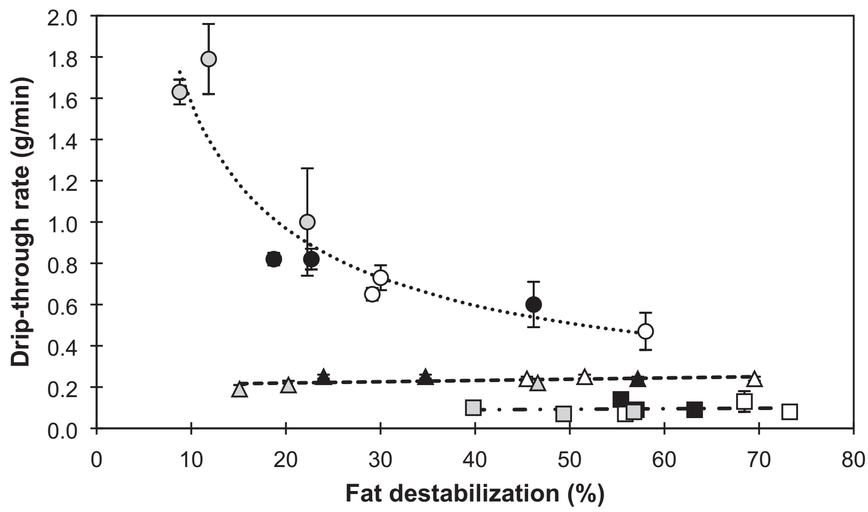

Figure 3–Drip-through rate compared with fat destabilization extent. The error bars stand for standard deviation of mean values among six samples. Gray, 50% overrun; black, 75% overrun; hollow, 100% overrun. Circle, 0% stabilizer; triangle, 0.2% stabilizer; square, 0.4% stabilizer.

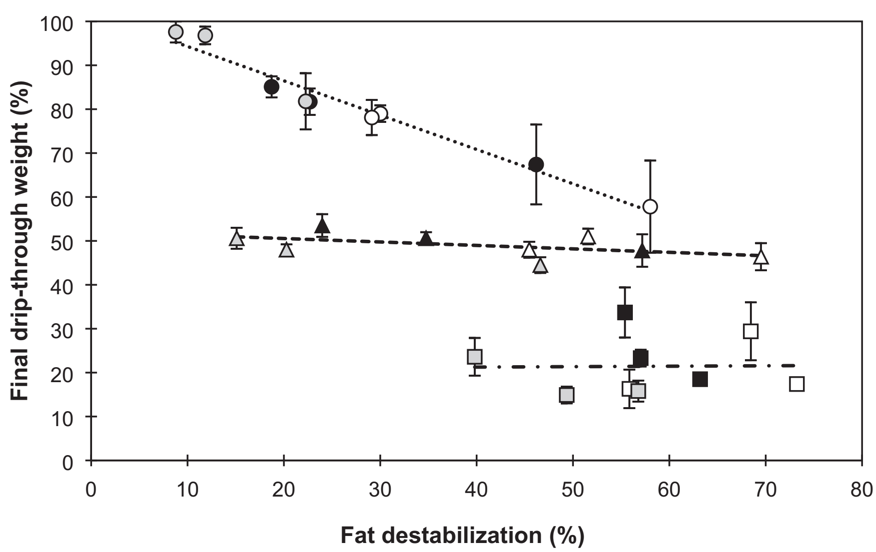

Figure 4–Final drip-through weight compared with fat destabilization extent. The error bars stand for standard deviation of mean values among six samples. Gray, 50% overrun; black, 75% overrun; hollow, 100% overrun. Circle, 0% stabilizer; triangle, 0.2% stabilizer; square, 0.4% stabilizer.

between fat destabilization and final height across all ice creams ($r = 0.8571$, $P < 0.0001$). The structure provided by fat clusters and air cells stabilized on the mesh after meltdown test.

Mix viscosity. There was a strong positive correlation between ice cream mix viscosity (at 50 s^{-1} shear rate) and induction time ($r = 0.8806$, $p < 0.0001$). As shown in Figure 6, increasing stabilizer level increased ice cream mix apparent viscosity, which in turn extended the time for the first drop dripping through the mesh. This relationship was independent of polysorbate 80 or overrun levels. When ice crystals start melting and diluting the serum phase, the induction time is correlated with the viscosity of melted ice cream on the surface to counter the gravitational force. The more viscous the serum phase, the longer time it takes to flow along the ice cream surface and drip through the screen.

An inverse correlation was found between mix viscosity (at 50 s^{-1} shear rate) and drip-through rate ($r = -0.6679$, $P < 0.0001$), which agrees with previous findings (Amador et al., 2017; Muse & Hartel, 2004). Ice creams with no added stabilizer had the fastest drip-through rate across all samples, whereas ice creams with 0.4% stabilizer had the lowest drip-through rate. Details can be found in Supporting Information. Note that with the increase in mix viscosity, ice cream drip-through rate decreased almost independent of overrun and fat destabilization levels as shown in Figure 7. Specifically, without additional stabilizers, ice creams with low fat destabilization level (8.8% and 11.8%) had relatively high drip-through rates (1.63 g/min and 1.79 g/min) as shown in Figure 7. During meltdown, water from the melted ice crystals diluted the serum phase, decreasing its apparent viscosity. Low viscosity of serum phase with a good mobility drained rapidly through the lamella, resulting in a high drip-through rate. In contrast, ice cream with high mix viscosity, above about 0.08 Pa·s (50 s^{-1} shear rate), had a limited mobility for drainage and led to a low drip-through rate.

A strong negative relationship was found between mix viscosity (at 50 s^{-1} shear rate) and the final drip-through weight as shown in Figure 8 ($r = -0.9121$, $P < 0.0001$), indicating that ice cream mix viscosity (and hence, serum viscosity) was a dominant factor that affected the amount of ice cream remaining on the screen

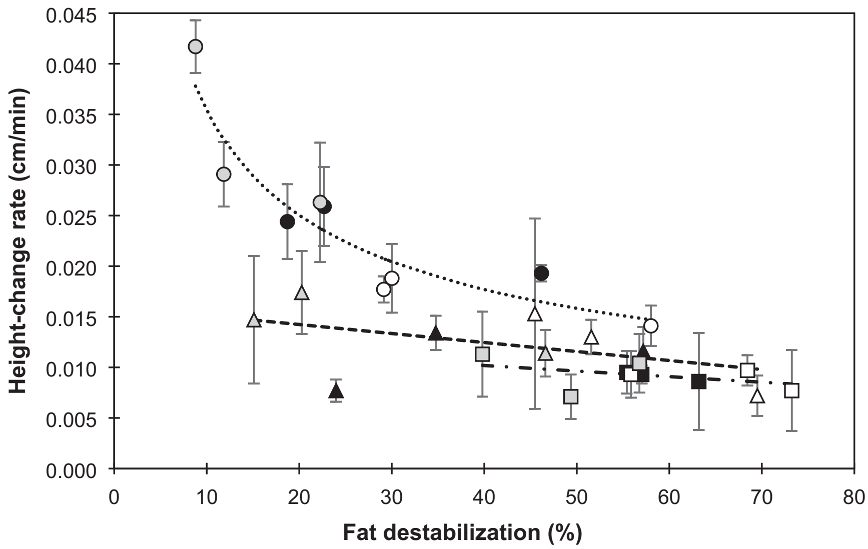

Figure 5–Height-change rate compared with fat destabilization extent. The error bars stand for standard deviation of mean values among six samples. Gray, 50% overrun; black, 75% overrun; hollow, 100% overrun. Circle, 0% stabilizer; triangle, 0.2% stabilizer; square, 0.4% stabilizer.

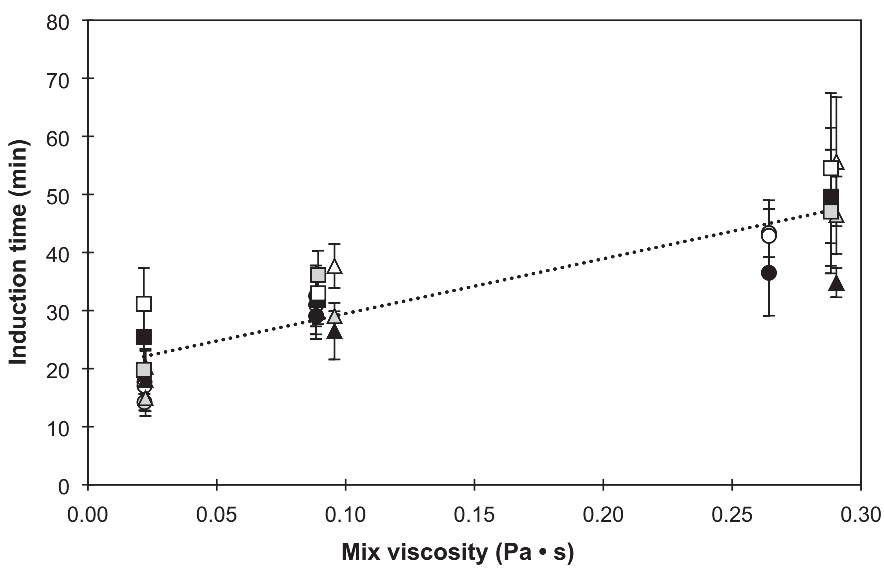

Figure 6–Induction time compared with mix viscosity (50 s^{-1} shear rate). The error bars stand for standard deviation of mean values among six samples. Gray, 50% overrun; black, 75% overrun; hollow, 100% overrun. Circle, 0% polysorbate 80 (PS80); triangle, 0.015 PS80; square, 0.03% PS80.

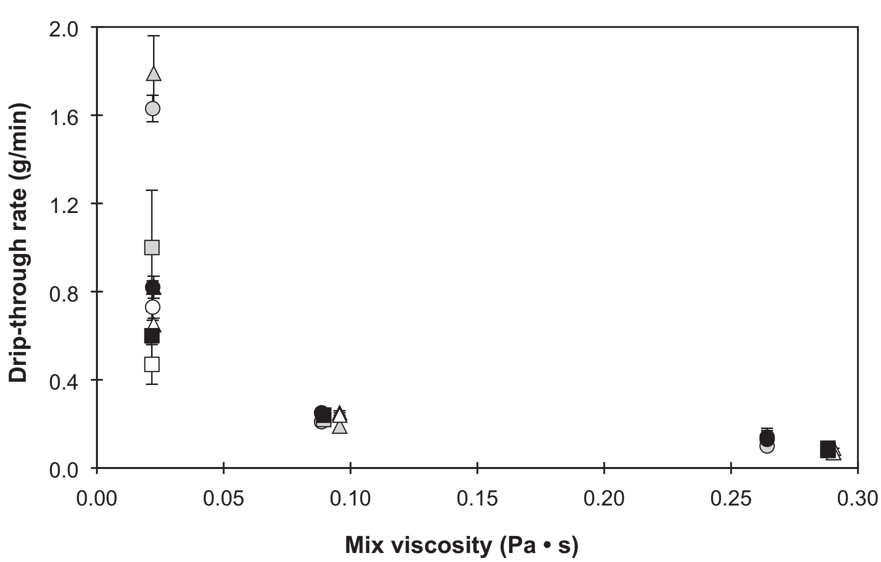

Figure 7–Drip-through rate compared with mix viscosity (50 s^{-1} shear rate). The error bars stand for standard deviation of mean values among six samples. Gray, 50% overrun; black, 75% overrun; hollow, 100% overrun. Circle, 0% polysorbate 80 (PS80); triangle, 0.015% PS80; square, 0.03% PS80.

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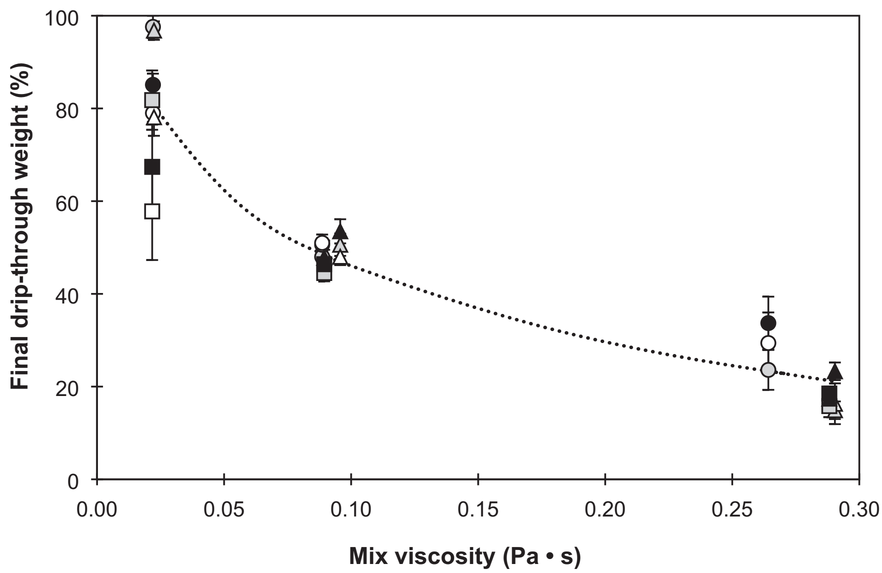

Figure 8–Final drip-through weight compared with mix viscosity (50 s^{-1} shear rate). The error bars stand for standard deviation of mean values among six samples. Gray, 50% overrun; black, 75% overrun; hollow, 100% overrun. Circle, 0% polysorbate 80 (PS80); triangle, 0.015% PS80; square, 0.03% PS80.

after 6 hr. With a higher viscosity (at 50 s^{-1} shear rate), there was less melted ice cream dripping through the mesh and more remnant foam being left on the top.

Ice cream mix viscosity (at 50 s^{-1} shear rate) also had a negative correlation with height-change rate as shown in Figure 9. With an increase in viscosity, the rate of ice cream collapse decreased. This trend was similar to the effect on drip-through rate (Figure 7). During meltdown process, ice cream samples with the lowest fat destabilization (8.8% and 11.8%) gradually melted from the outer layer, shrunk to a core, and gave a low height-change rate during the first hour of meltdown (Figure 2). The fast height-change rate was mainly due to the remaining core rapidly dripping through in the latter part of meltdown (Figure 2). For the rest of ice cream samples, the structure collapsed somewhat, but then stopped when the fat globule clusters and air cells jammed to a certain height. Thus, the height-change rate was limited within a narrow range.

A strong correlation was found between ice cream mix viscosity (at 50 s^{-1} shear rate) and final height ($r = 0.8051$, $P < 0.0001$) as shown in Figure 10. Serum phase with high viscosity provided a better shape and structure retention due to the resistance of drainage, and thus maintained a higher final height at the end of meltdown. Especially, the final height of ice cream with 50% overrun had a wide range from 0% to 58% when mix viscosity (at 50 s^{-1} shear rate) varied as compared to ice creams with 75% and 100% overrun (ranging from 16% to 60% and from 34% to 59%, respectively). When mix viscosity (at 50 s^{-1} shear rate) increased to 0.29 Pa·s, the effect of overrun was minimized.

Overrun. Kurultay, Öksüz, and Gökçebag (2010) noted that at a constant 30% total solid level, overrun had an inverse correlation with induction time in the drip-through test. However, in this study, no correlation was found between overrun and induction time ($r = 0.1639$, $P = 0.4141$). From careful observation of the early stages of melting, the external surface of the samples melted and flowed first, leading to the initial drip. It appeared that heat penetration into the sample was minimal prior to the first drip so that thermal diffusivity was not the primary factor governing the induction time for first drip.

The correlation of ice cream with high overrun having low drip-through rate was only observed in the samples without stabilizer ($r = -0.8058$, $P = 0.0087$). This trend was not seen with stabilizer added at 0.2% or 0.4%. As shown in Figure 7, once the mix viscosity (at 50 s^{-1} shear rate) increased to above 0.08 Pa·s, drip-through rate was limited below 0.4 g/min regardless of overrun and polysorbate 80 levels. There was no effect of overrun in this narrow range of drip-through rate. On the other hand, early studies conducted by Sofjan and Hartel (2004) and Sakurai et al. (1996) found that ice cream (no polysorbate 80 added) with high overrun (100%) had low melting rate and better shape resistance at the end of meltdown test. Also, Warren and Hartel (2018) found that the trend of high overrun decreased drip-through rate was mostly seen in the ice cream without polysorbate 80. Although the finding partially agrees with Warren and Hartel (2018), further study is needed on the effect of overrun on drip-through rate.

Although overrun was found to have no correlation with final drip-through weight across the entire dataset ($r = -0.0896$, $P = 0.6569$), a trend of decreased final weight with increasing overrun was seen in the ice creams without added stabilizer. As mentioned above, final weight was highly correlated with fat destabilization when no stabilizer was added. While air cells were stabilized by fat clusters, ice cream with high overrun increased fat destabilization level, which in turn tended to create a large fat network to prevent further drainage. Under this circumstance, overrun indirectly affected final weight. On the other hand, the effect of mix viscosity (at 50 s^{-1} shear rate) dominated during meltdown. High viscosity of serum phase reduced the mobility of air cells and fat clusters. Thus, fat clusters and air cells jammed within the lamella and prevented further drainage regardless of overrun levels. Further study is needed to illustrate the effect of air cell size on the remnant foam.

There was no correlation between overrun and height-change rate ($r = -0.3187$, $P = 0.1051$), although a trend of decreased height-change rate with increasing overrun was seen in the ice creams without stabilizer ($r = -0.8060$, $P = 0.0087$). Also, the correlation of overrun and final height was only seen in ice creams without added stabilizer ($r = 0.9518$, $P < 0.0001$). Among ice creams with low serum phase viscosity, 50% overrun samples gave the lowest final height (0% to 13%) compared to 75% overrun

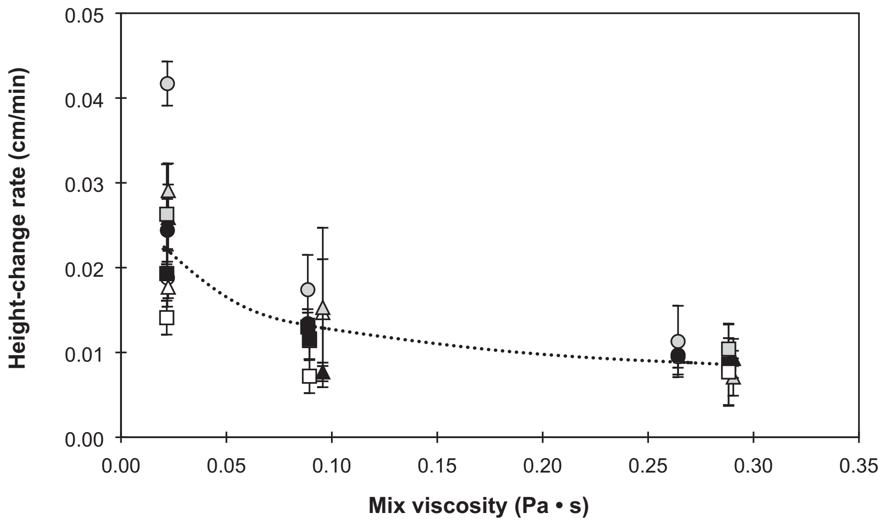

Figure 9–Height-change rate compared with mix viscosity (50 s^{-1} shear rate). The error bars represent standard deviation of mean values among six samples. Circle, 0% polysorbate 80 (PS80); triangle, 0.015% PS80; square, 0.03% PS80. Gray, 50% overrun; black, 75% overrun; hollow, 100% overrun.

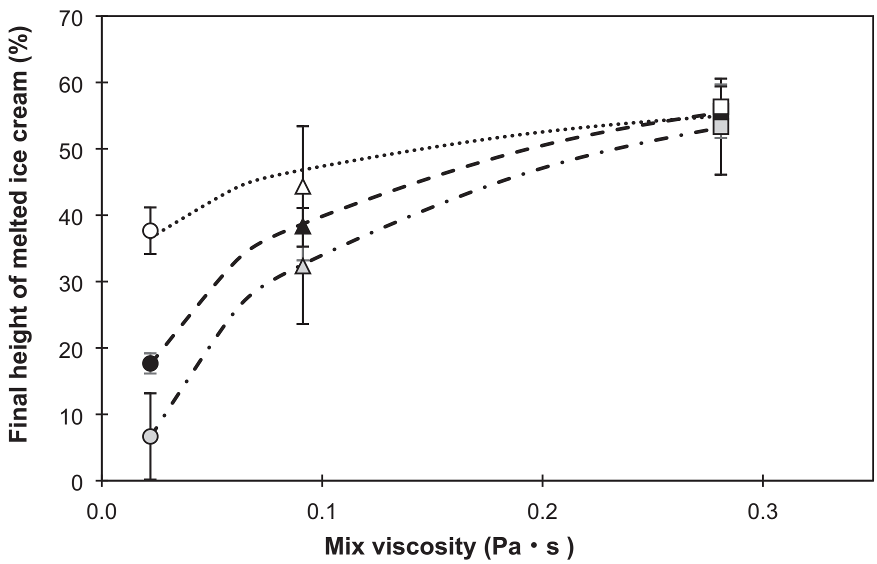

Figure 10–Final height of melted ice cream compared with mix viscosity (50 s^{-1} shear rate). The error bars represent the standard deviation of mean values among three formulas regardless of polysorbate 80 level. Circle, 0% stabilizer; triangle, 0.2% stabilizer; square, 0.4% stabilizer. Gray, 50% overrun; black, 75% overrun; hollow, 100% overrun.

(16% to 20%) and 100% overrun (34% to 40%). Still, the effect of mix viscosity (at 50 s^{-1} shear rate) dominated the drainage process.

Conclusions

This study found that drip-through rate was not the only indicator to describe dynamic ice cream meltdown process. By analyzing the entire meltdown curve as well as height-change curve, additional insight on the effects of ice cream microstructure on meltdown was found.

In general, ice cream mix viscosity (at 50 s^{-1} shear rate) was found to dominate the meltdown process. When there were no stabilizers present, ice cream meltdown was affected by the microstructure elements, such as fat destabilization and overrun. However, when there was stabilizer in the ice cream, the viscosity of serum phase became the main factor through the effect on drainage.

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Author Contributions

B. Wu and R. W. Hartel designed the study. B. Wu conducted the experiment, collected test data, interpreted results, and drafted the manuscript. D. O. Freire helped conduct the experiment and collect test data. R. W. Hartel edited the manuscript.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Supplemental Information

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