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Modeling of the effect of freezer conditions on the hardness of ice cream using response surface methodology

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ABSTRACT

The effect of conventional continuous freezer parameters [mix flow (L/h), overrun (%), drawing temperature (°C), cylinder pressure (kPa), and dasher speed (rpm)] on the hardness of ice cream under varying measured temperatures (−5, −10, and −15°C) was investigated systematically using response surface methodology (central composite face-centered design), and the relationships were expressed as statistical models. The range (maximum and minimum values) of each freezer parameter was set according to the actual capability of the conventional freezer and applicability to the manufacturing process. Hardness was measured using a penetrometer. These models showed that overrun and drawing temperature had significant effects on hardness. The models can be used to optimize freezer conditions to make ice cream of the least possible hardness under the highest overrun (120%) and a drawing temperature of approximately −5.5°C (slightly warmer than the lowest drawing temperature of −6.5°C) within the range of this study. With reference to the structural elements of the ice cream, we suggest that the volume of overrun and ice crystal content, ice crystal size, and fat globule destabilization affect the hardness of ice cream. In addition, the combination of a simple instrumental parameter and response surface methodology allows us to show the relation between freezer conditions and one of the most important properties—hardness—visually and quantitatively on the practical level.
Key words: ice cream, hardness, continuous freezer, response surface methodology

INTRODUCTION

Ice cream is one of the most palatable frozen desserts in the dairy category, and designing a good texture to meet consumer acceptance is a requisite for manufacturers. Hardness (i.e., the resistance of ice cream to deformation by an external force) is a major physical attribute of ice cream and one of the factors that determines the quality of ice cream: ice cream that is too hard is considered less optimal because of the difficulties associated with its scoopability. Marshall et al. (2003) noted that an ice cream store often keeps several containers of products in a single cabinet from which each is to be dipped or scooped, and only one temperature setting is available for the cabinet. Therefore, it is important to understand the factors affect hardness, and furthermore, how hardness is regulated.

Ice cream is a complex food colloid consisting of air bubbles, fat globules, ice crystals, and an unfrozen serum phase (Goff, 1997), and studies have described the effect of the microstructure of ice cream on its hardness. According to Wilbey et al. (1998), hardness is related to the proportion of frozen water and inversely related to the overrun (Wilbey et al., 1998; Muse and Hartel, 2004; Sofjan and Hartel, 2004). In terms of fat globules, hardness increases as the level of the emulsifier or destabilized fat increases (Tharp et al., 1998; Muse and Hartel, 2004).

Ice cream hardness can be controlled in one of two ways. The first is to control the ice cream formulation, and many researchers have studied the effect of food ingredients on hardness (Prindiville et al., 1999, 2000; Roland et al., 1999a,b; Muse and Hartel, 2004). However, restricting the control of hardness to formulation of the ice cream mix often results in sensory limits for ice cream development, because this method mainly depends on a freezing point determined by the concentration of the water-soluble substitutes such as milk solid nonfat (**MSNF**), minerals, glycerin, sweeteners (e.g., monosaccharide, sucrose) or low molecular polyols. In particular, the initial freezing point of the ice cream mix is highly dependent on the sweetener content of the mix (Marshall et al., 2003). Muse and Hartel (2004) focused on the physical properties of the ice cream mix, and found that ice cream was harder when the apparent viscosity of the mix was increased by regulation with a different sweetener.

The second way is to control process conditions. Sakurai et al. (1996) focused on the effect of continuous

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freezer conditions on hardness. They found that a lower drawing temperature and a higher dasher capacity have an inverse relationship to hardness and suggested that ice creams with larger ice crystals were harder than those with smaller ice crystals. Drewett and Hartel (2007) investigated the effect of freezer parameters (drawing temperature, dasher speed, throughput rate) on distributions of ice crystal size; they found that residence time (throughput rate) had the most pronounced effect on mean ice crystal size. Decreasing ice crystal size improves smoothness and ice crystal detectability (Russell et al., 1999).

The freezing process is one of the most important processes in the commercial production of ice cream, because it is the main source of variation in microstructure. From this point of view, the above studies are reasonable, but they do not achieve a quantitative understanding of the relationship between freezer conditions and hardness.

It is clear that each structural component, independently or interactively, affects the physical properties of ice cream; therefore, it is critical to understand comprehensively the effect of structural attributes on these physical properties. However, it is difficult to change just one aspect of a discrete phase to investigate the effect on hardness, as these discrete phases have a pronounced relationship with one another.

With regard to the physical properties of ice cream, several researchers have shown that a dynamic oscillation test is a valuable tool to provide insight into the development of ice cream (Goff et al., 1995; Adapa et al., 2000; Windhab and Wildmoser, 2002; Eisner et al., 2003; Wildmoser and Windhab, 2003; Wildmoser et al., 2004; Granger et al., 2004, 2005). Wildmoser et al. (2004) researched the relationship between rheological properties and the microstructure of ice cream. They found that an ice cream sample taken at approximately −15°C and made using the low-temperature extruder process (ULTICE) is softer than an ice cream sample taken at −5°C made using a conventional freezer. Although the study on low-temperature extrusion (Wildmoser et al., 2004) is valuable work and very informative, continuous freezers used by ice cream manufactures are conventional freezers and their minimum outlet temperature is, in general, about −6°C (Bolliger et al., 2000; Windhab and Wildmoser, 2002). In practice, it is difficult to freeze an ice cream mix to −15°C only using conventional freezers. From the viewpoint of physical property measurement, Goff et al. (1995) noted a difference in small, microscale deformation measurement, where the structure remains (such as oscillation thermo-rheometry), and large, macroscale deformation measurement, where the structure is crushed. A penetrometer is categorized as a macroscale deformation measurement instrument. It consists of a cone and vertical shaft assembly that is allowed to sink into a solid fat under the force of gravity for a standard period, after which the depth of penetration is measured (Bourne, 2002). This instrument is often used to measure the hardness of ice cream (Muse and Hartel, 2004; Sofjan and Hartel, 2004). The advantage is that a penetrometer is an inexpensive instrument that can easily be adapted for measuring the deformability of foods (Bourne, 2002).

In our previous report (Inoue et al., 2008), we designed response surface modeling that showed the relationship between freezer conditions and 3 structural elements (fat destabilization, mean air cell diameter, and mean ice crystal diameter). Using these highly predictable models, the condition of microstructures as a function of freezer conditions can be confirmed. Therefore, it is possible to investigate the relationship between hardness and these structural elements visually if hardness is expressed as a function of freezer parameters.

The objective of this study was to create statistical models that comprehensively show the effect of continuous freezer conditions, within a practical range, on the hardness of ice cream measured with a penetrometer; to predict freezer parameter conditions for the hardness desired; and to investigate the relationship between hardness and the structural elements of ice cream.

MATERIALS AND METHODS

Preparation of Ice Cream Samples

Test ice cream mix formulations were based on 11.32% unsalted butter (Morinaga Milk Industry Co. Ltd., Tokyo, Japan), 10.13% skim milk powder (Morinaga Milk Industry Co. Ltd.), 7.5% sucrose (Dai-Nippon Meiji Sugar Co. Ltd., Tokyo, Japan), 7.0% high fructose corn syrup (total solid 67.5%, Sanwa Cornstarch Co. Ltd., Nara, Japan), 6.0% DE27 corn syrup powder (K-SPD-M, Showa Sangyo Co. Ltd., Tokyo, Japan), 0.25% emulsifier (glyceryl mono-distearate, Taiyo Kagaku Co. Ltd., Mie, Japan), and 0.25% stabilizers (45% locust bean gum, 45% guar gum and 10% carrageenan, Taiyo Kagaku Co. Ltd.). The mix contained 9.5% milk fat, 9.8% MSNF, and 37.8% total solids.

The ice cream mix was prepared by adding dry ingredients to water at 70°C using a high shear blender (Yasuda Co. Ltd., Tokyo, Japan). The mix was pasteurized for 30 s at 95°C in a plate heat exchanger (MD Plate Exchanger FBS-3 SS, Morinaga Engineering, Tokyo, Japan) and homogenized in a 2-stage homogenizer (Sanmaru, Mishima, Japan) at 15.0 and 5.0 MPa. It was then cooled to 5°C and aged for 1 d.

Table 1. Coded and uncoded settings of freezer condition according to a central composite face-centered design

Freezer condition	Symbol		Level		
	Coded	Uncoded	−1	0	+ 1
Mix flow (L/h)	X_1	Mix	50	75	100
Drawing temperature (°C)	X_2	Tem	−6.5	−5.0	−3.5
Overrun (%)	X_3	Ovr	30	75	120
Cylinder pressure (kPa)	X_4	Cyl	150	300	450
Dasher speed (rpm)	X_5	Das	114	222	330

According to the experimental design described below, the samples were frozen in a continuous freezer CS-200-R404A with a standard type #30 dasher (CP Engineering Inc., Tokyo, Japan) and placed in 130-mL conical sampling cups. The top surface of the ice cream samples was cut flat and the samples were stored at −35°C.

Hardness

The hardness of the ice cream was measured by a modified method of Muse and Hartel (2004) using a penetrometer (KRS-505-A, Kuramochi Scientific Instrumental Manufactory Company, Japan). A 62-g aluminum probe (40° cone with a maximum diameter of 24 mm) was aligned so that it touched the surface of the ice cream and was then allowed to penetrate the samples under gravity for 5 s. Each ice cream sample was penetrated at 3 places on its largest smooth surface and these mean values were used as the depth of penetration after the ice temperature of the ice cream was equilibrated to the measured temperature. To take into consideration the frozen water content of the ice cream, the depths of penetration (**DP**) were measured at −5, −10, and −15°C, and coded as DP-5, DP-10, and DP-15, respectively. In general, the depth of penetration was inversely proportional to the hardness. The percentage of water frozen in the ice cream was calculated using the methods of Bradley (1984) and Bradley and Smith (1983). The freezing point depression of this mix was calculated to be −2.8°C.

Design of Experiments

A central composite face-centered design was used for this part of the experiments, which includes the 5 freezer conditions [mix flow (**Mix**; L/h), overrun (**Ovr**; %), drawing temperature (**Tem**; °C), cylinder pressure (**Cyl**; kPa), and dasher speed (**Das**; rpm)] as factors and the 3 depths of penetrations (DP-5, DP-10, and DP-15) as responses. Tables 1 and 2 show the uncoded and coded terminologies and settings. With consideration to the mechanical limits of the freezer and the practical settings for actual ice cream production, the upper and lower settings to which the freezer functions were chosen as the extreme factors.

The quadratic model shown below was used for the modeling of factors and responses. The model parameters are predicted in a least squares multiple regression analysis:

$$Y = b_0 + \sum_{i=1}^{5} b_i X_i + \sum_{i=1}^{5} b_{ii} X_i^2 + \sum_{i=1}^{4} \sum_{j=2}^{5} b_{ij} X_i X_j \left(i < j\right), \quad [1]$$

where Y is the response, X_i and X_j are the levels of the factors, b_0 is a constant, and b_i, b_{ii}, and b_{ij} are the coefficients for the main effects, the second-order effects, and the interactions, respectively.

The significances of the coefficients were examined using the *t*-test. An ANOVA was carried out to assess this model; MODDE software (Umetrics AB, Umeå, Sweden) was used to plan the experiment and perform statistical analysis.

Cryo-Scanning Electron Microscopy

The hardened ice cream was frozen and then sliced in liquid nitrogen. The slices were placed on a previously chilled grid and inserted into a SM-200 scanning electron microscope (Topcon Co. Ltd., Tokyo, Japan) to which a liquid nitrogen cold module C1002 (Gatan

Table 2. Coded and uncoded responses and calculated water frozen contents at measured temperature in ice cream

Response	Coded	Uncoded	Measured temperature (°C)	Ice crystal content (%)[1]
Depth of penetration (mm)	Y_1	DP-15	−15.0	77
	Y_2	DP-10	−10.0	67
	Y_3	DP-5	−5.0	40

[1]Ice crystal content was calculated according to Bradley (1984) and Bradley and Smith (1983).

UK, Oxford, United Kingdom) was attached. The scanning electron microscope chamber was held at −95°C to de-aerate the samples by sublimation, and the samples were etched. The images of the ice cream were analyzed using Image Pro Plus ver. 4.0 (Media Cybernetics, Bethesda, MD).

RESULTS AND DISCUSSION

Sampling Conditions

Table 3 shows the actual conditions under which the ice cream samples were taken and the responses obtained in the analysis. As described in a previous report (Inoue et al., 2008), almost all the samples were taken under the conditions specified in the plan (central composite face-centered design); however, it was not possible to take samples under the planned conditions for samples 4, 6, 7, and 11. For reasons having to do with the equipment, the overrun in sample 4 was not increased to the planned value of 120%, the combination of drawing temperature and overrun in sample 11 was not possible, and the combinations of overrun and dasher speed in samples 6 and 7 were not possible. The continuous freezer specifications did allow an increase of the air volume to obtain the planned overrun and air was supplied to the cylinder, but because the speed of the dasher specified in the conditions was too low, the air was not distributed in a uniform manner in the ice cream. As a result, the samples removed after deaeration turned out not to have the specified overrun. Even though the dasher speed was high, it was not possible to take a sample under the planned conditions for sample 11 because of the limit of the freezing ability: under high mix flow rate (100 L/h), high overrun (120%), and high dasher speed (333 rpm), the drawing temperature could not be brought down to −6.5°C. The sampling conditions were therefore changed to be as close to the originally specified conditions as possible, as shown for samples 4, 6, 7, and 11 in Table 3.

Response Surface Modeling

The main, second-order, and interaction terms were used to fit a quadratic polynomial regression model to the response values provided in Table 3. Table 4 and Table 5 show the regression coefficients and results of the ANOVA. The ANOVA tables show that the variance of the 3 models we designed were highly significant (R^2 values exceeding 0.88 were found for all 3 responses). In the variances that we could not model, the variances of the model error were shown not to be significantly compatible with the variances of the pure error (level of significance 0.05).

The regression coefficients indicate that Ovr had the highest effective main term followed by Tem in all 3 models. This result shows that primarily 2 factors (Ovr and Tem) contributed to the hardness of ice cream, because the regression coefficients of all other factors (Mix, Das, and Cyl) were approximately one order of magnitude smaller than the above 2 factors (Table 4).

Influence of Tem and Ovr on Hardness

Figure 1 shows the contour plots of the response surfaces for each model to incorporate the largest effective parameter of Ovr and the second-largest effective parameter of Tem. All other parameters were fixed at their central points: Mix of 75 L/h; Cyl of 300 kPa; Das of 222 rpm. A comparison of 3 contour plots (Figure 1, panels a, b, and c) shows that the DP-5 model had the largest penetration value, followed by DP-10 and DP-15. As for the frozen water in the ice cream mix (Table 2), the hardness of the ice cream was proportional to the frozen water content in the ice cream mix as described in several reports (Wilbey et al., 1998; Muse and Hartel, 2004).

With respect to the influence of Ovr and Tem, the depth of penetration had a maximum value when Ovr was at the upper limit (120%) and Tem was approximately −5.5°C in all 3 models; penetration slightly decreased for samples made with a drawing temperature of −6.5°C. This finding shows that hardness is inversely proportional to Ovr, and that Tem has an optimum value (approximately −5.5°C in each model) to obtain softer ice cream within the range of this study (the range of drawing temperature is from −3.5 to −6.5°C and formulation is constant).

Relationship Between Hardness and Microstructure

An understanding of the correlation between hardness and microstructure provides useful knowledge to ice cream manufacturers. Figure 2 shows the microstructure of ice creams with higher hardness (lower value of penetration; sample 2) and lower hardness (higher value of penetration; sample 1). Larger ice crystals were observed in the harder ice cream of sample 2 (Figure 2a), whereas smaller ice crystals were observed in the softer ice cream of sample 1 (Figure 2b). There was no significant difference in air cell size. These figures show the relationship between hardness and microstructure.

As mentioned earlier, ice cream is a complex multiphase food. However, understanding of the specific relationship between structural elements and physical properties is limited. A statistical model we designed revealed that small ice crystals were formed at the lowest Tem (−6.5°C) and highest Ovr (120%; Inoue et al.,

Table 3. Actual freezer conditions during sampling and the 3 responses[1]

Sample no.	Coded factor[2]					Response[3] (± SE)		
	Tem	Mix	Cyl	Das	Ovr	DP-5	DP-10	DP-15
1	−1	−1	1	−1	−1	18.10 ± 0.26	13.30 ± 0.15	12.00 ± 0.12
2	−1	1	−1	−1	−1	10.50 ± 0.23	6.93 ± 0.23	2.70 ± 0.15
3	1	−1	−1	−1	−1	14.90 ± 0.06	8.90 ± 0.15	6.57 ± 0.22
4	1	1	0.56	−1	−1	14.50 ± 0.50	9.40 ± 0.21	5.90 ± 0.59
5	−1	−1	−1	1	−1	14.63 ± 0.24	10.93 ± 0.07	7.60 ± 0.21
6	−1	1	0.56	1	−0.61	9.97 ± 0.24	6.97 ± 0.03	8.33 ± 0.24
7	1	−1	0.56	1	−0.61	14.70 ± 0.25	11.13 ± 0.09	8.93 ± 0.15
8	1	1	−1	1	−1	9.87 ± 0.07	6.87 ± 0.79	4.93 ± 0.47
9	−1	−1	−1	−1	1	14.00 ± 0.10	8.23 ± 0.07	7.80 ± 0.38
10	−1	1	1	−1	1	13.10 ± 0.25	12.53 ± 0.23	8.30 ± 0.17
11	1	0.20	0.78	−1	1	17.63 ± 0.19	13.40 ± 0.23	8.97 ± 0.19
12	1	1	−1	−1	1	13.83 ± 0.33	9.77 ± 0.09	7.27 ± 0.29
13	−1	−1	1	1	1	20.20 ± 0.42	15.77 ± 0.23	11.17 ± 0.30
14	−1	1	−1	1	1	11.30 ± 0.00	7.70 ± 0.06	5.37 ± 0.12
15	1	−1	−1	1	1	16.23 ± 0.19	9.77 ± 0.03	7.97 ± 0.27
16	1	1	1	1	1	16.03 ± 0.09	12.10 ± 0.12	8.40 ± 0.26
17	0	−1	0	0	0	16.30 ± 0.17	11.57 ± 0.18	9.53 ± 0.13
18	0	1	0	0	0	16.67 ± 0.12	10.20 ± 0.06	6.70 ± 0.15
19	−1	0	0	0	0	16.73 ± 0.22	12.27 ± 0.03	8.57 ± 0.12
20	1	0	0	0	0	16.77 ± 0.15	12.23 ± 0.13	9.33 ± 0.15
21	0	0	0	−1	0	16.70 ± 0.30	12.60 ± 0.31	8.50 ± 0.21
22	0	0	0	1	0	17.40 ± 0.10	12.57 ± 0.13	9.53 ± 0.27
23	0	0	0	0	−1	20.00 ± 0.23	12.03 ± 0.24	11.10 ± 0.12
24	0	0	0	0	1	17.40 ± 0.26	12.43 ± 0.03	9.57 ± 0.23
25	0	0	−1	0	0	15.73 ± 0.28	9.63 ± 0.15	9.50 ± 0.15
26	0	0	1	0	0	18.10 ± 0.23	15.40 ± 0.10	11.50 ± 0.15
27	0	0	0	0	0	15.97 ± 0.20	12.80 ± 0.12	12.13 ± 0.13
28	0	0	0	0	0	15.53 ± 0.23	12.67 ± 0.30	9.80 ± 0.29
29	0	0	0	0	0	15.30 ± 0.15	12.47 ± 0.19	8.40 ± 0.06
30	0	0	0	0	0	16.93 ± 0.20	12.33 ± 0.13	9.97 ± 0.20
31	0	0	0	0	0	18.43 ± 0.23	13.00 ± 0.12	8.47 ± 0.07

[1]Samples 4, 6, 7, and 11 could not be taken in exact accordance with the original central composite face-centered design, but were taken under conditions as close to the planned conditions as possible.

[2]Mix = mix flow; Tem = drawing temperature; Ovr = overrun; Cyl = cylinder pressure; Das = dasher speed.

[3]DP-5 = depth of penetration at −5°C (mm); DP-10 = depth of penetration at −10°C (mm); DP-15 = depth of penetration at −15°C (mm).

2008); these response surfaces were strongly dependent on Tem when it was greater than −5.0°C. However, when Tem was less than −5.0°C, not only Tem but also Ovr markedly influenced response value. The contour plots also show the effect of Tem and Ovr on the microstructure of ice cream; the shape of the response surface of DP-15 (Figure 1a) had a similar tendency to that of the ice crystal diameter constructed by the statistical model (Inoue et al., 2008), and the correlation coefficients between hardness (measured at −5, −10, and −15°C) versus ice crystal size have relatively high values of −0.647, −0.644, and −0.629, respectively. These results indicate that the size of the ice crystals is a significant component that affects hardness; decreasing the mean ice crystal diameter decreases the hardness of the ice cream. These results were in agreement with studies by other authors (Sakurai et al., 1996; Muse and Hartel, 2004).

Wildmoser et al. (2004) showed that ice cream taken from a low-temperature extruder was softer than from a conventional freezer using storage modulus (G′) as an index of hardness. They suggested that a smaller ice crystal size and a smaller degree of connectivity of ice crystals make ice cream less stiff. However, a lower drawing temperature changes not only the ice crystal phase but also other components of the ice cream microstructure. As far as fat globule is concerned, the freezing process causes the ice cream mix emulsion to undergo partial coalescence or fat destabilization, during which clumps and clusters of fat globules form and build an internal fat structure or network in the frozen product by entrapping air within the coalesced fat (Walstra, 1987). Destabilized fat provides a network among the air cells in the ice cream, and thus increases the hardness of the ice cream. As several researchers (Kokubo et al., 1996, 1998; Christensen and Andersen, 2003) have described, the lower the drawing temperature, the more fat destabilization occurs. Therefore, in terms of fat globule in ice cream, it is possible that a lower drawing temperature makes ice cream harder.

Table 4. Regression (*b*) coefficients and their *P*-values for the complete models for prediction of the 3 responses[1]

	DP-5		DP-10		DP-15	
Item	*b* coefficient	*P*-value	*b* coefficient	*P*-value	*b* coefficient	*P*-value
Constant	17.151	0.000***	12.513	0.000***	9.713	0.000***
Tem	−1.229	0.019*	−0.722	0.000***	−1.045	0.011*
Mix	−0.153	0.741	−0.394	0.014*	−0.258	0.465
Cyl	0.391	0.426	0.310	0.051	0.531	0.167
Das	0.126	0.805	0.380	0.028*	−0.073	0.849
Ovr	1.712	0.006**	2.258	0.000***	1.806	0.001***
Tem × Tem	−1.170	0.251	−1.592	0.000***	−1.585	0.054
Mix × Mix	−0.905	0.368	−0.227	0.445	−0.750	0.326
Cyl × Cyl	−0.605	0.543	0.108	0.713	−0.685	0.368
Das × Das	1.206	0.245	−0.194	0.518	0.622	0.419
Ovr × Ovr	−0.686	0.501	0.192	0.524	0.860	0.273
Tem × Mix	0.223	0.663	0.086	0.574	0.128	0.740
Tem × Cyl	0.131	0.782	−0.118	0.408	0.259	0.474
Tem × Das	0.070	0.092	0.063	0.000***	0.016	0.579
Tem × Ovr	0.378	0.462	0.093	0.538	0.213	0.580
Mix × Cyl	−0.783	0.122	−0.647	0.001***	−0.282	0.439
Mix × Das	0.761	0.134	0.590	0.002**	0.368	0.322
Mix × Ovr	−0.722	0.192	−0.619	0.002**	−0.740	0.087
Cyl × Das	0.285	0.588	−0.231	0.157	−0.495	0.227
Cyl × Ovr	0.569	0.324	0.168	0.326	0.335	0.437
Das × Ovr	−0.399	0.493	0.165	0.344	−0.816	0.083
R^2	0.887		0.987		0.899	
R^2 adjusted	0.660		0.962		0.697	

[1]Mix = mix flow; Tem = drawing temperature; Ovr = overrun; Cyl = cylinder pressure; Das = dasher speed; DP-5 = depth of penetration at −5°C; DP-10 = depth of penetration at −10°C; DP-15 = depth of penetration at −15°C.

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

Table 5. Analysis of variance of 3 depth of penetration (DP) models[1]

Model	df	SS	Mean SS	*F*-value	*P*-value
DP-5					
Total	31	7,743.620	249.794		
Constant	1	7,539.480	7,539.480		
Total corrected	30	204.142	6.805		
Regression	20	181.013	9.051	3.913	0.015
Residual	10	23.130	2.313		
Lack of fit	6	16.581	2.764	1.688	0.319
Pure error	4	6.548	1.637		
DP-10					
Total	31	4,066.010	131.162		
Constant	1	3,904.340	3,904.340		
Total corrected	30	161.678	5.389		
Regression	20	159.641	7.982	39.179	0.000
Residual	10	2.037	0.204		
Lack of fit	6	1.757	0.293	4.182	0.094
Pure error	4	0.280	0.070		
DP-15					
Total	31	2,392.640	77.182		
Constant	1	2,262.080	2,262.080		
Total corrected	30	130.568	4.352		
Regression	20	117.366	5.868	4.445	0.010
Residual	10	13.202	1.320		
Lack of fit	6	4.026	0.671	0.292	0.913
Pure error	4	9.176	2.294		

[1]Depth of penetration (mm) is the penetration value measured at –5°C (DP-5), –10°C (DP-10), and –15°C (DP-15).

A fat destabilization model (Inoue et al., 2008) showed a maximum value (87.8%) when the drawing temperature was −6.5°C (lower limit) and the overrun was 120% (upper limit). With respect to the DP models, which show the penetration value into ice cream as a function of freezer parameters, it can be seen that hardness has a tendency to increase in reverse proportion to fat destabilization. Although it may seem that these results contradict some reports (Tharp et al., 1998; Muse and Hartel, 2004), the drawing temperature at which maximum penetration value was measured was not −6.5°C (fat destabilization shows maximum value), but a slightly higher temperature (approximately −5.5°C). These data indicate that a high level of fat destabilization results in harder ice cream. The types and amount of emulsifier in an ice cream mix formula affect the fat destabilization level of ice cream (Goff and Jordan, 1989; Barfod et al., 1991; Goff et al., 1999; Zhang and Goff, 2005). Ice cream produced in low-temperature extrusion equipment behaves differently with respect to emulsification compared with conventional freezing (Bolliger et al., 2000). An improvement of the microstructure and creaminess by using a low-temperature extruder can be observed only with the emulsifier with a low-to-intermediate iodine value, and a highly unsaturated emulsifier leads to very large fat aggregates, which have a negative effect on the creaminess of ice cream (Eisner et al., 2003). It is obvious that optimization of the freezing process corresponding to the ice cream mix formulation is needed to regulate the hardness of ice cream.

According to the response surface contour plots, the hardness of ice cream greatly depends on overrun (content of air in the ice cream) and ice crystal content, as shown by the results of several studies mentioned previously (Wilbey et al., 1998; Muse and Hartel, 2004; Sofjan and Hartel, 2004). Hardness also depends on the balance between ice crystal size and fat destabilization, which is mainly affected by drawing temperature if the ice cream mix formulation is constant. In this study, the Tem that made ice cream with the lowest hardness was not the lowest limit temperature of −6.5°C, but a slightly warmer temperature of about −5.5°C.

In this work, 3 structural elements (air cell size, ice crystal, and fat destabilization) were treated as factors to be considered in relation to ice cream hardness. The interactions among structural elements make it difficult to investigate the effect of structural elements on hardness, whereas response surface methodology is a very profitable tool that enables a comprehensive and convenient visual understanding of the relationship among these factors.

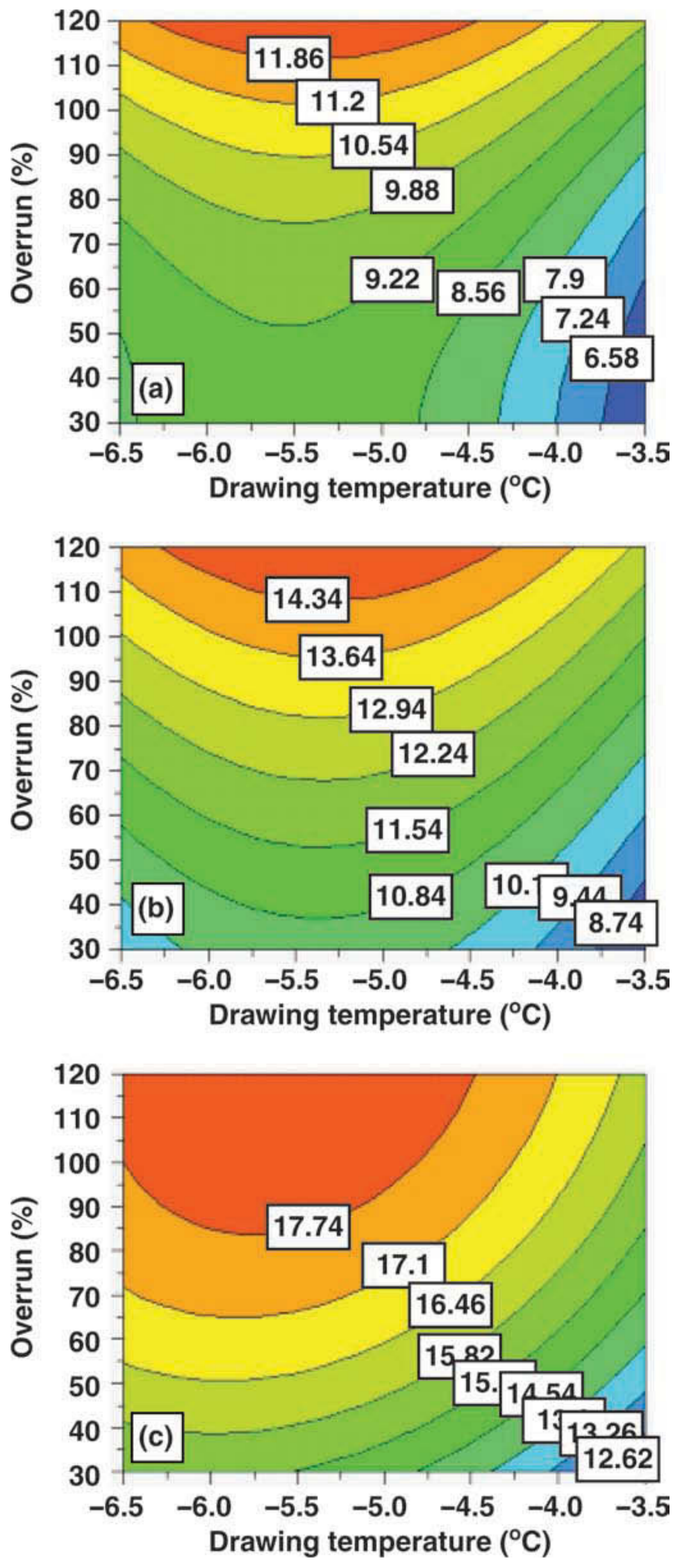

Figure 1. Contour plots of the effect of overrun and drawing temperature on depth of penetration predicted by 3 models: a) DP-15, b) DP-10, and c) DP-5, where DP-15, DP-10, and DP-5 = depth of penetration at –15°C, –10°C, and –5°C. The other process parameters were set at their center values: mix flow rate of 75 L/h, cylinder pressure of 300 kPa, and dasher speed of 222 rpm.

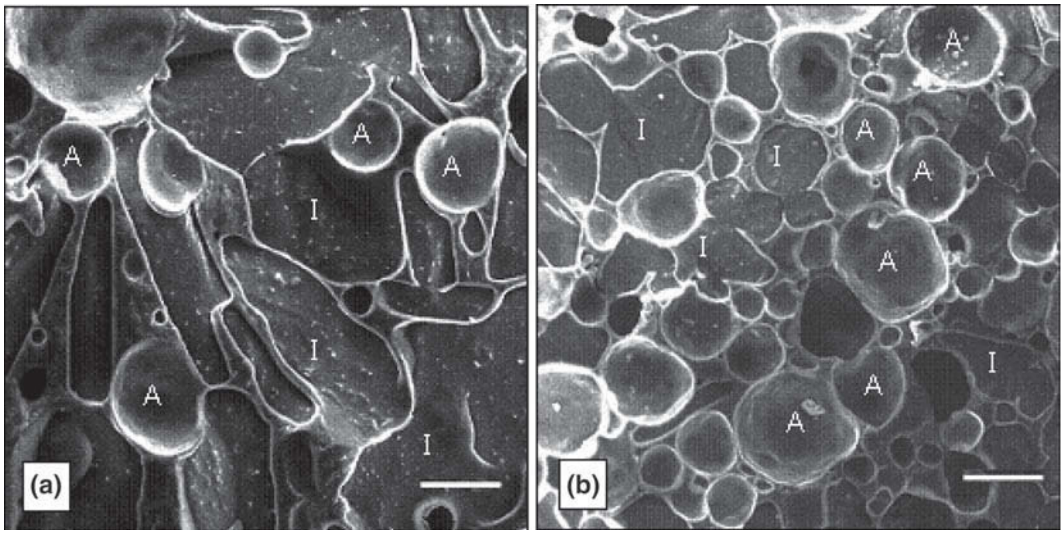

Figure 2. Microstructure of harder and softer ice cream: a) harder ice cream in DP-15 (sample 2); b) softer ice cream in DP-15 (sample 1), where DP-15 = depth of penetration at –15°C. A = air bubble; I = ice crystal. Bar = 50.0 µm.

CONCLUSIONS

Response surface methodology was successfully applied to model the effects of freezer conditions (Mix, Ovr, Tem, Cyl, and Das) on the hardness of ice cream. Using these models, we expected to obtain the optimum freezing conditions required to make ice cream with the hardness level desired, because the models show quantitatively the relation between hardness and freezer parameters. For example, the DP-15 model showed that overrun and drawing temperature should be set at 120% and −5.5°C, respectively, to make the softest (DP = 11.86, at −15°C) ice cream, and, as another example, the DP-5 model showed that the drawing temperature and overrun should be set at −5.5 to −6.0°C and about 70% to make ice cream that has a DP of about 17 at −5°C. These models also provide insight into the development of the ice cream structure. A higher volume of air content, a smaller ice crystal size, and a lower level of fat destabilization are important attributes for softer ice cream if the measured temperature is constant. The physical property (determined by the microstructure) is one of the most important characteristics in ice cream quality; therefore, regulating processing conditions using a statistical model, and not relying solely on food ingredients, is profitable for ice cream manufacturers.

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