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Effect of the Fat Globule Sizes on the Meltdown of Ice Cream

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ABSTRACT

The meltdown of ice cream is influenced by its composition and additives and by fat globule size. The objective of this study was to examine the effect of fat globule size and fat agglomerate size on the meltdown stability of ice cream. Therefore, an ice cream mix (10% milk fat) was homogenized at pressures ranging from 0 to 30 MPa in single-stage, double-stage, and selective homogenization processes. The ice cream, produced on a continuous ice cream freezer, was characterized by an optimized meltdown test while, in addition, the fat globule sizes and the free fat content were determined in the mix and the molten ice cream. The meltdown was dependent on the fat agglomerate sizes in the unfrozen serum phase. Agglomerates smaller than a critical diameter led to significantly higher meltdown rates. Homogenization pressures of at least 10 MPa were sufficient to produce a stable ice cream. Furthermore, proof was provided that double-stage homogenization is not necessary for fat contents up to 10% and that selective homogenization is possible to produce stable ice creams. Based on these results a model was deduced describing the stabilizing mechanisms during the meltdown process.
(**Key words:** homogenization; fat globule size; meltdown stability; ice cream)

Abbreviation key: $\mathbf{D_{50,3}}$ = median value of the volume-based size distribution.

INTRODUCTION

From a physical point of view, ice cream is a complex multiphase system in which air, fat, and ice crystals are dispersed in a highly viscous, concentrated, unfrozen solution (Caldwell et al., 1992a, 1992b; Goff, 1997; Marshall and Arbuckle, 1996; Walstra and Jonkman, 1998). Fat plays an important role in the stabilization of the ice cream structure, as partially coalesced fat is mainly responsible for stabilizing the air bubbles and the foam structure. Keeney (1958) has established that a certain amount of fat destabilization is necessary to obtain good textural properties. Experiments from Berger and White (1971) and Berger et al. (1972) proved that fat destabilization has a significant influence on parameters such as dry appearance, creamy mouthfeel, and meltdown behavior of the ice cream. Because of the combination of shear forces and ice crystallization in the freezer, fat globules are mechanically damaged, which causes agglomeration and partial coalescence of the fat globules. However, Goff and Jordan (1989) found that neither the ice crystallization nor the shear forces alone are effective enough to cause a significant fat destabilization. Sakurai et al. (1996) and Kokubo et al. (1996, 1998) determined that the lower the drawing temperature and the higher the dasher speed and volume the higher is the amount of destabilized fat.

Several investigations have shown that the addition of emulsifiers leads to a significantly increased fat destabilization (Berger, 1990; Goff, 1997; Goff et al., 1987; Goff and Jordan, 1989; Graf and Müller, 1965; Lin and Leeder, 1974). If emulsifiers instead of proteins are incorporated into the fat globule membrane, it becomes mechanically more unstable. The effect of the emulsifiers can be improved by an aging step (Berger, 1990; Kielmeyer and Schuster, 1986; Marshall and Arbuckle, 1996), as the resulting fat crystallization and protein desorption additionally weaken the fat globule membranes.

Because new surfaces are formed during homogenization, homogenization conditions may influence fat destabilization and the meltdown characteristics of the ice cream. Kielmeyer and Schuster (1986) ascertained that the fat globule membrane consists of more proteins if high pressures and double-stage homogenization are applied. Therefore, the membrane becomes more stable and the fat is less available for the extraction solvent during the free fat estimate analysis. Schmidt and Smith (1989) also determined a lower fat destabilization and a wet appearance of the ice cream at higher

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homogenization pressures (28.1-MPa). Furthermore, they found no differences in the fat destabilization and textural parameters between 3.5 and 14 MPa. In a more recent study, Thomsen and Holstborg (1998) found that the homogenization pressure only has a minor effect on the final product.

Therefore, the objective was to study the effect of the fat globule sizes and fat agglomerate sizes, which result from the homogenization conditions, on the meltdown of ice cream. In addition, a model was to be deduced describing the stabilizing mechanisms during the meltdown process.

MATERIALS AND METHODS

Composition and Process

The standard ice cream mix formulation consisted of 10% milk fat, 11% nonfat milk solids, 10% sucrose, 5% glucose syrup, 0.3% emulsifier blend (Cremodan Super, Danisco Ingredients, Brabrand, Denmark), 0.1% guar, 0.1% locust bean gum and demineralized water. All dry ingredients were mixed with demineralized water; we took the water content of the fluid ingredients into account.

The mix was pasteurized (85°C, 30 s) and homogenized at 70°C by applying different pressure conditions [double-stage (stage 1/stage 2): 0/0, 5/1, 10/2, 17/4, 20.5/5, 30/6 MPa; single-stage: 5, 10, 17, 20.5, 30 MPa)]. For selective homogenization, emulsifiers were added to the cream (30% fat) and homogenized with 5/1, 7.5/1.5, 10/2, 12.5/2.5 and 15/3 MPa. Subsequently, the homogenized cream was mixed with the remaining ingredients, and ice cream was produced in a continuous ice cream freezer [modified Gelmark 80, Tetra Laval Hoyer, Italy; Koxholt (2000)]. The overrun was adjusted to 80%, and the freezer-outlet temperature was set at –5.5°C.

The samples were taken directly from the freezer in conical tubs ($d_{bottom} = 53$ mm, $d_{top} = 62$ mm, h = 30 mm) with a volume of approximately 75 ml. The samples were hardened in freezing cabinet at –40°C for 24 h and then stored overnight in a freezing cabinet at –20°C, after which the tests were performed.

Meltdown Test

The meltdown tests were carried out in a climatized chamber at 18°C and 75% relative humidity. For the test (Koxholt, 2000) the ice cream sample was placed on a grid (material: polyvinyl chloride; size: 10 cm × 10 cm; thickness 4 mm; hole diameter: 10 mm; distance between the holes in a row 2 mm and between the rows 3 mm). A petri dish was placed underneath the grid on scales to collect and weigh the drip losses. For the evaluation of the drip test, the meltdown is defined as the mass of the drip loss (m_D) divided by the total mass of the ice cream sample (m_0) and plotted against time. The maximum meltdown rate corresponds to the highest gradient in the ascending meltdown curve. In addition, the fat and protein content were determined in the drip losses.

The standard deviation (10 replications) within the ascending curve was 18% at its maximum, and for the final degree of meltdown after 300 min it was 5%.

Fat Globule Sizes and Free Fat Content

Fat globule sizes. To measure the fat globule sizes in the mix and the fat agglomerate sizes in the thawed ice cream, we performed laser diffraction spectroscopy (LS 130, Coulter Electronics, Krefeld, Germany) after a 1:10 dilution with distilled water at 40°C. The standard deviation for a fivefold measurement was 0.02 μm (mean 0.73 μm). The measurement for each experiment was performed twice.

Free fat content. The total extractable fat content of the molten ice cream (related to the total mass of the ice cream) was determined by the extraction method of Fink (1984). The standard deviation for a 20-fold measurement was 0.25% (mean 0.61%).

RESULTS AND DISCUSSION

Double-Stage Homogenization

In a first set of experiments, the ice cream mix was homogenized by applying the following pressures (stage 1/stage 2): 0/0, 5/1, 10/2, 17/4, 20.5/5, 30/6 MPa.

Figure 1 illustrates the fat globule size distributions after homogenization in the ice cream mixes and in the molten ice cream. In addition, in Table 1 the median values $D_{50,3}$ and the $D_{95,3}$ values of the size distributions are shown. As expected, the fat globule sizes decreased as the homogenization pressure increased.

Fat globules are mechanically damaged in the ice cream freezer by the shear forces and the ice crystallization process, which leads to the release of fluid fat and a partial agglomeration of the fat globules. We were able to verify this effect by the differential fat globule size distribution in the molten ice cream (Figure 1). Distributions in the frozen product are broader than in the homogenized ice cream mixes, and the characteristic second peak at larger sizes indicates the fat agglomerates. The lower the homogenization pressure, the larger were the fat globules and agglomerates in the molten ice cream, indicated by the $D_{95,3}$ values (Table 1). This is because larger globules are more exposed to the shear forces. For the nonhomogenized (0/0 MPa) sample, this led to visible macroscopical churning. How-

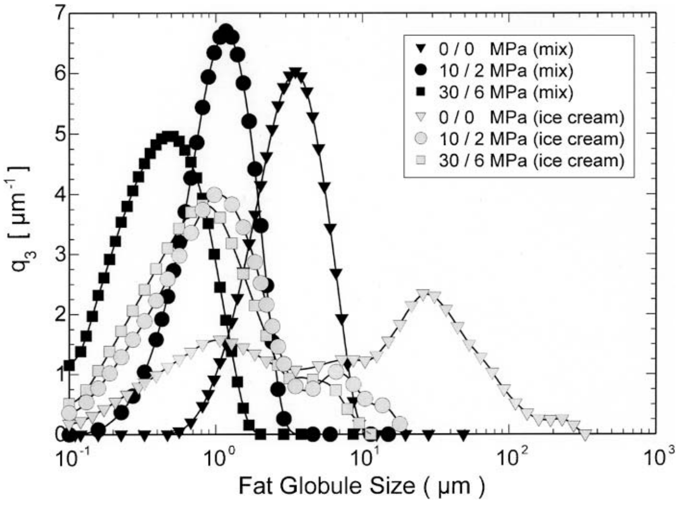

Figure 1. Fat globule size distributions in ice cream mixes and molten ice creams after double-stage homogenization at different pressures.

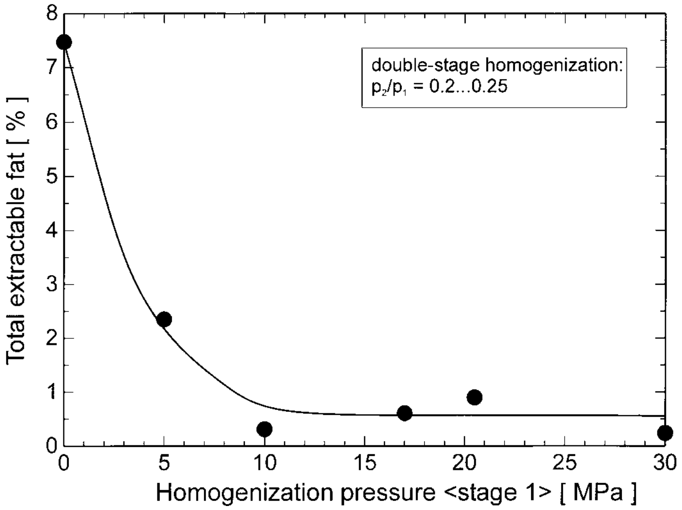

Figure 2. Effect of the homogenization pressure on the total extractable fat content in molten ice cream.

ever, the comparison between ice cream mix and ice cream shows that a remarkable proportion of small fat globules is still in the molten ice cream, which seems to have remained unaffected. This finding is in accordance with transmission electron microscopy studies from Berger (1990), in which quite small fat globules were seen at the air-serum interface.

While hardly any (<0.1%) extractable fat was found in the homogenized and aged ice cream mixes, a significant amount was detected in the ice creams (Figure 2). For the nonhomogenized sample, the intensive churning in the freezer resulted in a total extractable fat content of 7.5%, which is 75% of the total fat. Corresponding to the fat globule sizes, the total extractable fat content decreased significantly at 5 MPa but remained almost constant at 10 MPa and higher. The average value of 0.6% for the total extractable fat content was quite low, and the related "free fat" was insufficient to form a fat-stabilized foam with coalesced fat bridges as in the case in nonhomogenized whipped cream, which has a total extractable fat content of about 20%. In the literature, values between 1 and 2% total extractable fat were published for ice creams (Berger and White, 1971; Kielmeyer and Schuster, 1986). This small difference is because different types of emulsifiers were used, because the overrun in this work was lower than in most studies, and because different sample preparations and extraction methods were applied. Thus, ice creams that were produced exhibited a stable structure and good sensory properties, although the extractable fat content seemed low.

Table 1. Median values $D_{50,3}$ and $D_{95,3}$ values of the volume-based fat globule/agglomerate size distributions in the ice cream mix and molten ice cream after double-stage homogenization.

Homogenization pressure (MPa) stage 1/stage 2	$D_{50,3}$ (µm)		$D_{95,3}$ (µm)	
	Ice cream mix	Ice cream	Ice cream mix	Ice cream
0/0	3.33	7.95	7.87	95.91
5/1	1.61	1.40	4.01	18.01
10/2	1.08	1.05	2.23	8.70
17/4	0.73	0.91	1.67	6.58
20.5/5	0.67	0.85	1.41	6.05
30/6	0.44	0.82	1.16	5.11

As shown in Figure 3, all ice creams, with the exception of the sample, which was homogenized at 30/6 MPa,

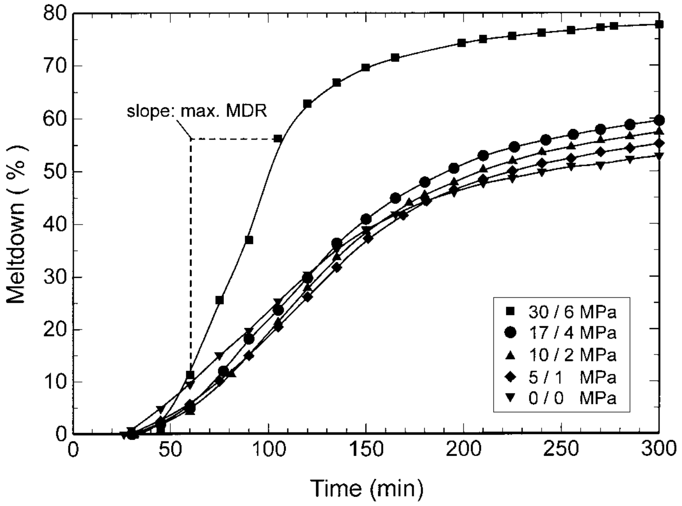

Figure 3. Effect of the homogenization pressure on the meltdown of ice cream (max. MDR: maximum meltdown rate).

had a similar meltdown behavior. The time until the first drop took about 30 min for all samples, as it is mainly dependent on the surface properties of the sample and the amount of frozen water. It is hardly influenced by the inner structure. The sample homogenized at 30/6 MPa melted fastest and had inhomogeneous meltdown behavior. As no correlation between the extractable fat content and the meltdown rates was established, the fat agglomerate size appeared to be the decisive parameter. Therefore, in Figure 4 the maximum meltdown rate is plotted against the fat globule size ($D_{50,3}$) in the molten ice cream. It can be deduced from the curves that below a critical fat globule diameter ($D_{50,3} \approx 0.85$ μm) ice cream melts significantly faster. Above this point the ice cream melted slightly more slowly as fat globule diameters increased. To check the extent to which the fat globules are retained in the foam matrix, the fat content in drip losses were determined. The effect of the fat globule size on the fat content in the drip losses was directly correlated with the maximum meltdown rate (Figure 4).

Clearly, during melting, fat globules larger than the critical diameter are retained in the foam lamellae and stabilize the foam structure, while smaller fat globules flow out of the foam matrix.

Single-Stage Homogenization

To examine whether single-stage homogenization is sufficient for ice cream mixes with 10% fat, ice creams were produced from standard ice cream mixes homogenized at 5, 10, 17, 20.5, and 30 MPa.

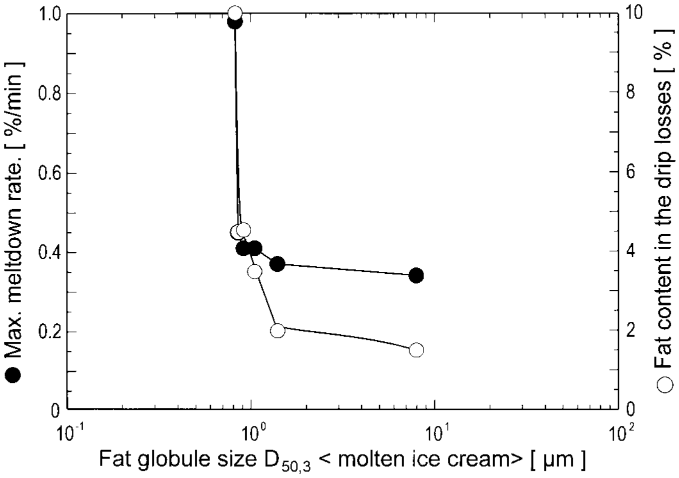

Figure 4. Effect of the fat globule size ($D_{50,3}$) in the molten ice cream on the maximum meltdown rate and the fat content in the drop losses of ice creams.

Table 2. Median values $D_{50,3}$ and $D_{95,3}$ values of the volume-based fat globule/agglomerate size distributions in the ice cream mix after single-stage and double-stage homogenization.

Homogenization pressure (MPa) stage 1	$D_{50,3}$ (μm)		$D_{95,3}$ (μm)	
	Single-stage	Double-stage	Single-stage	Double-stage
5	1.74	1.61	5.42	4.01
10	1.14	1.08	3.73	2.23
17	0.73	0.73	1.81	1.67
20.5	0.70	0.67	1.78	1.41
30	0.57	0.44	1.32	1.16

When the fat globule sizes in ice cream mixes are compared (Table 2), it becomes evident that the number of homogenization stages scarcely affects fat globule size. The ice cream mix contains enough material to build the secondary fat globule membrane during homogenization. Thus, only a few fat clusters are formed, indicated by the slight differences for the $D_{95,3}$ values. The fat globule sizes in the molten ice creams were in the same range because the agglomeration in the freezer is dependent on the sizes in the ice cream mix (not shown).

Corresponding to the fat globule sizes, the ice creams also showed the same meltdown behavior after single-stage homogenization as they did for double-stage homogenization. The measurements of the maximum meltdown rates of the single-stage homogenized ice creams correlated with the fat globule size in the same way as for ice creams after double-stage homogenization.

Selective Homogenization

In a further set of experiments, the possibility of a selective (partial-stream) homogenization process was investigated. For this, cream, adjusted to 30% fat by skim milk, was mixed with the emulsifier blend and homogenized in a double-stage process at pressures between 5/1 and 15/3 MPa. Then, the homogenized cream was mixed with the remaining ingredients and pasteurized.

Figure 5 shows the median values $D_{50,3}$ of the fat globule size distributions in the ice cream mixes and the molten ice creams. The fat globule sizes are slightly smaller after selective homogenization than are those after full-stream homogenization, which is in contradiction to the homogenization of pure cream (Eibel, 1986). The cause is found in the emulsifiers; as the total amounts of the emulsifiers were added to the cream before homogenizing, the percentage of the emulsifier content was significantly higher than in the ice cream mix during the full-stream experiments. At the same time, the protein content was lower, which led to a

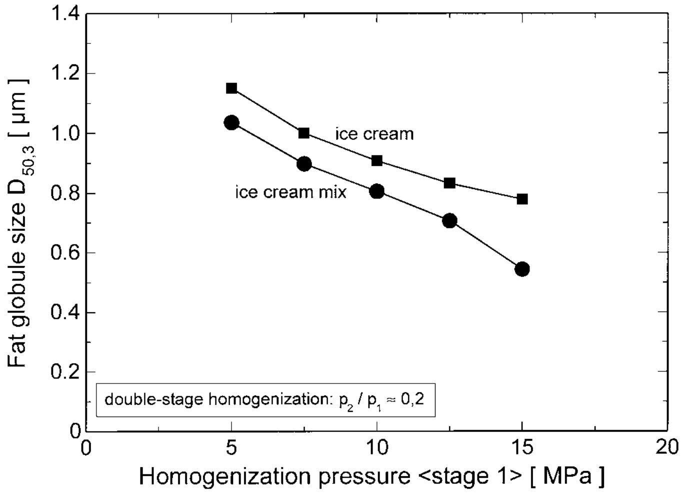

Figure 5. Median values ($D_{50,3}$) of the fat globule/agglomerate size distributions in the ice cream mix and molten ice cream after selective homogenization with different pressures.

higher emulsifier-protein ratio. Both facts enhance the formation of small fat globules.

The slowest meltdown rate was determined for a fat globule size ($D_{50,3}$) of approximately 1.15 µm (Figure 6) after homogenization at 5/1 MPa. The ice cream started to drip after 33 min, and the final meltdown stood at 55% after 300 min. The critical fat globule size was slightly higher ($D_{50,3} \approx 1$ µm) than for ice creams after full-stream homogenization. The air bubbles were probably larger as more emulsifiers were incorporated in the fat globule membrane and were not available to support the stabilization of the air-serum interface.

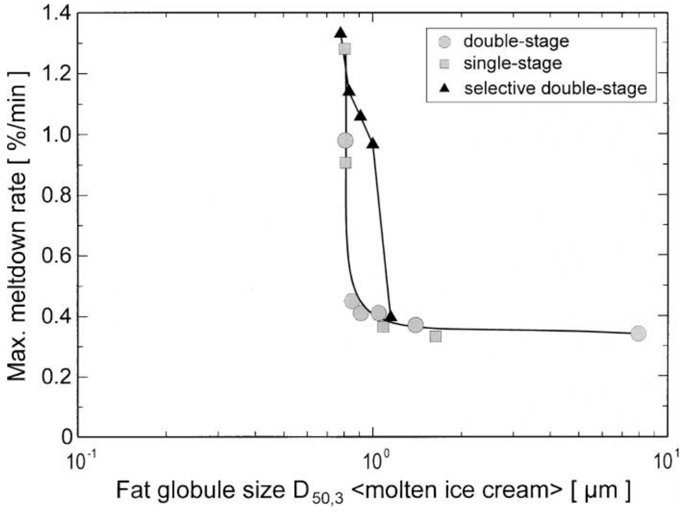

Figure 6. Maximum meltdown rate of ice creams as a function of the fat globule sizes ($D_{50,3}$) in the molten ice cream after selective, single- and double-stage homogenization.

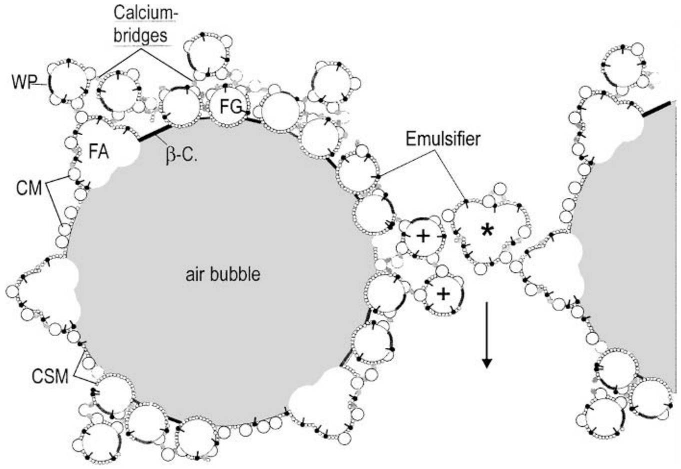

Figure 7. Model for a stabilized air bubble and the foam lamella during the meltdown of ice cream (FG: intact fat globule; +: intact fat globule attached to the air bubble via calcium bridges; FA: partial destabilized fat agglomerate; *: fat agglomerate that blocks the foam lamella; CM: casein micelle; CSM: casein submicelle; β-C.: β-casein; WP: whey protein).

Only larger fat globules and agglomerates were able to be retained in the resulting wider foam lamellae.

Model for the Stabilization of the Foam Structure in Ice Cream

The above results clearly showed that stable ice creams with a slow meltdown do not necessarily have high "free fat" values. A large amount of small fat globules and agglomerates was also present in the molten ice cream; the foam structure in ice cream cannot be stabilized in the same way as is possible in nonhomogenized whipped cream. Furthermore, our own transmission electron microscopy studies (Koxholt, 2000) as well as investigations by Berger (1990) have shown that air bubbles in stable ice creams are not only stabilized by partially destabilized fat agglomerates. There are also areas of the air bubble surface that are covered with comparatively small and intact fat globules and other areas where no fat can be found. The fat-free regions must be stabilized by proteins and emulsifiers; an attachment of caseins on the surface of the air bubble was already described and visualized via electron microscopy by Buchheim (1992).

Based on these results, the following model was deduced for the stabilization of the air bubbles in ice cream (Figure 7):

Depending on the amount of fat destabilization, the air bubble surface is more or less stabilized by partially destabilized fat agglomerates as in a nonhomogenized whipped cream. At the same time, there are regions that are covered with intact fat globules, proteins, and emulsifiers. Further, fat globules and agglomerates can be attached to the air bubble via calcium bridges between the caseins in the fat globule membranes as in homogenized whipped cream (Besner, 1997). This coating with fat globules, which are covered by proteins, stabilizes the air bubbles. This also explains the mousse-like meltdown residue that remained stable for 24 h, although the amount of total extractable fat was below 1%.

In a frozen state, the ice cream structure is mainly stabilized by ice crystals and the high viscosity of the unfrozen serum phase. However, the experiments clearly showed that during the melting process the meltdown rate is highly dependent on the fat agglomerates in the unfrozen serum phase. This effect was also observed by Goff (1999) in a transmission electron microscopy study. The model in Figure 7 describes the relevant stabilizing mechanisms. When the fat globules and agglomerates reach sizes in the range of the width of the foam lamellas (critical fat globule diameter) they block them and impede the drainage of the serum. Additionally, they form loose bridges between the air bubbles and prop them up against each other, which leads to a mechanically stable, mousse-like foam matrix. Larger fat globules and agglomerates that are attached to the air bubbles by calcium bridges support this effect. The fat globules and agglomerates smaller than the critical diameter flow out of the ice cream matrix with the serum phase. If there are too many of these globules and agglomerates, ice cream is unstable and melts faster. In further research work the same stabilizing effect was observed for whey protein particles (Koxholt, 2000; Koxholt et al., 1999) and the stabilization of a homogenized whipped cream was described in a similar way by Graf and Müller (1965).

CONCLUSIONS

Foam Stabilization

The fat agglomeration in the freezer and the resulting fat agglomerate sizes have a significant impact on the meltdown behavior of ice cream. However, the amount of "free fat" is not high enough to form a continuous network of agglomerated fat to stabilize the foam structure as in nonhomogenized whipped cream. Depending on the mechanical damage of the fat globules, the air-serum interface is more or less covered with partially destabilized fat agglomerates, but there are also regions that are stabilized by intact fat globules and milk proteins. As in homogenized whipped cream, further fat globules and agglomerates are attached via membrane proteins of the fat globules and prevent the air bubbles from collapsing. Thus, stable ice cream with low meltdown rates is possible, even though only a small amount of destabilized fat is present.

If the fat agglomerates in the unfrozen serum phase reach sizes above a critical diameter they block the foam lamellae and impede the drainage. But, this effect depends on the lamella width and therefore on the air bubble size and the overrun.

Homogenization Technology

For all homogenization processes, smaller fat globules and agglomerates were determined in the ice cream mix and ice cream at higher homogenization pressures. For cream with a fat content of up to 10%, there were no significant differences in the fat globule size distributions after double- and single-stage homogenization. The formation of fat clusters, such as is the case in untreated cream with higher fat contents after single-stage homogenization, was not observed because enough membrane material is present in the ice cream mix. The meltdown behavior is not affected by the homogenization pressure over a wide range. However, the optimal pressure depends on the individual composition and the demands on quality parameters such as the mouthfeel.

Furthermore, the results showed that a selective or partial-stream homogenization of ice cream mix is possible without structural defects occurring. From a scientific point of view, this enables the selective study of the impact of specialty ingredients on the fat globule membrane and the resulting structure formation in a real ice cream system. Ice cream producers are able to save energy as it is directly proportional to the volume that has to be homogenized. In addition, shear-sensitive ingredients with special functional properties such as particulated whey proteins could be added to the nonhomogenized part of the ice cream mix.

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