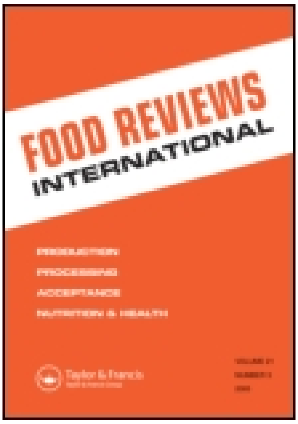

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Application and Functions of Stabilizers in Ice Cream

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Ice cream as a complex food consists of small air cells dispersed in a partially frozen, continuous aqueous phase. Its desired quality is achieved by both proper processing and formulation. Stabilizers are substances that, despite their low usage level in ice cream mix, have very important functions, such as increase in viscosity of ice cream mix, aeration improvement, cryoprotection, and control of meltdown. Various materials, including both commercial and local gums, have been used as stabilizers. In this review, types of stabilizers, their functions, and limitations on excessive use of stabilizers in ice cream are discussed.

Keywords functional properties, hydrocolloids, rheology, wheying off, sensory evaluation

Introduction

Ice cream is a frozen dairy product consumed in the frozen state where the freezing and whipping processes are important unit operations for the development of the desired structure, texture, and palatability.[1]

There are many formulation and processing factors that influence the texture and acceptability of ice cream. Stabilizers are one such ingredient, which, in spite of the low level in the formulation, impart specific and important functions to the finished product. In 1915, the word *stabilizer* was assigned to a group of substances that, at that time, were known as *holders*, *colloids*, *binders*, and *fillers*.[2] They were also referred to as *improvers*, a term used to refer to enzymes or blends of enzymes and gums.[3] *Colloids*, *hydrocolloids*, and *gums* are other names of these substances, which indicate that these materials are macromolecules, mostly polysaccharides, that are capable of interacting with water. Interaction with water also allows some of these compounds to interact with proteins and lipids in the mix.[4] Stabilizers normally contain $\sim 10^3$ monomer units and have molecular weights of $\sim 10^5$–10^6.[5]

The primary purposes for using stabilizers in ice cream are to produce smoothness in body and texture; retard or reduce ice and lactose crystal growth during storage, especially during periods of temperature fluctuation; provide uniformity to the product; and provide some degree of shape retention during melting. They also contribute to mix viscosity, stabilize the protein in the mix to avoid wheying off, help in suspension of flavoring particles,

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create a stable foam with easy cutoff and stiffness at the barrel freezer for packaging, slow down moisture migration from the product to the package or the air, and assist in preventing shrinkage of the product volume during storage.[1,2,6]

Stabilizers must also have a clean, neutral flavor, not bind to other ice cream flavors, contribute to acceptable meltdown of the ice cream, and provide desirable texture upon consumption.[1] Despite their natural sources, under European law they are considered food additives and, therefore, they have associated E numbers.[5] A good stabilizer should be nontoxic, readily disperse in the mix, not produce excessive viscosity or separation or foam in the mix, not clog strainers and filters, provide ice cream with desirable meltdown, be economical, and not impart off flavor to the mix.[4]

The amount and kind of stabilizer required in ice cream depend on its properties, mix composition, and ingredients used; processing times, temperatures, and pressures; storage temperature and time; and many other factors.[2,4] Usually 0.1–0.5% stabilizer is utilized in the ice cream mix. Mixes high in fat or total solids (40%), chocolate mixes, or ultra-high-temperature pasteurized mixes require less stabilizer than do mixes that are low in total solids (37%), are high-temperature, short-time (HTST) pasteurized, or are to be stored for extended periods of time.[2]

Many valuable studies have been published about ice cream stabilizers, with review articles, books, and book chapters relating various aspects of ice cream. For example, Hartel[7] reviewed ice crystallization during manufacturing of ice cream and stated the effects of different factors in this phenomenon. Mechanisms and kinetics of recrystallization in ice cream were also reviewed by this author.[8] Milk protein and food hydrocolloid interactions and protein–polysaccharide incompatibility have been investigated by Sybre *et al.*[9] and Doublier *et al.*,[10] respectively. In a review article, Adapa *et al.*[11] discussed the mechanisms of ice crystallization and recrystallization in ice cream and factors influencing them, especially stabilizers. Goff[12] discussed the formation and stabilization of structure in ice cream and related products with an emphasis on colloidal aspects. Dickinson[13] reviewed hydrocolloids at interfaces and the roles of these materials on properties of dispersed systems, emulsifying capacity of some hydrocolloids, and protein–polysaccharide complexes at interfaces. Goff[14] discussed the roles of hydrocolloids in frozen foods. The freezing process, structure formation, and physicochemical changes in frozen foods and the influence of polysaccharide stabilizers on these phenomena were also discussed in this book chapter.

However, there is no comprehensive review available in the literature concerning various aspects of stabilizers in ice cream. So, the aim of this review was to investigate the different kinds of stabilizers and their specific characteristics and the varied functions of these substances in ice cream, including the effects on rheological properties of ice cream and ice cream mix, phase separation, overrun, crystallization and recrystallization, melting behavior, and sensory characteristics. Finally, limitations on the excessive use of stabilizers in ice cream are mentioned.

Types and Characteristics of Individual Stabilizers in Ice Cream

A variety of substances have been used as stabilizers. Gelatin, an animal protein derivative, was one of the first materials used as an ice cream stabilizer, although it has largely been replaced by polysaccharide hydrocolloids in modern ice cream manufacture.[15] Some of the common stabilizers and their characteristics are listed below.

- Gelatin (E441)[16]: This relatively expensive stabilizer is effective at concentrations of 0.3–0.5%; however, it may not prevent the effects of heat shock.[4] It is also not acceptable to certain religious and vegetarian populations. The use of gelatin as a stabilizer produces thin mixes that require a long aging period. Gelatin disperses easily and does not cause wheying off or foaming.[4]

- Guar gum (E412)[5]: Guar gum is extracted from the seeds of a tropical legume, *Cyamoposis tetragonolba*, called *guar*. It has been grown in India and Pakistan for centuries and, for a short time and to a limited extent, in the United States.[6] It is the least expensive stabilizer and effectively decreases the undesirable effects of heat shock in ice cream.[4] It readily disperses and does not cause excessive viscosity in the mix. Generally, 0.1–0.2% is required in a mix and, therefore, this substance is considered to be a strong stabilizer.[4]
- Sodium carboxymethyl cellulose (*CMC*) (E466)[5]: This chemically modified natural gum is a linear, long-chain, water-soluble, and anionic polysaccharide. Purified sodium carboxymethyl cellulose is a white-to-cream–colored, tasteless, odorless, free-flowing powder.[17] CMC forms weak gels by itself but gels well in combination with carrageenan, locust bean gum, or guar gum.[2] It is a strong stabilizer and only 0.1–0.2% is needed in a mix. It imparts body and chewiness to ice cream.[4]
- Locust bean gum (carob bean gum) (LBG) (E410)[5]: Locust bean gum is obtained from the beans of the tree *Ceratonia siliqua*, grown mostly in the Mediterranean area.[6] This strong stabilizer is used at 0.1–0.2% levels and causes phase separation in ice cream mixes.[4] LBG is only partially soluble in cold water and it must be heated above 85°C to hydrate fully.[5] For the following reasons it was reported to be an ideal gum in stabilization of ice cream[17,18]:
  - It creates a uniform, medium, and reproducible viscosity that is not destroyed by agitation.
  - It cools uniformly and allows easy incorporation of air into the mix.
  - It provides superior heat-shock resistance.
  - It does not produce any taste or flavor-masking properties to the mix.
  - It forms a cryo-gel, which can be effective in cryo-protection.
- Carrageenan (Irish moss) (E407)[5]: This stabilizer was originally derived from red algae called *Chondus crispus*.[6] The major sources of this gum are now the two tropical red seaweeds, *Eucheuma cottonii* (now called *Kappaphycus alarezii*) and *E. spinosum* (now *E. denticulatum*), which are commercially farmed in the Philippines, Indonesia, and Tanzania. The extract of *Kappaphycus alarezii* is almost pure kappa carrageenan (with less than 10% iota), whereas the extract of *E. denticulatum* is a relatively pure iota carrageenan (less than 15% kappa). The extracts of Gigartinacean algae (Chilean carrageenophytes), *Gigartina skottsbergii*, *Sarcothalia crispate*, and *Mazzaella laminarioides*, however, are gelling carrageenans that are weaker and less interactive with kappa casein in milk than *C. crispus* extracts. These gelling carrageenans have been found to be copolymers of kappa and iota carrageenan, which the industry refers to as *kappa-2 carrageenan*, *kappa/iota hybrids*, or *weak-gelling kappas*.[19] Carrageenan is used in many stabilizer blends at levels of 0.01–0.02% to prevent phase separation (wheying off) through its interaction with milk protein.[4]
- Xanthan (E415)[5]: This bacterial exopolysaccharide is obtained by the growth of *Xanthomonas campestris* in culture.[6] Its blend with guar gum and/or locust bean gum makes an effective stabilizer for ice cream, ice milk, sherbet, and water ices. A combination of xanthan gum with sodium alginate is reported to serve as a milk shake stabilizer.[20]
- Alginates: Alginates, or algin, is a generic term for the salts and derivatives of alginic acid. This acidic polysaccharide occurs as the insoluble mixed calcium, sodium, potassium, and magnesium salt in the Phaeophyceae, brown seaweeds.[21]

Alginates dissolve in cold water and gel in the presence of calcium and acid. However, because of their price, they are not widely used.[2] Sodium alginate, a member of this group, has an E number of 401.[5]

- Microcrystalline cellulose (Cellulose gel) (MCC) (E460)[15]: MCC has effective application in foam stabilization and overrun control.[17] The addition of 0.4% and higher levels of MCC to ice cream mix results in the formation of a gel, which preserves the original texture of frozen dessert products during storage and distribution by increasing their resistance to heat shock and by maintaining the three-phase system of air–fat–water in these products.[17] MCC also allows for reduction of fat and solids content by 2 to 4% with minimal loss of texture.[17] Like carrageenan, cellulose gel has the capability to prevent whey separation in mixes, thereby countering the destabilizing effects of some soluble gums.[17]

In addition to these above-mentioned common substances, other, more local, hydrocolloids have been used as ice cream stabilizers.[22–34] Salep, for example, is obtained by milling dried tubers of wild orchids[23] and is applied as an essential ingredient for the production of traditional ice cream in Iran[29] and Turkey.[23] This kind of ice cream, which is called *kahramanmaras* or *maras* in Turkey, differs from common ice cream in its high sugar content, natural flavor, and sticky gummy body, especially due to salep addition.[30] *Maras*-type ice cream is served hard and a knife should be used during consumption, due to its unique textural properties.[31] Compared to other stabilizers, salep is used in higher content, generally 0.78–1%, in ice cream formulation.[23,30] In addition to stabilizing properties, salep has health benefits.[29] Salep contains approximately 11–44% high polysaccharides (glucomannan). Glucomannan is classified as a hydrocolloid; it absorbs 200 mL of water per gram.[34] According to Farshoosh and Riazi,[35] salep varieties grown in Iran come in two forms, one with branched or palmate tubers and the other with rounded or unbranched tubers. The palmate-tuber salep (PTS), at similar concentrations to rounded-tuber salep (RTS), produces solutions with more pseudoplasticity and higher consistency. For this reason, BahramParvar *et al.*[28] concluded that PTS is a better ice cream stabilizer compared to RTS. These authors used this kind of salep and another Iranian local gum (*Lallemantia royleana* seed gum) compared to CMC, which is a well-known commercial gum, in ice cream formulation. Although products prepared using only salep (PTS) showed greater differences compared to ice cream containing CMC, all variations were not significant.[28]

Lallemantia royleana, with the vernacular name of *Balangu* or *Balangu Shirazi*, is a member of the Labiatae family and has an extensive distribution in different regions of European and Middle East countries, especially Iran. Balangu seed is a good source of polysaccharides, fiber, oil, and protein and has some medicinal, nutritional, and human health properties.[36] It adsorbs water quickly when soaked in water and produces a sticky, turbid, and tasteless liquid.[37] In comparison with CMC, Balangu seed gum (BSG) did not have a significant effect ($P > 0.05$) on most characteristics of ice cream and could serve as a suitable stabilizer.[28] BahramParvar *et al.*[27] also studied the effects of different levels of substitution of CMC and PTS by BSG. They found a synergistic effect between CMC and BGS in elevation of ice cream mix viscosity. However, such a regular trend was not observed in the case of BSG and PTS. Often, different levels of this replacement (0–100%) improved sensory characteristics of ice cream, although most differences were not significant.

Other local gums have also been studied. For instance, Uzomah and Ahiligwo[22] investigated the effects of the water-soluble gums extracted from seeds of achi (*Brachystegea eurycoma*) and Ogbono (*Irvingia gabonesis*; commonly found in Nigeria) on quality characteristics of an ice cream mix and ice cream. These characteristics were compared to those of similar products made with commercial food gums. Only values of achi seed gum ice cream fell within the ranges of values obtained for the ice cream containing commercial gums. Moreover, Rincon *et al.*[25] examined a mixture of gums from *Acacia glomerosa*, *Enterolobium cyclocarpum*, and *Hymenaea courbaril* (species grown in Venezuela) as stabilizers in the preparation of ice cream. Quality characteristics of the product (viscosity, overrun, meltdown, shape factor, and sensory properties) were determined and compared to ice creams made with a mixture of commercial gums. The mixture of Venezuelan hydrocolloids provided suitable viscosity for ice creams with the corresponding overrun and texture. It gave better foaming properties and air incorporation than the commercial gums tested and had the highest score of flavor, creaminess, overall acceptability, and lowest score of iciness. Based on these studies, local gums can be successfully used in preparation of ice cream.

It could be concluded that each stabilizer has own characteristics, and to gain synergism in function and improve their overall effectiveness, individual stabilizers are usually mixed.[4] For example, because of the higher solubility of guar compared to locust bean gum at cold temperatures, guar gum is used more in HTST pasteurization systems. Carrageenan is a secondary hydrocolloid used to prevent phase separation of a mix and also generally improves protein stability in the presence of such negative influences as shear, low pH, change in salt balance, among others.[9,21,38] Hence, it is included in most blended stabilizer formulations. Multiple stabilizer ingredients are also used to reduce the overall cost of the stabilizer system.[2] For example, Guven *et al.*[30] produced ice creams containing four different combinations of LBG, CMC, guar gum, and sodium alginate and a control sample using only salep extract. They concluded that the use of combinations of suitable stabilizers instead of only one led to better results.

Functions of Stabilizers in Ice Cream

Effects of Stabilizers on Rheological Properties of Ice Cream Mix

Rheology is a branch of physics concerned with the composition and structure of flowing and deformable materials.[2] Knowledge of the rheological characteristics of foodstuffs is important for quality control, texture, processing, and the selection of the proper equipment.[24] Smooth texture and cooling sensation, which are the most commonly desired attributes of ice cream during consumption, could be provided by an ice cream mix with optimum rheological properties.[26]

Ice cream mixes exhibit non-Newtonian pseudoplastic behavior, meaning that there is a nonlinear relationship between shear stress and shear rate, with the apparent viscosity decreasing with increasing shear rate. The pseudoplasticity or shear thinning behavior has been related to the increased alignment of constituent molecules of the system.[35] Generally, the power law model is used to fit the rheological properties of the ice cream mix[23]:

$$\tau = K\dot{\gamma}^{n} \qquad (1)$$

where τ is the shear stress (Pa), K is the consistency index (Pa.s^n), $\dot{\gamma}$ is the shear rate (s^{-1}), and n is flow behavior index (dimensionless). The values n and K are important rheological properties of fluid foods, because the flow of these foods is characterized in terms of these quantities.[25] The smaller the n value, the greater the departure from Newtonian behavior and, hence, the greater the pseudoplasticity. The consistency index, which is considered to be a measure of the viscous nature of the food, increases with stabilizer concentration.[39] It has been reported that neutral gums exhibited a greater increase in non-Newtonian behavior with concentration than anionic gums.[23]

Viscosity, which is one of the most important rheological properties of ice cream mix and the unfrozen portion of ice cream, is influenced by mix composition (mainly stabilizer and protein), type and quality of the ingredients, processing and handling of the mix, concentration (total solid content), and temperature.[2] The viscosity of ice cream mix is set through mix composition, particularly stabilizer content and level.[24] Although it is generally understood that mix viscosity is important to impart desirable qualities of ice cream, the specific rheological parameters required are not well understood. Generally, as the viscosity increases, the resistance to melting and the smoothness of texture increases, but the rate of whipping decreases.[2]

Numerous studies have investigated the rheological properties of ice cream and ice cream mix and factors influencing these characteristics.[22–24,26,39,40] Goff and Davidson[41] reported that the flow behavior index (*n*) of ice cream mixes is around 0.7, although other investigators have found values from 0.37 to 0.98. Values of flow behavior index and consistency index of some ice cream mixes containing stabilizers are presented in Table 1. Previous studies have shown that an increase in concentration and decrease in temperature increases pseudoplasticity (decreases *n* values).[35,39] Kaya and Tekin[23] showed that salep concentration had a greater effect on viscosity than temperature. In another study,[42] shear thinning behavior of ice cream mix, along with instrumental hardness of the ice cream, was indicative of the creaminess and wateriness of samples. Wateriness is a sensory property that has been applied when the sample melts unusually quickly into an uncharacteristically thin, water-like fluid. The use of hydrocolloids improved creaminess and reduced wateriness.[42]

The time-dependent flow behavior (thixotropy) of ice cream mix has been studied by Kus *et al.*[24] Their samples showed slightly thixotropic behavior, which increased as salep content increased. In this case, thixotropy appeared as time-dependent thinning behavior that reflected the destruction of the product structure during flow and the subsequent recovery of the viscosity when flow was stopped. The power law model was used to model the forward and backward measurements of the flow curves of ice cream mixes. The ice cream mixes showed pseudoplastic flow behavior after destruction of the thixotropic structure. A first-order stress decay model, as the second-order structural kinetic, was found to fit the experimental data well. Such information is useful to analyze the flow of ice cream mix in pipelines during startup and steady conditions and for proper design of pipes and pumps in ice cream processing plants. The characterization of the time-dependent rheological properties of ice cream is also important for correlating physical parameters with sensory evaluation.

The effects of stabilizers on mechanical and stress relaxation properties of ice cream mix and sugar solutions containing hydrocolloids have also been investigated. Thermomechanical analysis indicated that these materials decrease the rate of thermal deformation, increase apparent viscosity, and decrease compliance at −26°C in frozen 20% sucrose solutions (proposed as model ice cream mixes).[1] Stabilizers also decreased the molecular relaxation properties[1,43] and increased storage (elastic component) and loss moduli (viscous component) in ice cream mixes compared to unstabilized mixes of the same composition.[1]

Dogan and Kayacier[26] investigated the effects of ageing on the rheological parameters of *kahramanmaras*-type ice cream mix. By evaluating *n*, *K*, and apparent viscosity

Table 1
Power law model parameters, K and n, for different ice cream mixes containing different hydrocolloid stabilizers

n	K (Pa.s^n)	Explanation	Reference
0.68–0.98	—	Ice cream mix containing 0.05–0.40% guar gum	(32)
0.48–0.88	—	Ice cream mix containing 0.05–0.40% locust bean gum	(32)
0.48–0.55	4.8–6.7	Ice cream mix containing 0.3% stabilizer (a blend of carrageenan, CMC, and locust bean gum)	(104)
0.37–0.66	0.07–1.26	Regular, light, low-fat, and fat-free ice cream mix containing 0.3% commercial stabilizer–emulsifier blend (Party Pride®)	(99)
0.77–0.95	0.03–2.42	Mixture of milk–sugar–salep (0.4–1%)	(23)
0.58–0.91	0.72–2.87	Ice cream mix including 0, 0.3, and 0.5% commercial stabilizer blend, C-196, which contained 12% carrageenan, 33% guar gum, and 55% carboxymethyl cellulose	(57)
0.73–0.93	0.36–1.19[a]	Ice cream mix with buffalo milk using optimum levels[b] of various stabilizers (gelatin, 0.45%; sodium alginate, 0.40%; acacia, 0.75%; karaya, 0.25%; guar gum, 0.075%; or ghatti gum, 0.25%)	(40)
0.48–0.53	14.5 ± 0.13–21.1 ± 0.51	Ice cream mix including 0.15% commercial stabilizer blend, C-196, which contained 12% carrageenan, 33% guar gum, and 55% carboxymethyl cellulose	(93)
0.37–0.76	0.20–21.17	Non-fat ice cream mix containing 0.5–1.5% salep at 5°C	(24)
0.55–0.69	0.58–2.16	Commercial ice cream mix containing 10% fat and mixture of locust bean gum, guar gum, and carrageenan as stabilizer[c]	(33)
0.47–0.75	0.80–7.45	*Maras*-type ice cream[d] mix (containing mixture of guar, carboxymethylcellulose, and salep as stabilizer)[c]	(33)
0.34–0.36	3.72–4.33	Ice cream mix containing 4 g salep and 1 g gelatin per one liter of milk	(26)
0.47 ± 0.02	6.47 ± 0.86	Regular ice cream mix (containing 10% milk fat) with 0.65% stabilizer–emulsifier mixture of Cremodan SE 30	(105)
0.36–0.50	2.6–12.0	Ice cream mix containing different levels of fat and 1% stabilizer blends (different ratios of salep, guar gum, and gelatin)	(31)

(*Continued*)

Table 1
(Continued)

n	K (Pa.s^n)	Explanation	Reference
0.45–0.95	0.07–1.95	Ice cream mix containing 0.1 and 0.2% stabilizer (xanthan, CMC, sodium alginate, or guar as primary stabilizer and κ-carrageenan as secondary stabilizer, blended with primary stabilizers at a ratio of 1:9)	(42)
0.79 ± 0.04	0.16 ± 0.04	Ice cream mix with 0.2% stabilizer (guar gum and microcrystalline cellulose at 1:1 ratio)	(55)
0.45–1.15	0.05–6.82	Ice cream containing 0.3, 0.4, and 0.5% Balangu seed gum, palmate tuber salep, and carboxymethylcellulose	(39)

[a]K for ice cream mix without stabilizer was 0.29.
[b]Optimum level of each gum determined based on the preliminary trials.
[c]Amount of ingredients in formulation were not mentioned in the article.
[d]Traditional Turkish ice cream that contains salep as stabilizer (see more in text).

values, they suggested that 24 hours of aging at 0°C would be a proper ageing time for the ice cream mix. After 24 hours, K and apparent viscosity reached the highest values, whereas the n reached the lowest value. However, it has been indicated for ice cream mixes containing commercial stabilizers that about 4 hours of aging is sufficient.(2)

Effects of Stabilizers on Phase Separation

Because most polysaccharides of commercial interest are incompatible with milk proteins in solution, phase separation occurs.(9,44–50) resulting in a change of functional behavior of the proteins and polysaccharides, a visual separation of a clear serum, and a loss of pleasing quality in the product.(50) This problem, which can be attributed to a depletion flocculation mechanism, is especially apparent and problematic in soft-serve ice cream mixes during quiescent storage of up to 3 weeks at 5°C.(45,46,49) Different gums have different effects on phase separation. For example, Thaiudom and Goff(50) found that among the stabilizers studied, xanthan gum was the most incompatible with milk proteins, followed by guar gum and LBG.

Other ingredients in ice cream could differently affect wheying off as well. Schorsch *et al.*(48) showed that addition of sucrose led to a concentration effect on the protein phase and dilution of the locust bean gum phase. The effect of molecular conformation on phase separation was explained by Bourriot *et al.*(45,46) A lower intrinsic viscosity or hydrodynamic molecular volume of the polysaccharide (for example, LBG or hydrolyzed guar gum compared to guar gum) led to smaller occupied volumes, which contribute to less exclusion of the polysaccharide in mixtures. Thus, the aggregation of milk proteins decreases and, consequently, phase separation is reduced.(46,51)

κ-Carrageenan is added in ice cream as a secondary stabilizing agent at levels lower than 0.05% to control phase separation.(38,49,50,52) This control occurs according to the following mechanisms: (a) absorption of κ-carrageenan on the casein micelles and formation of a gel network, which leads to the sedimentation of caseins when κ-carrageenan is in the helix conformation[53]; and (b) phase separation between polysaccharides and casein at temperatures above coil–helix transition and rapid inhibition of phase separation because of the capability of helical κ-carrageenan to form linkages with caseins.[38,54,55] However, κ-carrageenan only inhibits macroscopic phase separation, and such stable systems remain microscopically phase separated.[49,50]

Doublier *et al.*,[10] in a review on polysaccharide–protein interactions, concluded that future efforts in this area should be focused on the study of the relationships between the structure and the molecular interactions. The influence of these molecular interactions on the molecular structure and on phase ordering kinetics in biopolymer mixtures was also suggested for further study.

Effects of Stabilizers on Volume Increase (Overrun)

Ice cream and related products are generally aerated and characterized as frozen foams.[11] Increasing ice cream volume is one role of stabilizers, brought about through increasing viscosity and maintaining the air bubbles. The amount of air in ice cream is important because it influences quality and profits but also because of legal standards that must be met.[2] Further, the air cell structure has proven to be one of the main factors influencing melting rate, shape retention during meltdown, and the rheological properties in the molten state, which are correlated to creaminess. Smaller air cells improve the product quality regarding these three indicators.[56]

Chang and Hartel[57] studied the effects of operating conditions (freezing, not freezing, and partial freezing) and formulation (fat, emulsifier, and stabilizer content) on development of air cells. Change in stabilizer level (0, 0.3, and 0.5% C-196 stabilizer, which contained 12% carageenan, 33% guar gum, and 55% CMC) had no effect on drawing temperature and overrun. Addition of stabilizer, however, reduced air cell size compared to a similar ice cream mix made without stabilizer. Changes in air cell size could be directly attributed to changes in rheological properties of the ice cream during freezing. As freezing commenced, the apparent viscosity increased, which caused a reduction in maximum air cell size due to the increased shear stress applied to disrupt the air cells.

Changes in air cells during storage of ice cream occur due to three primary mechanisms: disproportionation (Ostwald ripening), coalescence, and drainage. The rates of change in air cells based on these mechanisms were found to depend on both process conditions (storage temperature) and formulation (emulsifier and stabilizer). A decrease in storage temperature led to a decrease in rate of air cell coarsening, primarily because the drainage mechanism was inhibited but also because the rates of disproportionation and coalescence were reduced. Addition of stabilizer inhibited air cell coarsening due to the increased viscosity of the fluid phase.[58]

Disproportionation, which develops due to differences in Laplace pressure between air cells, may also be controlled by increasing viscosity of the serum phase and forming a thick film on the surface of the air cells.[59] According to Chang and Hartel,[58] disproportionation of air cells was inhibited by addition of stabilizers.

Drainage involves the rise of air cells and subsequent downward flow of the serum phase due to gravity. The larger the air cell, the faster it rises. Drainage by itself does not change the air cell distribution but rather changes the film thickness between the air cells and promotes coalescence. Increasing the viscosity of the serum phase, which may be achieved by addition of stabilizer or by decreasing storage temperature, is one way to retard drainage.[60]

Shrinkage and expansion, two important defects in ice cream, may also be related to addition of stabilizers. *Shrinkage* has been defined as the loss of volume in ice cream before any part of the product has been removed from the container and is a special type of weak-body and texture defect.[61] Expansion of product shows up in the hardening room or after shipping ice cream, by expanded or popped lids. Both problems are related to the use of differing protein sources, low-fat products, increase in the practice of producing ice cream at a very high level of overrun, and wide geographic distribution of product involving altitude changes or via air transport.[2,61]

Small air cells, heat shock, excessive overrun, small ice crystals, improper blending of ingredients, insufficient stability in the lamella, weak body, excess fat agglomeration, too much emulsifier, or not enough stabilizer are some of the causes of shrinkage in ice cream.[61,62] Conflicting results have been reported by previous researchers regarding the use of stabilizers and emulsifiers to reduce or eliminate shrinkage and expansion of ice cream.[61]

In spite of the importance of the air phase in ice cream, its effects are often overlooked, and further investigations into the composition and competition amongst constituents of the air interface seem necessary.

Effects of Stabilizers on Thermodynamic Properties

Differential scanning calorimetry (DSC) is an advantageous technique applied to determine glass transition temperatures and to measure the heat involved in thermal transitions. Through the total enthalpy change, it is possible to determine the quantity of ice formed in a certain process.[43] DSC indicated that thermodynamic properties such as glass transition, heat capacity, and ice content determined by the melting endotherm are similar in systems with and without the presence of a stabilizer.[1,15,63,64] However, these materials provided resistance to thermal deformation[63] and significantly affected the thermal conductivity values. It has been shown that ice cream mixes having the highest locust bean gum–to-guar ratio had the highest thermal conductivity. Ice cream mixes with more locust bean gum also froze faster, because the relatively lower amounts of bound water made them less viscous compared to ice creams containing guar gum.[11] Herrera *et al.*,[43] in investigating the thermal properties of fructose or sucrose frozen solutions containing hydrocolloids, found that melting onset was not affected by the addition of hydrocolloids. However, another study has shown that increasing the concentration of a hydrocolloid decreased the heat of fusion of water in hydrocolloid–water solutions, implying that less water was able to freeze as the concentration of hydrocolloid was increased. It was concluded that the decrease in the heat of fusion was due to the water binding ability of hydrocolloids.[65]

Cryoprotective Role of Stabilizers

The mechanisms by which stabilizers affect the freezing properties or limit recrystallization have been extensively studied but are still not fully understood. Stabilizers have little[66–68] or no[69,70] impact on the initial ice crystal size distribution in ice cream at the time of draw from the scraped surface heat exchanger or on the initial ice growth during quiescent freezing and hardening.[71–73] However, they do limit the rate of growth of ice crystals during recrystallization.[64,66,69–71,74,75]

The cryoprotective effect of hydrocolloids on ice cream can be explained by three potential mechanisms, as follows.[1,2,6,8,42,64]

Viscosity and Molecular Mobility. According to the first mechanism, the increase in viscosity due to the addition of stabilizers is correlated to the control of ice crystal growth.[64,76–79] However, despite many studies, no definitive correlation between mix viscosity and recrystallization has been found. Budiaman and Fennema[77,78] assessed the linear rate of water crystallization in various hydrocolloid suspensions at temperatures ranging from −3 to −5°C. For any given hydrocolloid suspension, the linear rate of water crystallization decreased as viscosity was increased, but it differed among hydrocolloid suspensions adjusted to the same viscosity. Thus, viscosity, over the range investigated, is not a good predictor of the capacity of a hydrocolloid to inhibit crystallization. It was suggested that the beneficial effects of hydrocolloids on the texture of frozen desserts may originate from some attributes other than control of crystal size. According to Harper and Shoemaker,[72] mix viscosity does not correlate well with stabilizer action, and locust bean gum was not an effective inhibitor of recrystallization under their test conditions. They also reported that migratory recrystallization was the predominant mechanism and that the effect of temperature fluctuations was quantitatively greater than recrystallization at constant storage temperature. The functionality of a stabilizer may be enhanced as the polymer concentration is increased, but different stabilizers are not equally effective for retarding ice crystal growth at the same level of viscosity.[80] Bolliger *et al.*[81] found a linear relationship between a normalized "breakpoint" apparent viscosity (i.e., the viscosity at which a significant change in slope of concentration-viscosity occurred) and recrystallization rate. They proposed that at least some aspects of stabilizer functionality with respect to recrystallization protection come from the increased viscoelasticity that results from freeze-concentration of the polysaccharide in the unfrozen phase of ice cream, perhaps due to hyper-entanglements and solution structure formation. This concept was related to the rate at which water can diffuse to the surface of a growing crystal during temperature fluctuation or the rate at which solutes and macromolecules can diffuse away from the surface of a growing ice crystal.

Martin *et al.*,[82] by time domain proton nuclear magnetic resonance (NMR), showed that addition of locust bean gum did not affect the diffusion rate or mobility of either the sugar or water molecules over distances up to 10 μm in unfrozen solutions. However, this technique measures the water diffusion or translational displacement of water (or sugar) molecules at intermolecular distances, usually less than 10 nm, whereas the water migration from one crystal to another involved in melt–regrow recrystallization mechanisms implies that distances between ice crystals usually longer than 10 μm. Contrary to this result, Herrera *et al.*[43] reported that hydrocolloids decreased molecular mobility for both frozen sucrose and fructose solutions, especially for the addition of xanthan/LBG blend. It has been suggested that studying the relation between water mobility in freeze-concentrated matrix and recrystallization rate may be helpful in understanding the mechanism of stabilizer action and also controlling the ice recrystallization.[83,84]

Cryo-Gel Formation. The second mechanism of hydrocolloid action correlates the cryoprotectivity of hydrocolloids with their capacity to form cryogels as a result of heat shock during storage.[73,85,86] These structures limit or restrict the diffusion characteristics of water and solutes within their networks. They also hold free water as water of hydration around the polysaccharide structure.[1] It has been found that recrystallization rates increase with increasing self-diffusion coefficients of water in the freeze-concentrated matrix of sugar solutions.[83,84] Gel firmness has been connected to inhibition of ice crystal growth and a change in ice crystal morphology.[73] However, a firm gel has not always been effective at retarding ice crystal growth, probably because a firm gel would be more fragile and more easily ruptured by the ice front, whereas a more flexible gel would exert a stronger opposing force for ice front propagation. It has also been reported that stabilizers that do not form a gel yet have an effect in retarding ice crystal growth.[12,69,87] In Regand and Goff,[87] the fact that some nongelling stabilizers (xanthan, CMC, alginate) were more effective in retarding recrystallization than gelling stabilizers (gelatin, carrageenan, LBG) suggests that steric blocking of the interface or inhibition of solute transport to and from the ice interface caused by gelation of the polymer is not the only mechanism of stabilizer action. Water holding by the stabilizer and proteins, and in some cases steric hindrance induced by a stabilizer gel-like network, probably caused a reduction in water mobility of the system, promoting ice recrystallization mechanisms of melt–regrow instead of melt–diffuse grow. These mechanisms result in the preservation of ice crystal size and in a small span of ice crystal size distribution.

Hydrocolloid Phase Separation. Finally, the incompatibility of hydrocolloids with proteins provoking phase separation may contribute to retarding recrystallization.[80,87] Goff *et al.*[18] found that the formation of an LBG network, combined with the presence of phase-separated protein, was most effective at controlling ice recrystallization.

It is obvious that different stabilizers have different cryoprotective functionality. For example, Hagiwara and Hartel,[64] Miller-Livney and Hartel,[79] and Marshall *et al.*[2] reported that polysaccharide stabilizers that are used commonly to control ice crystal growth in ice cream include locust bean gum, sodium carboxymethylcellulose, alginate, carrageenan, and xanthan gum. Adapa *et al.*,[11] in a review of ice crystallization in ice cream, mentioned galactomannans (guar and locust bean gum) as the most widely used stabilizers to inhibit ice crystal growth. LBG has been shown to reduce recrystallization rates better than guar gum,[18,38,65,86] probably because of differences in structure.[85,88] Moreover, it has now been clearly accepted that LBG, in contrast to guar gum, does gel at high concentrations under specific conditions upon ageing[18] or following freeze–thaw cycles.[88,89] Tanaka *et al.*[89] have also established that the gel strength increases with the number of freeze–thaw cycles. However, an increase in the ratio of guar to locust bean gum (25:75 to 75:25) caused an increase in the structure of the ice cream mixes, because guar gum binds four times as much water as locust bean gum.[11] Therefore, ice cream mixes containing larger amounts of guar gum compared to locust bean gum require more energy to freeze.[90]

In general, from the results of these various studies, stabilizers modify the kinetic properties of the unfrozen phase, rather than any thermodynamic properties associated with water (e.g., ice equilibrium). Also, it has been proposed that the desirable effects of stabilizers on the sensory properties of ice cream result from their abilities to alter surface properties of ice crystals or to alter the perception of ice crystals in the mouth.[1,2,15,91] Moreover, it has been indicated that the effects of hydrocolloid addition in frozen desserts cannot be attributed to one particular factor but to several interaction effects.[43]

Effects of Stabilizers on Melting Rate

When ice cream is in the form of a cone or stick novelty, melting rate is of greatest importance to the consumer. The slow meltdown, slow serum drainage, good shape retention, and slower foam collapse are some of the desired important quality parameters of ice cream.[92] If the product melts too fast, a messy situation can occur. A fast-melting product is undesirable also because it tends to become heat shocked readily. However, a very slow rate of melting can also be indicative of defective ice cream.[2]

As the ice cream melts, heat transfers from the warm air surrounding the product into the ice cream to melt the ice crystals. Initially the ice melts at the exterior of the ice cream and there is a local cooling effect. The water from the melting ice must diffuse into the viscous unfrozen serum phase, and this diluted solution then flows downwards (due to gravity) through the structural elements (destabilized fat globules, air cells, and remaining ice crystals) to drip.[93] Fat destabilization, ice crystal size, and consistency coefficient of ice cream mix were found to affect the melting rate of ice cream.[93] Emulsifiers that promote destabilization and partial coalescence of fat globules greatly decrease the melting rate of ice cream and promote shape retention.[2,93]

One function of stabilizers in ice cream is to increase the melting resistance, as reported in numerous studies.[22,28,30,93] Hydrocolloids, due to their water-holding and microviscosity enhancement ability, significantly affect melting quality of ice cream.[2] Moreover, it seems that the influence of stabilizers on thermal properties of ice cream such as thermal conductivity, melting onset, and heat of fusion[11,43,65] could affect the melting rate.

Effects of Stabilizers on Sensory Characteristics

In addition to other functions, hydrocolloids influence the sensory properties of ice cream.[25,42,94] Although there are many reports dealing with the effect of hydrocolloids on texture perception and flavor release of dairy emulsions,[95–98] there are insufficient experimental data on the particular action of hydrocolloids on specific sensory components of ice cream texture and flavor.[42]

Viscosity of the serum phase affects the mouthfeel (i.e., body and texture) of the ice cream; better body and texture further improve the overall acceptability of the product.[40] Numerous studies have attempted to correlate viscosity and sensory properties.[39,40,42,99] Minhas *et al.*[40] investigated the relationship between concentration of stabilizers, viscosity, body and texture, and overall acceptability of ice cream. The stabilizer concentration was highly correlated with the viscosity of ice cream mixes and, in most cases, with body and texture. Viscosity of ice cream mix was highly correlated with body and texture of ice creams containing guar, gelatin, and acacia but not with karaya and sodium alginate. Viscosity of an ice cream mix was also highly correlated with the overall acceptability of ice creams containing guar, gelatin, acacia and sodium alginate. A negative correlation between viscosity, body and texture, and overall acceptability was noted using *ghatti*. Best-fit regression equations were created to predict sensory attributes of ice cream from the mix viscosity and concentration of stabilizers. Successful models for overall acceptability were generated for guar, gelatin, acacia, and sodium alginate, although it was not possible to form meaningful predictive equations from the experimental data available for overall acceptability scores associated with *karaya* and *ghatti*. This was likely a function of the poor correlation of concentration and viscosity with overall acceptability for these stabilizers.

Soukoulis *et al.*[42] furnished important information for the correlation of objective and sensory properties and discrimination of stabilizing systems based on quality criteria, using principal components and cluster analysis of instrumental and sensory data. In this research, hydrocolloid type and content significantly influenced vanilla flavor release, with higher hydrocolloid content leading to better vanilla flavor perception. Samples with xanthan and sodium alginate, which exhibited greater shear thinning behavior, had higher vanilla flavor scores. An increase in hydrocolloid content improved creaminess and reduced wateriness. Samples containing 0.2% sodium alginate or xanthan gum, which had the highest viscosity and the most pronounced shear thinning behavior, provided the best texture.

Stabilizers also decrease the icy sensation via their influence on recrystallization and sensory perception of ice crystals.[100,101]

Ice Cream Defects Caused by Stabilizers

Although stabilizers have very beneficial functions in ice cream, their excessive use may create problems. These limitations include undesirable melting characteristics, excessive mix viscosity, and contribution to a heavy, soggy body.[1] Stabilizer/emulsifier components may also impart off-flavors, because they are prone to oxidation if not kept in a dry and cool environment.[2] Baer *et al.*[102] and Schaller-Povolny and Smith[103] distinguished ice cream containing hydroxy propyl methyl cellulose and inulin gums as being more gummy and chewy than other samples, respectively.

Conclusion

Because ice cream is a complex colloidal system, many factors should be taken into account in producing high-quality ice cream. Stabilizers, despite being used in very small amounts in ice cream, have been claimed to have one or more of the following functions: increase viscosity of ice cream mix, improve aeration and body, control meltdown, and restrict growth of crystals of ice during storage. In addition, stabilizers improve the sensory characteristics of ice cream by retarding iciness, enhancing creaminess, and decreasing wateriness. However, many polysaccharides of commercial interest are incompatible with milk proteins in solution, and phase separation often occurs, resulting in a change of functional behavior of the proteins and polysaccharides, a visual separation of a clear serum, and a loss of pleasing quality in the product.

Despite numerous studies, the exact mechanism of stabilizer action in ice cream is not clear. However, it seems that the effects of hydrocolloids in frozen desserts cannot be attributed to one particular factor but to several interaction effects. Because individual stabilizers have specific roles and seldom perform all of the desired functions, synergistic mixtures are often used. Often, trial and error is required to determine the right combination and concentrations of the available hydrocolloids to perform the functions desired for a given formula and market niche.

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