Effect of Certain Surfactants on the Swelling, Solubility and Amylograph Consistency of Starch[1]

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ABSTRACT

The effects of certain mono- and triglycerides and other surfactants on unmodified wheat and corn starch slurries were examined by the Viskograph E. All emulsifiers and surfactants tested caused a lower consistency than the control during the first stage of consistency increase and reduced consistency throughout most of the second stage of consistency increase. Certain monoglycerides went through apparent phase changes, which may have caused them to interact more fully with the starch and reduce consistency below that of the control. When carboxymethylcellulose (CMC) was used to create a background consistency, its consistency could not be deducted from the consistency of a starch plus CMC slurry to obtain the consistency of a starch-only slurry. All monoglycerides tested reduced starch swelling when compared to the control at temperatures of 60–80°C. Monoglycerides with 18 carbons, both saturated and monounsaturated, reduced swelling at 90°C. However, a 10 monoglyceride increased swelling at 90 and 95°C. The increased swelling was also shown by light micrographs and consistency measurements. In general, triglycerides did not affect swelling. All monoglycerides reduced starch solubility compared to that of the control. No triglycerides had an effect on starch solubility. Swelling occurred in two stages, but solubility showed a relatively smooth increase as temperature increased. This suggests that swelling is related to the two stages of consistency increase found with such instruments as the amylograph or viskograph.

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Starch granules swell in the presence of water. The swelling can be reversed upon the removal of the water, if the system is not heated above its gelatinization temperature (Hoseney 1986). The presence of substances such as sugars, certain lipids, and salts affects this critical temperature (Harbitz 1983, Eliasson 1986). Granule swelling continues as starch and water are heated above the gelatinization temperature. In addition, starch solubility increases during heating. The extent of swelling and solubilization may be affected by the presence of certain lipids (Osman and Dix 1960; Gray and Schoch 1962; Ghiasi et al 1982a,b; Moorthy 1985).

Osman et al (1961) showed that in excess water, certain lipids interacted with starch, the amylose fraction in particular, to form complexes. The formation of these complexes may be the mechanism by which certain lipids affect the swelling of the starch granules (Ghiasi et al 1982a). Those complexes also may affect the amount of soluble starch leached from granules (Hoover and Hadziyev 1981, Ghiasi et al 1982a), as well as other properties of starch, such as gelatinization temperature (Harbitz 1983, Eliasson 1986) and viscosity characteristics (Osman and Dix 1960, Gray and Schoch 1962, Derby et al 1975, Ghiasi et al 1982b, Moorthy 1985). A positive correlation between the complexing ability of monoglycerides (MG) with different hydrocarbon chain lengths, and their ability to reduce starch swelling and solubility in excess water, was reported by Hoover and Hadziyev (1981).

Heating starch granules in an aqueous suspension causes them to swell and leach solubles into the surrounding aqueous phase. This produces a viscous paste. The change in consistency that takes place as a function of the temperature can be followed with the amylograph. The addition of a gum such as carboxymethyl cellulose (CMC) to provide a background viscosity allows the visualization of the two stages of starch swelling (Crossland and Favor 1948). Without the gum, the amylograph is not sensitive enough to show the first stage of swelling.

The first stage of swelling (≈60–75°C) is apparently the result of the granules swelling as they imbibe water (Schoch 1965, Collison 1968). The uptake of water is limited below the gelatinization temperature of the starch. The second stage of swelling (≈75–95°C) appears to be more complicated. In addition to the swelling of the granules, starch molecules start to solubilize. This exudate causes a large increase in consistency at higher temperatures (Miller et al 1973). Ghiasi et al (1982b) showed that, to achieve a maximum consistency, both the solubles and the remnants of the granules were necessary.

Fatty compounds, such as monoglycerides (MG), can reduce the swelling and solubility of starch (Lord 1950, Leach et al 1959, Gray and Schoch 1962). Ghiasi et al (1982a) showed that sodium stearoyl lactylate (SSL) and monoglycerides (MG) inhibited swelling and solubility of wheat starch at temperatures <85°C. At higher temperatures, SSL did not affect solubility, but MG did. In the amylograph, Ghiasi et al (1982b) reported that SSL and MG reduced the first-stage viscosity and delayed the second stage to a higher temperature. Wheat starch solubility at 95°C was inhibited by monoglycerides but not by SSL; however, both surfactants equally affected amylograph viscosity. Thus, amylograph viscosity does not depend entirely on starch solubility.

The effect of natural surfactants, polar and nonpolar wheat flour lipids, on the amylograph properties of wheat starch was reported by Medcalf et al (1968). They found that polar lipids reduced viscosity at both stages of the pasting curve. The nonpolar lipids had relatively little effect.

Christianson et al (1981) studied the effect of a number of gums (guar, xanthan, and carboxy methylcellulose) on the amylograph curve. They concluded that the early onset of the initial viscosity was attributable to the first stage of swelling and was dependent on media viscosity only. They also concluded that further development of paste viscosity was attributable to interactions of solubilized starch, gums, and swollen starch granules.

The objective of this study was to examine the effect of various lipids on the swelling, solubility, morphology, and amylograph consistency of starch in an excess water system.

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MATERIALS AND METHODS

Materials

An unmodified wheat starch (Midsol 50, donated by Midwest Grain Products, Inc., Atchison, KS) and an unmodified corn starch (Amaizo PFP starch donated by American Maize Products) were used. Commercially available lipids and surfactants examined included a hydrated monoglyceride (HMG) (Panatex, ≈20% monoglyceride (donated by ADM Arkady, Olathe, KS); sodium stearoyl lactylate (SSL) (Emplex, American Ingredients Co., Kansas City, KS); sodium dodecyl sulfate (SDS) (Fisher Scientific, Pittsburgh, PA); and hexadecyltrimethylammonium bromide (CTAB) (Fisher Scientific, Pittsburgh, PA). Additional lipids were donated by Grünau (Illertissen, Germany). These lipids included monoglyceride samples with hydrocarbon chains of 10 carbons (C_{10}MG), 18 carbons (C_{18}MG), and monounsaturated 18 carbons (C_{18}'MG). Sodium carboxymethylcellulose (CMC) (7HF, Aqualon Co., Wilmington, DE) was used to create a background consistency.

Methods

Hydration of monoglycerides. Small particles of the solid C_{18}MG were produced by scraping a large sample with a metal spatula. The C_{18}'MG was not as hard at room temperature and scraping produced shavings. An MG (2.0 ± 0.001 g) was combined with 20 ml of distilled water at room temperature. The lipid-water system for MG was heated in a 75°C water bath for 10 min. Samples were swirled by hand frequently during heating. After removal from the bath, the sample was swirled frequently during cooling to room temperature.

Consistency, Viskograph-E. The Viskograph-E (Brabender, Hackensack, NJ) was used to examine consistency changes. CMC, when used in the system, was included to create a background consistency so that both first- and second-stage increases in consistency could be seen. When the gum was not present, the first-stage increase in consistency was not distinct. A concentrated buffer was prepared according to method 22-10 (AACC 1983). Portions (35 ml) of the concentrated buffer were diluted to 460 ml for each treatment. For tests containing CMC, ≈350 ml of the dilute buffer was placed in a Waring Blendor (Dynamics Corporation of America, New Hartford, CT). The CMC (1.15, 2.30, 4.60 ± 0.01 g) was added as the blender speed was increased from 30 to 50% of low speed with a variable transformer for ≈15 sec. The starch (25 ± 0.1 g), together with any surfactant, was added to the dispersion and blended at 30% of low speed for 5 sec. At higher CMC concentrations, it was necessary to use a higher percentage of low speed. The slurry was transferred to the Viskograph-E bowl. A rubber spatula and 70 ml of the remaining buffer were used to wash the container. The remainder of the dilute buffer was used for a final rinse of the container. The temperature of the starch slurry was stabilized to 30 or 40°C, then heated at 1.5°C/min.

Differential scanning calorimetry (DSC). The presence of a phase transition for C_{18}MG and Panatex (HMG) was examined by DSC (Perkin-Elmer DSC-2, Norwalk, CT). An FTS Systems Flexi-cooler and temperature controller (FTS Systems, Inc., Stone Ridge, NY) were connected to the calorimeter. Indium was used for calibration of the calorimeter, and data were analyzed with DARES (Data Acquisition, Retention and Examination System for DSC, V.1.4, Industrial Technology Research Institute, Cambridge, UK). Analysis was performed on 1–2 mg samples in sealed aluminum pans at a heating rate of 10°C/min.

Starch swelling and solubility. A rotary evaporator was used to maintain the starch suspended in the excess water system during heating. The bath was preheated to and maintained at temperatures to obtain the desired starch dispersion temperatures (50, 60, 70, 80, 90, or 95 ± 0.2°C) by an immersion circulator (Isotemp

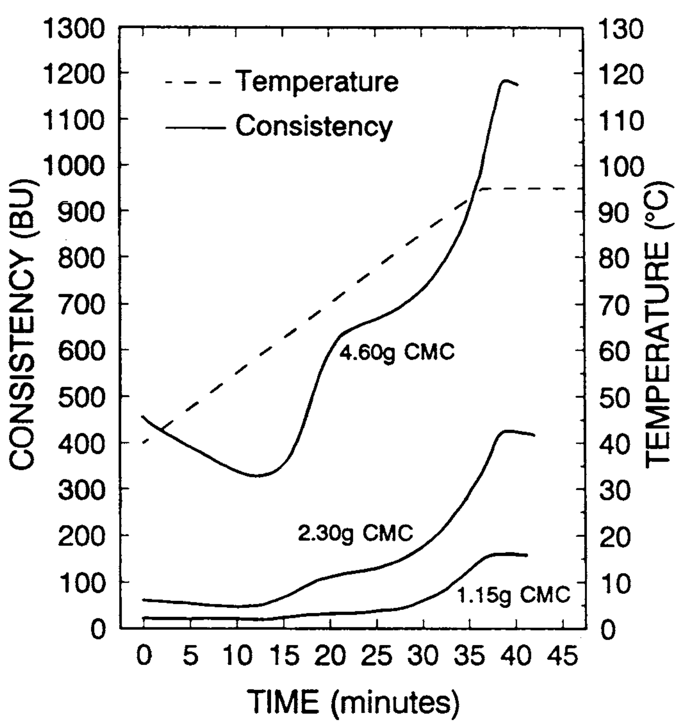


Fig. 1. Effect of certain carboxymethylcellulose (CMC) levels with 25 g of wheat starch on Viskograph-E consistency curve.

TABLE I
Effect of Carboxymethyl Cellulose (CMC) on Starch Suspension Consistency[a]

CMC (g)	Consistency at 96°C (BU) Starch + CMC	CMC	Calculated Consistency of Starch Alone
1.15	175	0	175
2.30	422	8	414
4.60	1,175	80	1,095

[a] Suspension contained 25 g of starch and 460 ml of diluted buffer.

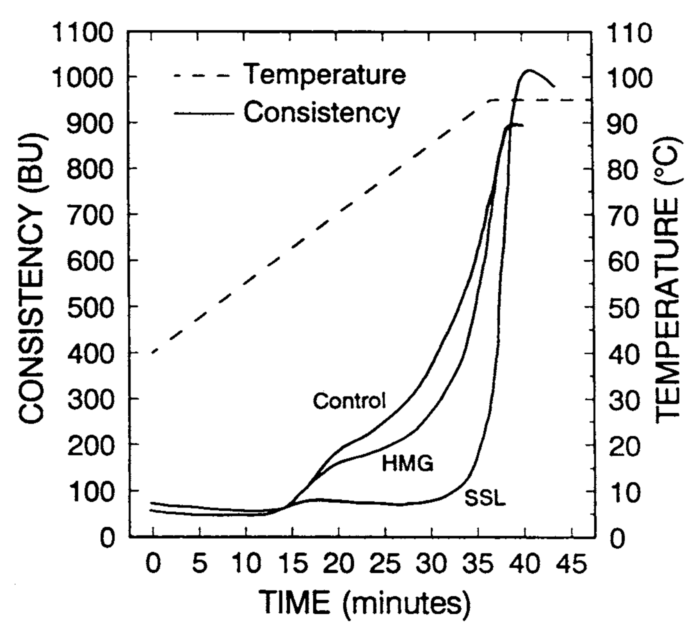


Fig. 2. Effect of a hydrated monoglyceride (HMG) and sodium stearoyl lactylate (SSL) on wheat starch paste consistency. Control contained starch and dilute buffer.

model 730, Fisher Scientific, Pittsburgh, PA). The required bath temperature was 1.5 to 2.0°C higher than the desired dispersion temperature. Starch (generally 25 g) was weighed, then transferred to a 50-ml round-bottom flask. Distilled water was added to obtain a starch concentration of 2% (w/w) dry solids. Surfactants were added at the same time as the starch. The flask was swirled to momentarily disperse the starch in the water, then attached to a rotary evaporator (Büchi Rotavapor R110, Flawil, Switzerland) by a plastic clasp. No vacuum was used. The rotary evaporator was turned on immediately after the flask was attached, then positioned so the contents of the flask were submerged in the bath. The rotating action (≈60 rpm) of the evaporator kept the starch and water mixed with minimum shearing. The flask was held in the bath for 10 min. A 40-ml centrifuge tube was weighed and tared. The flask then was removed from bath, and the sample was poured into the centrifuge tube. The net weight (±0.01 g) of the recovered sample was recorded. The sample was centrifuged at 2,000 × *g* for 10 min.

An aliquot of the supernatant was removed to determine soluble starch. The remaining supernatant was decanted and discarded. The centrifuge tube, along with the precipitate (gel), was weighed (±0.01 g). The percent swelling was based on the weight of the precipitate and of the sample. All determinations were made at least in triplicate.

The phenol-sulfuric acid method (Dubois et al 1956) was used to determine total carbohydrates in the recovered supernatant and, thus, estimate soluble starch. The percent soluble starch was corrected for dilutions and the original weight of the starch. Glucose was used as a standard and each sample was determined a minimum of three times. Photomicrographs were taken with an Olympus OM-2 35-mm camera mounted on an Olympus microscope.

Statistics

The General Linear Model procedure of the Statistical Analysis System (SAS Institute 1985) was used for data analysis. All means were calculated from at least two replicates. Fisher's least significant difference procedure at the 5% significance level was used to compare means.

RESULTS AND DISCUSSION

Effect of CMC on Viskograph-E Consistency

The effect of CMC concentration on consistency was found not to be a simple additive relationship. Doubling the amount of gum from 2.3 to 4.6 g caused the consistency to more than double from 8 to 80 BU at 95°C. Various levels of CMC then were combined with 25 g of wheat starch (≈5.15% of the total system) and 460 ml of diluted buffer (Fig. 1). As with CMC alone, the increase in consistency at any given temperature was proportionally greater than the increase in CMC content, i.e., doubling the CMC concentration more than doubled the consistency. Further, the difference in the consistency of the starch + CMC could not simply be eliminated by subtracting the CMC consistency (Table I).

The effect of starch concentration on consistency was also found to be a nonlinear relationship. For example, a paste with 25 g of wheat starch and 460 ml of buffer gave a peak consistency of 20 BU, and one with 60 g of starch gave a peak consistency of 1,430 BU. The change in consistency per gram of starch appeared to be independent of whether starch or CMC produced the base consistency.

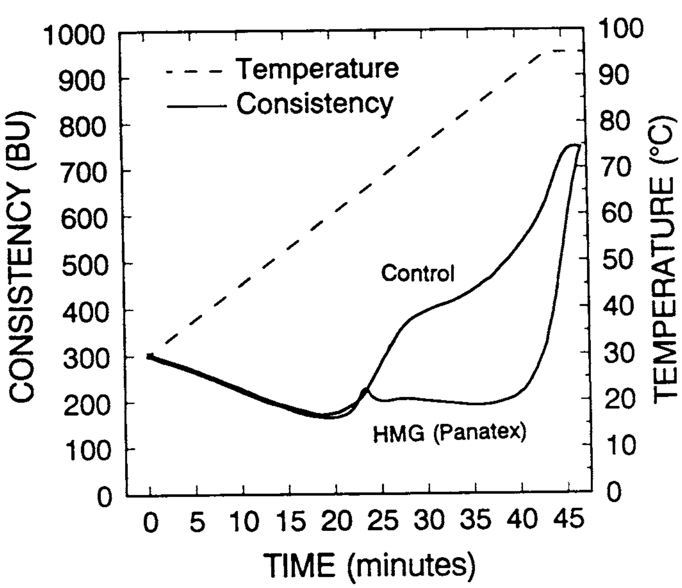


Fig. 3. Viskograph consistency curve of wheat starch with a hydrated monoglyceride (HMG). Control contained starch and dilute buffer.

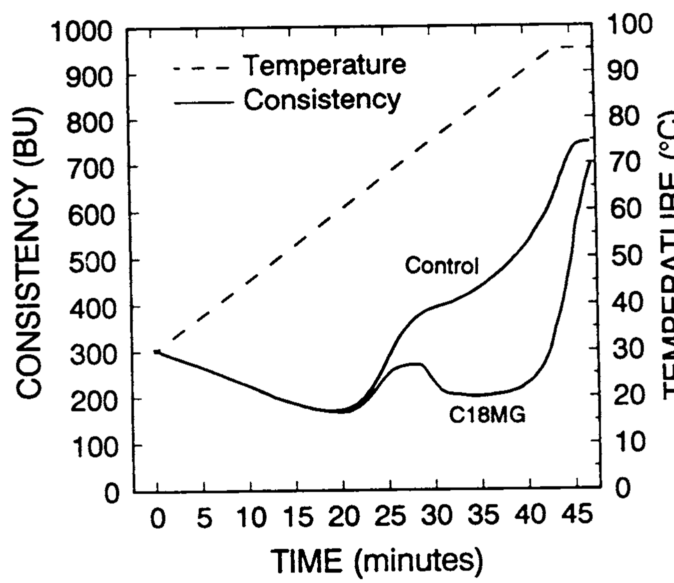


Fig. 4. Viskograph consistency curve of wheat starch monoglyceride samples with 18 carbons (C_{18}MG). Control contained starch and dilute buffer.

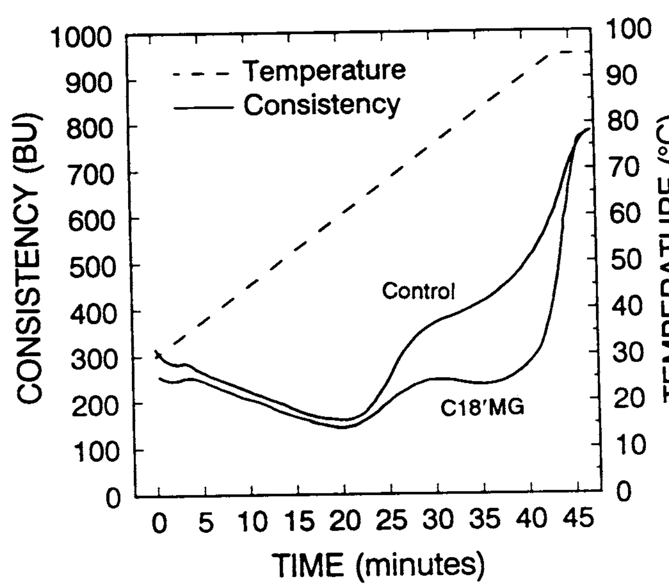


Fig. 5. Viskograph consistency curve of wheat starch monoglyceride samples with monounsaturated 18 carbons (C_{18}'MG). Control contained starch and dilute buffer.

In summary, the consistency of the starch in a starch + CMC system at a given temperature cannot be determined by simply subtracting a predetermined consistency value of the gum from the consistency found for both the CMC and starch.

Effect of Lipids on Starch Slurry Consistency with Viskograph-E

Effect of HMG or SSL on wheat starch slurry consistency. A commercial hydrated monoglyceride (HMG, 3.5 g of which provides about 0.7 g or 2% monoglyceride based on starch) affected consistency of a wheat starch slurry (35 g of starch + 2.3 g of CMC + 460 ml of buffer). The consistency reached during the first-stage swelling was lower when HMG was present. The onset of the first-stage increase in consistency was similar to that of the control. However, the increase in the second stage consistency appeared to be slightly delayed.

The effect of SSL (0.7 g) on first-stage swelling was much more pronounced than that of HMG (Fig. 2). The onset temperature of first-stage swelling did not appear to be affected by SSL, but the maximum consistency reached during this period was reduced. Further, the onset of the second stage was at a higher temperature when SSL was included. Finally, the maximum consistency reached during the second-stage swelling was greater than that of the control or treatment containing HMG, providing the system was held at the higher temperature for some time (Fig. 2). These results are similar to those of Ghiasi et al (1982b).

Discontinuity in consistency curve with certain MG. The consistency curve of a sample containing the HMG (3.5 g or ≈2% MG) with 25 g of wheat starch and 4.6 g of CMC had a discontinuity (Fig. 3). This discontinuity had not been seen with the same sample at lower levels of CMC (Fig. 2). The peak of the discontinuity occurred at ≈63°C. A small discontinuity in the consistency curve occurred even when HMG was present only with CMC (data not shown). This strongly suggests that the starch is not responsible for the event. Further, the discontinuity in consistency did not occur when CMC or starch alone was present. These results support the suggestion that the discontinuity in the curve involved the emulsifier. However, HMG (3.5 g) gave no discontinuity with low levels of starch (25 g) and no CMC (data not shown). Thus, a certain background consistency apparently is necessary to see the phenomenon.

Differential scanning calorimetry (DSC) showed a phase transition for HMG at ≈59°C. This is only slightly lower than the temperature at which the discontinuity occurred.

C_{18}MG reduced consistency during the first-stage swelling in a manner similar to HMG. A discontinuity also was found with C_{18}MG (Fig. 4), and it was much larger than that found with HMG. The peak of the discontinuity occurred at ≈72–73°C, 9–10°C higher than for HMG (63°C). The C_{18}MG melted at ≈68°C in the DSC, ≈9°C higher than the HMG. This temperature difference in melting between the two monoglycerides was similar to the temperature difference of the discontinuities in the consistency curve. The phase change at a higher temperature for the C_{18}MG could delay its effect on consistency to a higher temperature. After the discontinuity, the consistency was depressed further.

C_{18}'MG (hydrated, 6.1 or 0.555 g of MG or 2% starch), when used with 27.74 g of starch and 4.6 g of CMC, did not show a discontinuity in the consistency curve as did the C_{18}MG (Fig. 5). However, the C_{18}'MG reduced increases of the first- and second-stage consistencies below those of the control. Possibly, the C_{18}'MG did not go through a phase change or went through it earlier. The melting point of the C_{18}'MG was 33.5°C. In summary, the HMG and C_{18}MG appeared to go through phase changes that resulted in changes in the consistency.

Effect of HMG and SSL on corn starch slurry consistency. The effects of HMG (3.5 g) and SSL (0.7 g) on consistency of a corn starch slurry (35 g of starch + 2.3 g of CMC + 460 ml of buffer) were similar to the effects on wheat starch (Fig. 6). Compared to a control corn starch-CMC treatment, HMG reduced the first-stage consistency. SSL was more effective than HMG in reducing the consistency. Maximum consistency during the second-stage increase for the SSL treatment required that the system be held at 95°C for a longer period of time than for the HMG treatment. This was similar to the findings for wheat starch.

Effect of CTAB and SDS on consistency. Hexadecyltrimethylammonium bromide (CTAB, 0.7 g) reduced the consistency of a wheat starch slurry (35 g of starch + 2.3 g of CMC + 460 ml of buffer) during the first-stage swelling (Fig. 7) more than HMG,

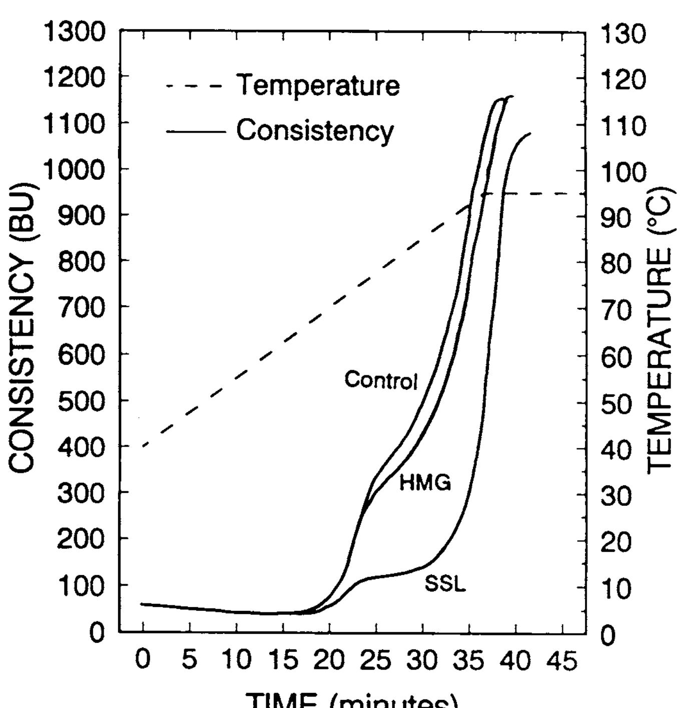


Fig. 6. Effect of a hydrated monoglyceride (HMG) and sodium stearoyl lactylate (SSL) on corn starch paste consistency. Control contained starch and dilute buffer.

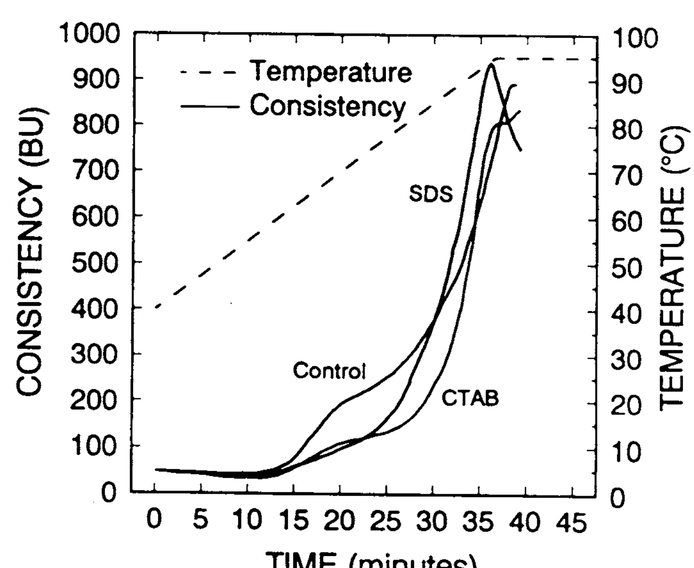


Fig. 7. Effect of sodium dodecyl sulfate (SDS) and hexadecyltrimethylammonium bromide (CTAB) on wheat starch paste consistency. Control contained starch and dilute buffer.

but less than SSL (Fig. 2). The onset temperature of the second stage was increased relative to the control. The maximum consistency appeared to be reached at a lower temperature when CTAB was present compared to the control. The maximum consistency remained stable as temperature increased.

SDS (0.7 g) reduced the rate of initial swelling of a wheat starch slurry (35 g of starch + 2.3 g of CMC + 460 ml of buffer) during the first stage, but swelling increased throughout this stage (Fig. 7). No plateau period occurred during the first stage as was found for the control. The point at which second-stage swelling began was more distinct for the treatment containing SDS than the control. The maximum consistency reached during the second-stage swelling for SDS was higher than that of the control, but occurred at a lower temperature (≈92.5°C). The consistency of the SDS system then dropped rapidly as the temperature approached 95°C.

Starch Swelling, Effect of Monoglycerides

The rotary evaporator maintained a low level of shear, while adequately suspending starch in water for uniform heating (Evans and Haisman 1979, Hansen et al 1990). In general, the presence of MG limited the swelling or water binding capacity of starch. However, the extent of swelling at each temperature differed for each MG (Fig. 8).

Starch swelling occurred in two stages (Fig. 8). These stages are similar to those reported by others (Crossland and Favor 1948, Gray and Schoch 1962, Miller et al 1973). This two-stage pattern was evident in the control system (starch and water with no added lipids) or when any MG was present.

All MG tested had no measurable effect at 50°C, but limited swelling occurred from 60 to 80°C (Fig. 8). Photomicrographs show the inhibition of swelling at 70°C for the C_{10}, C_{18}, and C_{18}'MG (Fig. 9). At 90°C, C_{10}MG increased starch swelling, whereas the MG that did not contain C_{10}MG reduced starch swelling. The gels from samples treated with C_{10}MG had a white layer on top. Examination of this layer by light microscopy showed no starch granules. The layer was obviously denser than the supernatant (soluble starch plus water) because it sedimented. Therefore, it must have been composed of more than just lipid and water. If it were just lipid, it would have floated on the supernatant. However, the layer was less dense than the gelatinized starch, because it was found on top of the granules. It was hy-

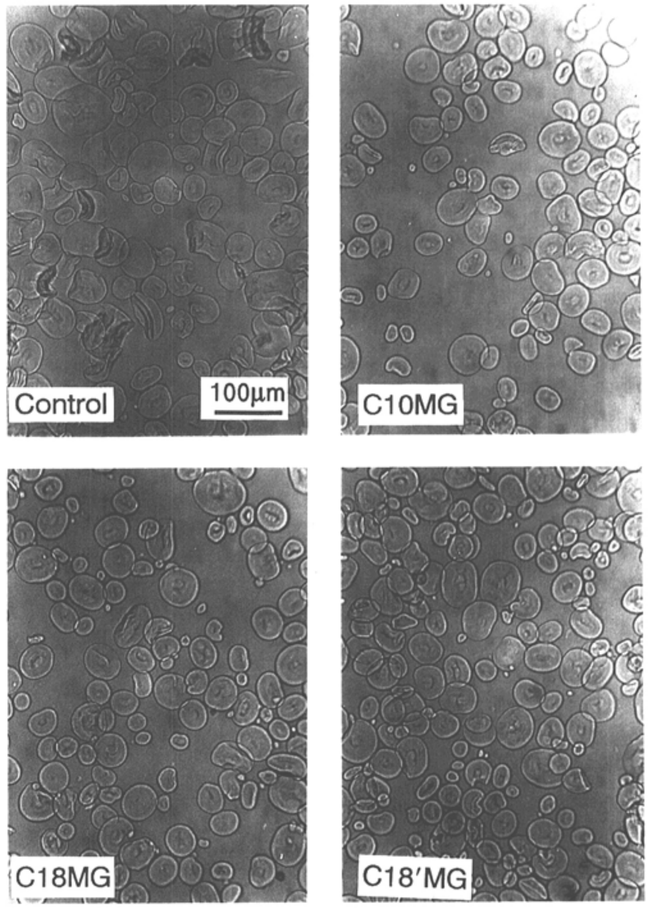


Fig. 9. Photomicrographs of wheat starch heated to 70°C. C_{10}MG, C_{18}MG, and C_{18}′MG = monoglyceride samples with hydrocarbon chains of 10, 18, and monounsaturated 18 carbons, respectively.

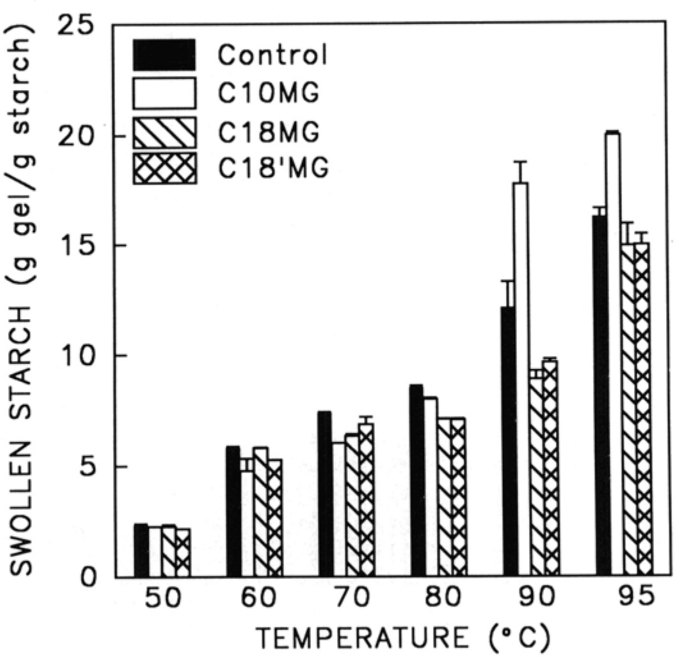


Fig. 8. Effect of various monoglycerides (MG) on the swelling of wheat starch in excess water. Control contained starch and distilled water. C_{10}MG, C_{18}MG, and C_{18}′MG = monoglyceride samples with hydrocarbon chains of 10, 18, and monounsaturated 18 carbons, respectively.

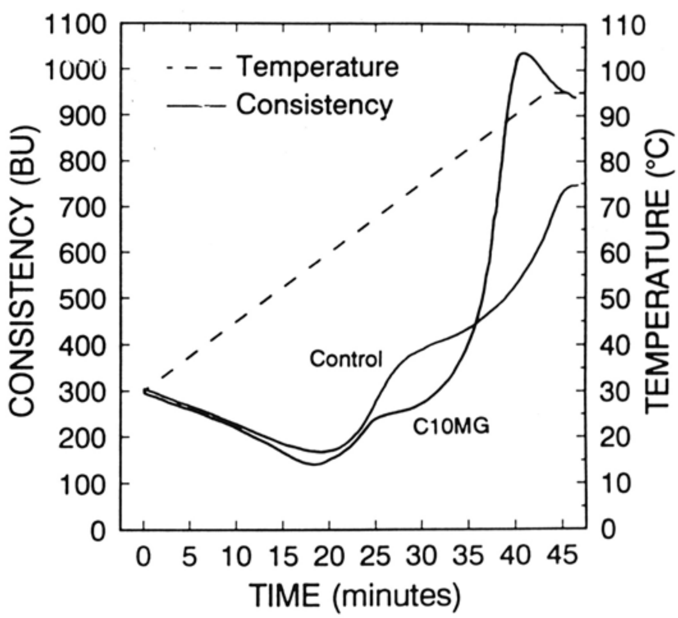
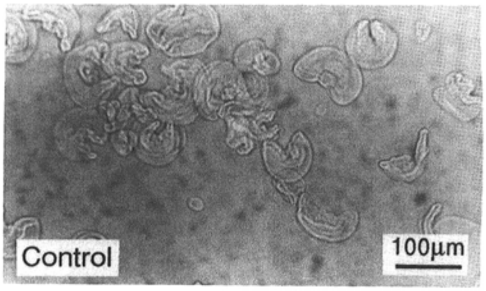
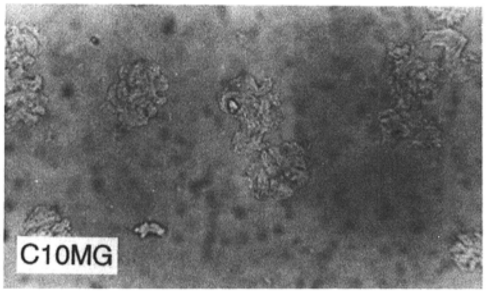


Fig. 10. Effect of monoglyceride samples with hydrocarbon chains of 10 carbons (C_{10}MG) on wheat starch slurry consistency.





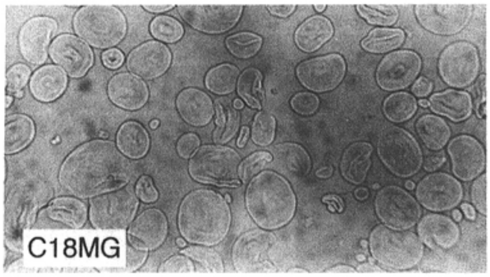


Fig. 11. Photomicrograph of wheat starch heated to 90°C. C_{10}MG and C_{18}MG = monoglyceride samples with hydrocarbon chains of 10 and 18 carbons, respectively.

pothesized that the white layer was C_{10}MG complexed with solubilized starch. The layer was not soluble in methanol or chloroform, which supported the supposition that it was not purely lipid. Adding butanol to the material caused a precipitation. Presumably, the butanol preferentially complexed with the starch at the expense of the existing starch-lipid (C_{10}MG) complex. These results support the hypothesis that the white layer found at the top of the gel after centrifugation contained the C_{10}MG complexed with starch.

The method used to determine swelling of starch actually measures the water-binding capacity of all solids in the system. If the C_{10}MG and soluble starch complex formed a gel with water and sedimented along with swollen starch, it would become part of the weight of the pellet. Thus, the effect of the C_{10}MG on starch swelling could not be differentiated from the gel-forming ability of the starch and C_{10}MG complex, because the two were measured together.

At 95°C, the C_{10}MG treatments showed greater swelling than did the control. Other MG treatments only slightly reduced swelling at this temperature as compared to 85°C, where the effects (differences) were more dramatic. The complex-forming ability of the C_{18} and C_{18}'MG may become impaired or altered at higher temperatures.

Hoover and Hadziyev (1981) reported that monocaprin (C_{10}MG) had less of an effect on swelling and other properties than other MG. This could not be confirmed by the methods used here. Consistency measurements supported the findings that C_{10}MG reduced swelling at temperatures below 85°C, but increased swelling above this temperature (Fig. 10). Photomicrographs (Fig. 9) also showed inhibited swelling at 70°C and increased swelling at 90°C (Fig. 11).

TABLE II
Effect of Sodium Stearoyl Lactylate (SSL) on the Swelling and Solubility of Wheat Starch[a]

	Starch Treatment	
	90°C	95°C
Swelling[b]		
Control	12.49 a	16.12 a
SSL	10.01 b	15.59 a
Solubility[c]		
Control	15.41 c	31.24 d
SSL	12.66 c	35.36 c

[a] Values followed by the same letter within a column were not statistically different at the 5% level.
[b] Measured as grams of gel per grams of original starch.
[c] % of original starch.

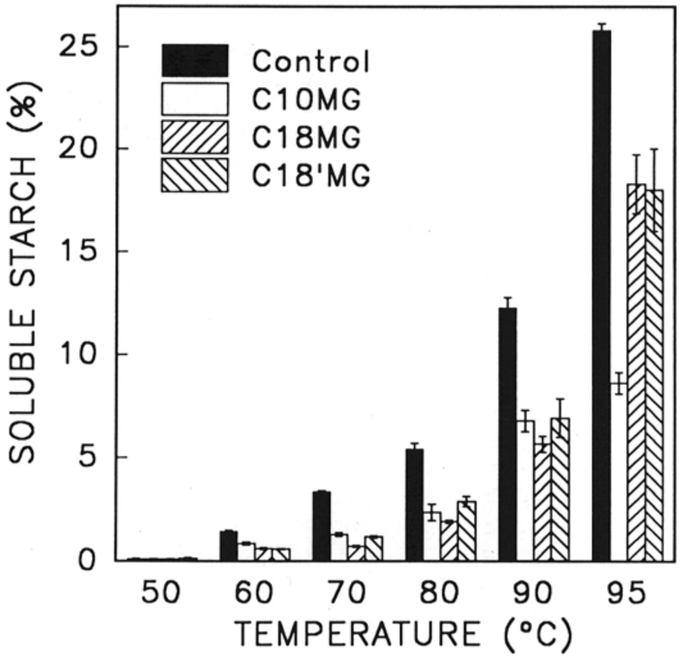


Fig. 12. Effect of various monoglycerides (MG) on wheat starch solubility in excess water. Control contained starch and distilled water. C_{10}MG, C_{18}MG, and C_{18}'MG = monoglyceride samples with hydrocarbon chains of 10, 18, and monounsaturated 18 carbons, respectively.

Starch Swelling, Effect of Triglycerides

Starch swelled in two stages, both alone and in the presence of 2% TG. Overall, the TG had little effect on swelling at any of the temperatures tested (data not shown). However, at 95°C, starch in the presence of C_{10}TG appeared to swell slightly more than starch alone.

Starch Swelling, Effect of SSL

SSL limited the swelling of starch at 90°C (Table II). The effect differed little from that of MG. At 95°C, SSL had no significant effect on starch swelling.

Soluble Starch, Effect of Monoglycerides

In general, the certain MG reduced starch solubility (Fig. 12) relative to the control. At 70, 80, and 90°C, C_{18}MG reduced solubility more than C_{10} or C_{18}'MG. The ability of C_{18}MG to reduce soluble starch more than C_{10}MG agrees with the findings of Hoover and Hadziyev (1981). Lagendijk and Pennings (1970) reported that C_{18}MG complexed with starch better than C_{18}'MG. This may have been responsible for the lower soluble starch value.

At 95°C, C_{10}MG reduced soluble starch to a much larger extent than the other MG. This may have been because, at an equal weight, C_{10}MG had more molecules present to complex with the soluble starch than did C_{18}MG. However, this does not explain why the effect of C_{18}MG was greater than that of C_{10}MG at lower temperatures.

Soluble Starch in Excess Water, Effect of Triglycerides

The solubility of starch with or without TG showed a slow increase from 50 to 80°C, followed by a more rapid rise from 80 to 95°C (data not shown). C_{10}TG was the only TG that had a significant effect on soluble starch and then only at 95°C.

Starch Solubility, Effect of SSL

The effect of SSL on starch solubility also was examined in excess water systems heated to 90 and 95°C (Table II). Relative to the control, this emulsifier did not affect starch solubility at 90°C. However, at 95°C, solubility was increased.

CONCLUSION

In general, MG, SSL, CTAB, and SDS limited first-stage swelling of wheat starch compared to the control. However, the surfactants had different effects on the second-stage increase, maximum consistency, the temperature at which it was reached, and the time necessary to achieve maximum consistency at the maximum temperature. PMG, HMG, C_{18}MG, C_{18}'MG, SSL, and CTAB reduced consistency through most of the second stage. However, SDS increased consistency relative to the control ≥84°C. Compared to the control, MG had little effect on the maximum consistency, which occurred at ≈95°C. Conversely, CTAB reduced maximum consistency and caused it to occur at a lower temperature. SSL increased the maximum consistency and caused it to occur after 2 min at 95°C. Likewise, SDS increased maximum consistency but caused it to occur at a lower temperature than in the control. The HMG and C_{18}MG went through apparent phase changes, which caused discontinuities to appear when higher concentrations of CMC were used. The phase changes appeared to enhance the interaction between starch and the MG.

Previous work (Rogers et al 1988, Martin et al 1991) had shown that TG had a strong antifirming effect. The suggested mechanism was that TG reduced swelling or solubility of the starch. The results reported here do not support that mechanism. Some other mechanism appears to be responsible for the antifirming effect of TG in bread crumb.

The effect of C_{10}MG on swelling and solubility of starch demonstrated that the mechanism that controls swelling may be different than the mechanism that controls solubility. This conclusion is supported by the effects of the other MG, C_{18}, and C_{18}', which had no effect on swelling at 95°C, but both restricted solubility.

Starch Swelling, Effect of Lipids

Starch swelling occured in two stages. This suggests that starch swelling is a contributing factor to the appearance of the two stages of consistency increase found with the Viskograph-E.

In general, MG limited the swelling of wheat starch at temperatures >60°C. However, the extent of the effect differed with the MG being tested. The effect of C10MG on swelling >80°C could not be determined accurately by the procedure used, because it apparently formed a complex with starch. Microscopic examination provided a direct method to confirm the effects of C_{10}, C_{18}, and C_{18}'MG on the swelling of starch. Overall, TG did not have a significant effect on the swelling of starch. SSL reduced starch swelling at 90°C, but had no effect at 95°C.

Starch Solubility, Effects of Lipids

Starch solubility was *not* found to increase in two stages as was swelling. This suggested that the swelling of starch contributed more significantly to the presence of two stages of consistency increase than did solubility.

Monoglycerides decreased starch solubility at temperatures >50°C. This included C_{10}MG at 90 and 95°C, which increased swelling at these same temperatures. In general, TG did not affect starch solubility.

LITERATURE CITED

AMERICAN ASSOCIATION OF CEREAL CHEMISTS. 1983. Approved Methods of the AACC. Method 22-10, approved May 1960. The Association. St Paul, MN.

CHRISTIANSON, D. D., HODGE, J. E., OSBORNE, D., and DETROY, R. W. 1981. Gelatinization of wheat starch as modified by xanthan gum, guar gum, and cellulose gum. Cereal Chem. 58:513-516.

COLLISON, R. 1968. Swelling and gelation of starch. Page 168 in: Starch and Its Derivates. J. A. Radley, ed. Chapman and Hall: London.

CROSSLAND, L. B., and FAVOR, H. H. 1948. Starch gelatinization studies. II. A method for showing the stages in swelling of starch during heating in the amylograph. Cereal Chem. 25:215-220.

DERBY, R. I., MILLER, B. S., MILLER, B. F., and TRIMBO, H. B. 1975. Visual observation of wheat-starch gelatinization in limited water systems. Cereal Chem. 52:702-713.

DUBOIS, M., GILLES, K. A., HAMILTON, J. K., REBERS, P. A., and SMITH, F. 1956. Colormetric method for determination of sugars and related substances. Anal. Chem. 28:350-356.

ELIASSON, A.-C. 1986. Viscoelastic behaviour during the gelatinization of starch. II. Effects of emulsifiers. J. Texture Stud. 17:357-375.

EVANS, I. D., and HAISMAN, D. R. 1979. Rheology of gelatinized starch suspensions. J. Texture Stud. 10:347-370.

GHIASI, K., HOSENEY, R. C., and VARRIANO-MARSTON, E. 1982a. Gelatinization of wheat starch. I. Excess-water systems. Cereal Chem. 59:81-85.

GHIASI, K., HOSENEY, R. C., and VARRIANO-MARSTON, E. 1982b. Gelatinization of wheat starch. IV. Amylograph viscosity. Cereal Chem. 59:262-265.

GRAY, V. M., and SCHOCH, T. J. 1962. Effects of surfactants and fatty adjuncts on the swelling and solubilization of granular starches. Staerke 14:239-246.

HANSEN, L. M., HOSENEY, R. C., and FAUBION, J. M. 1990. Oscillatory probe rheometry as a tool for determining the rheological properties of starch-water systems. J. Texture Stud. 21:213-224.

HARBITZ, O. 1983. Gel formation of potato starch in the presence of a surfactant. Starch/Staerke 35:198-202.

HOOVER, R., and HADZIYEV, E. 1981. Characterization of potato starch and its monoglyceride complexes. Starch/Staerke 33:290-300.

HOSENEY, R. C. 1986. Principles of Cereal Science and Technology. Am. Assoc. Cereal Chem.: St. Paul, MN.

LAGENDIJK, J., and PENNINGS, H. J. 1970. Relation between complex formation of starch with monoglycerides and the firmness of bread. Cereal Sci. Today 15:354-365.

LEACH, H. W., McCOWEN, L. D., and SHOCH, T. J. 1959. Structure of the starch granule. I. Swelling and solubility patterns of various starches. Cereal Chem. 36:534-544.

LORD, D. D. 1950. The action of polyethylene monostearate upon starch with reference to its softening action in bread. J. Colloid Sci. 5:360- 375.

MARTIN, M. L., ZELEZNAK, K. J., and HOSENEY, R. C. 1991. A mechanism of bread firming. I. Role of starch swelling. Cereal Chem. 68:498-503.

MEDCALF, D. G., YOUNGS, V. L., and GILLES, K. A. 1968. Wheat starches. II. Effect of polar and nonpolar lipid fractions on pasting characteristics. Cereal Chem. 45:88-95.

MILLER, B. S., DERBY, R. I., and TRIMBO, H. S. 1973. A pictorial explanation for the increase in viscosity of a heated wheat starch-water suspension. Cereal Chem. 50:271-280.

MOORTHY, S. N. 1985. Effect of different types of surfactants on cassava starch properties. J. Agric. Food Chem. 33:1227-1232.

OSMAN, E. M., and DIX, M. R. 1960. Effects of fats and nonionic surface-active agents on starch pastes. Cereal Chem. 37:464-475.

OSMAN, E. M., LEITH, S. J., and FLEŠ, M. 1961. Complexes of amylose with surfactants. Cereal Chem. 38:449-463.

ROGERS, D. E., ZELEZNAK, K. J., LAI, C. S., and HOSENEY, R. C. 1988. Effect of native lipids, shortening, and bread moisture on bread firming. Cereal Chem. 65:398-401.

SCHOCH, T. J. 1965. Starch in bakery products. Baker's Dig. 39(2):48-52, 54-57.

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