Dynamic Rheological Properties of Bread Crumb. II. Effects of Surfactants and Reheating[1]

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ABSTRACT

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Dynamic testing detected differences in the rheological properties of bread crumb that had been heated to 80°C by conventional or microwave ovens. Both G' and loss tangent of crumbs aged up to 120 hr and heated in a conventional oven were reduced to fresh bread values. Microwave heating did not fully reverse age-related changes in G', and the extent of reversal decreased as the age of the crumb at heating increased. The viscous component, G'', and therefore the tangent, increased to levels higher than those of freshly baked bread. Further, as the microwave exposure time increased, the tangent continued to increase. This effect was not attributable to a higher amount of moisture loss than that occurring during conventional heating. During storage, G' of the bread crumb containing the surfactants sodium stearoyl lactylate and hydrated monoglyceride did not reflect the change in firmness measured by empirical, static compression tests. The loss tangent of the surfactant-treated crumb remained equal to that of freshly baked bread throughout the aging period. This indicated that the empirically measured firmness was a composite of both the elastic and viscous properties of the material. Without shortening in the formula, G' of the crumb increased at a greater rate and to a greater extent than with shortening. It appears that the mechanism by which sodium stearoyl lactylate and hydrated monoglyceride reduce firmness is not the same as that by which shortening reduces it.

When stale bread is heated, it will recover its softness provided it has lost no moisture. At the same time, fresh bread aroma and flavor reappear (Kulp 1979). Either conventional oven or microwave reheating may be used for refreshing bread. However, microwave heating is known to produce crumb that is tough and rubbery if exposure to radiation lasts too long (Rosenberg and Bogl 1987). In studies on the firming mechanism of bread crumb, both microwave (Kim and D'Appolonia 1977) and conventional oven (Ghiasi et al 1984) reheating of staled bread have been employed. Kim and D'Appolonia suggested that at 2°C only starch retrogradation was responsible for crumb firming, but at 31°C an additional mechanism was involved. Ghiasi et al (1984) showed that even though the temperature of the reheated loaf exceeded the 60°C required to melt retrograded amylopectin, reversal of firming was still occurring. They concluded that retrogradation was not the sole cause of crumb firming.

Rogers et al (1988a), who tested crumb with the Kramer shear cell and the Instron universal testing machine, detected not only a peak compression force but also a distinct shoulder when the crumb was reheated by microwave. The shoulder, which was interpreted as indicating a resistance to pulling or stretching (toughness) of the crumb, was absent when reheating in a conventional oven.

Starch retrogradation is considered to be responsible for the firming of bread crumb as it ages (Krog and Davis 1984). The softening effect of surfactants on the crumb has been explained as the result of formation of a starch-surfactant complex that retards retrogradation (Tamstorf et al 1986). However, Rogers et al (1988b) demonstrated that crumb with 22% moisture content had a higher firming rate but a lower degree of retrogradation than a crumb containing 31% moisture. Shortening that does not complex with starch (Rogers et al 1988b) was shown to reduce both the rate and extent of crumb firming (Platt and Powers 1940). When shortening was present at levels above 6%, the firmness-reducing effect plateaued (Carlin 1947). In the absence of native flour lipids, shortening did not retard crumb firmness, thus leading to the suggestion that its effect involves interaction with the native lipids (Rogers et al 1988b).

The preceding discussion points to uncertainty regarding the basis for bread crumb firming. Dynamic rheological testing has been used to describe the material properties of viscoelastic systems (Ferry 1980) and, thus, can measure both rate and direction of change in the crumb's viscous and elastic components. In this study, dynamic methods were used to examine and add to the understanding of the mechanisms by which reheating and surfactants affect the rheology of bread crumb.

MATERIALS AND METHODS

Descriptions of the theory and operation of the rheometer have been given previously (Faubion et al 1985, Dreese 1987), as have its adaptations for bread crumb measurements (Persaud et al 1990).

Bread for reheating studies was made by a straight-dough procedure with the basic formula described previously (Persaud et al 1990). Dynamic measurements were taken on a section from the middle slice in a plane perpendicular to the long axis and going from top to bottom of the loaf as described previously (Persaud et al 1990).

Refreshing

Conventional oven reheating was carried out using the procedure of Ghiasi et al (1984). A Thelco Precision Scientific

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oven with fan circulation, set at 105°C, was used. At this temperature, 49 min was required for the center of the loaf to attain a final temperature of 80°C. Loaves to be measured immediately were cooled at room temperature (25°C) for 30 min before slicing and testing. To examine the effects of storage after heating, each cooled loaf, in its Reynolds oven bag, was sealed in another polyethylene bag before being stored at 25°C until required.

A Sharp model R-9630 microwave oven operating at 2,450 MHz was used for microwave heating. Because it was not possible to heat an entire loaf uniformly, the crumb section to be measured was heated. Each crumb section was mounted on perforated paper to prevent moisture condensation during heating to 80°C. This temperature required a power level of 0.280–0.285 amps for 5 sec. Samples measured immediately after reheating were covered and allowed to stand for 5 min before measurement. During the time between slicing and reheating the crumb sections were kept in Ziploc polyethylene bags.

After microwave heating, the crumb section and the dish used for reheating were covered until tested. If the crumb was aged after heating, the sample was placed in a Ziploc bag for about 30 min, after which it was transferred to another dry Ziploc bag for extended storage. This bagged sample was then sealed in a second Ziploc bag and stored at 25°C.

To compare the effects of moisture loss from the crumb due to microwave heating versus air-drying, sections of 48-hr-old bread crumb (middle slice) were microwave-heated for 4, 6, 8, and 10 sec at 0.283 amps and their moisture loss determined by AACC method 44-15A (AACC 1983). Moisture loss because of microwave heating was expressed either as a percentage of the original sample weight or as a percentage of the moisture content in the sample before microwaving. A duplicate set of samples was air-dried (30°C) to equivalent moisture losses.

Surfactants

Two commercially available surfactants were used, each at two concentrations (Table I). Emulsilac SK sodium stearoyl lactylate (SSL) was from US Emulsifier Inc., and GMS 90 hydrated monoglyceride (MGH) (21% α-monoglyceride) was from Breddo Inc. (Kansas City, MO). Control was the bread made with the basic formula containing 3% Kraft Richtex all-purpose vegetable shortening. No-shortening loaves were made with the basic formula minus the 3.0% shortening. The treated loaves were made with the basic formula plus the surfactants added at the concentrations shown in Table I.

Crumb firming in slices from surfactant-containing, control, and no-shortening loaves was tested by a static compression test with a Voland-Stevens LFRA texture analyzer (Voland Corp., Hawthorne, NY). Firmness values (grams) were obtained at a compression depth of 4.00 mm and rate of 2.00 mm/sec. All slices were 27.5–28.5 mm thick. Slices were compressed along two planes: in the center of a cross-sectional slice parallel to the long axis and in the center of a horizontal slice perpendicular to the long axis.

Dynamic Testing

Testing was done in simple shear at an oscillation frequency of 5 Hz. The results are presented as plots of log *G'* (plot A in the figures) or loss tangent (plot B) versus peak-to-peak strain or age of crumb at 0.2% strain. Each point is the mean of at least three independent determinations and 95% confidence interval error bars are indicated.

TABLE I
Surfactant Treatment Levels

Treatment[a]	Surfactant (% flour wt) Level 1	Surfactant (% flour wt) Level 2	Shortening (% flour wt)
SSL	0.375	0.5	3.0
MGH	1.0	2.4	3.0
SSL + MGH	0.375 + 1.0	0.5 + 2.4	3.0
Control	0	0	3.0
No shortening	no test	0	0

[a] SSL = Sodium stearoyl lactylate, MGH = hydrated monoglyceride.

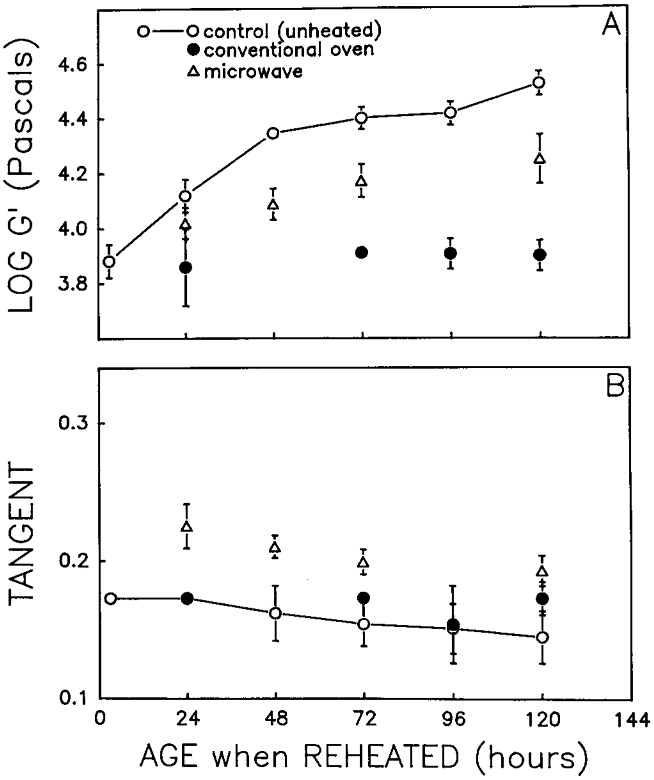

Fig. 1. Comparison of the effects of heating bread crumb aged up to 120 hr. Crumb sections were heated to 80°C and measurements (0.2% strain) were taken within 1 hr of heating.

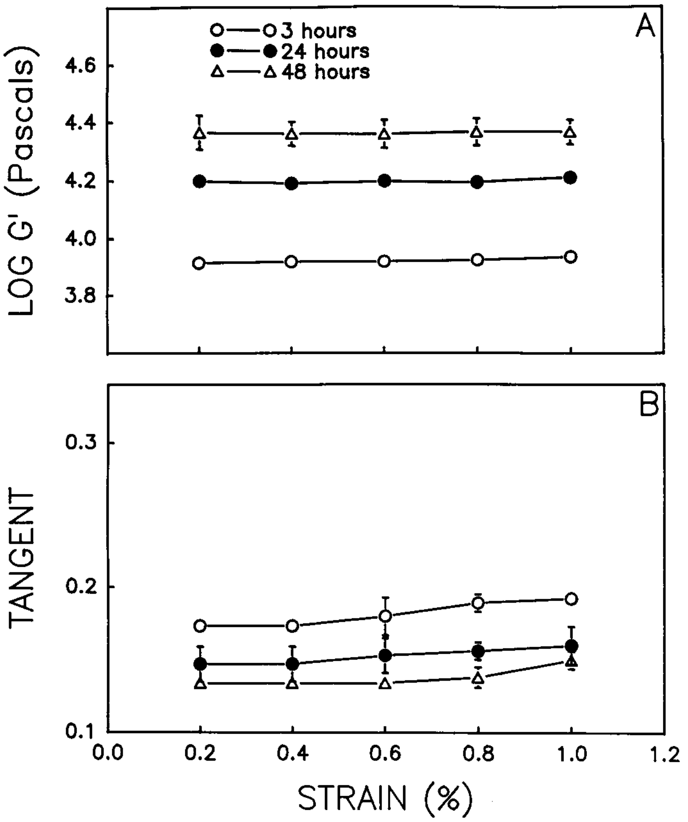

Fig. 2. Strain scans of 72-hr-old bread crumb reheated and measured within 3, 24, and 48 hr.

RESULTS AND DISCUSSION

Microwave Versus Conventional Refreshing

Regardless of the bread's age, when refreshing to 80°C was done in a conventional oven, the *G′* of bread crumb (Fig. 1A) at 0.2% strain was similar to that of freshly baked bread crumb. When the heating was by microwave, the age-related changes in *G′* were not fully reversed (Fig. 1A). Furthermore, the older the crumb when heated, the smaller the amount of reversal of *G′* (Fig. 1A). Although the samples were heated to the same final temperature, the microwave required 5 sec, whereas the conventional oven required 49 min. Thus it is possible that both the age-dependent increase in *G′* and its reversal are time-dependent processes.

Up to 120 hr of aging, the loss tangent of conventionally heated crumb was close to that of freshly made crumb (Fig. 1B). In contrast, there was a dramatic increase in tangent of microwave-heated crumb to levels above that of freshly baked bread (Fig. 1B). The magnitude of this increase diminished as the age of the crumb before heating increased (Fig. 1B). The fact that both *G′* and tangent are higher than those of freshly baked crumb means that the loss modulus, *G″*, increases to a much greater extent during microwave heating than during conventional heating.

Microwave energy is absorbed not only by water molecules, but also by other bread ingredients such as lipids (Lorenz et al 1973). This may have allowed these polymers in the crumb matrix greater ability to flow when deformed, hence the higher loss tangent. The larger elastic component (*G′*) of the microwave-heated crumb, coupled with its large increase in viscous (or fluid) component, may explain its toughness (leatheriness). The extent of change in tangent decreased as the age of the crumb increased (Fig. 1B). The reduction in loss tangent (*G″*/*G′*) is probably a consequence of the higher *G′* values (Fig. 1A).

Effect of Strain on the Refreshed Crumb

Strain scans (Fig. 2) of crumb that was 72 hr old when heated in a conventional oven showed that immediately after heating or during subsequent aging *G′* was not strain dependent. The tangent of the freshly heated crumb increased at strains above 0.6%. This strain dependence was less than that present in the freshly baked crumb (Persaud et al 1990). Thus, the factor(s) that caused the increase in the crumb's viscous properties (*G″*) at strains greater than 0.6% was only partially reversed by heating after 72 hr of storage.

Crumb that was microwave heated for 4 sec (data not shown) showed a small increase in tangent at 0.4% strain, comparable to that of the conventionally heated sample (Fig. 2B). Microwave heating for extended times (6, 8, and 10 sec) resulted in tangent values much higher than those of freshly baked bread at any measured strain level (Persaud et al 1990). There were no strain effects on either *G′* or loss tangent for crumbs that were heated more than 4 sec.

Aging of Refreshed Crumb

After heating, the *G′* of the older crumb increased at a greater rate than that of its unheated control (Figs. 3 and 4). The microwave-heated crumb reached higher *G′* values than did that heated in a conventional oven. Ghiasi et al (1984) observed a similar pattern in the recovery of firmness by bread that was heated in a conventional oven. Plots of the loss tangent (Figs. 3B and 4B) reflect the increase in the crumb's elastic component during storage after heating.

Microwave and conventionally reheated crumb samples lost 2.16% (Table II) and 1.1% (data not shown) of their sample weight in water, respectively. It is generally accepted (Kulp and Ponte 1981, Rogers et al 1988b) that the lower the moisture content of the crumb, the firmer it is and the faster it firms. This may have contributed to the difference in rate and extent of firming during storage after heating with microwave versus the conventional oven.

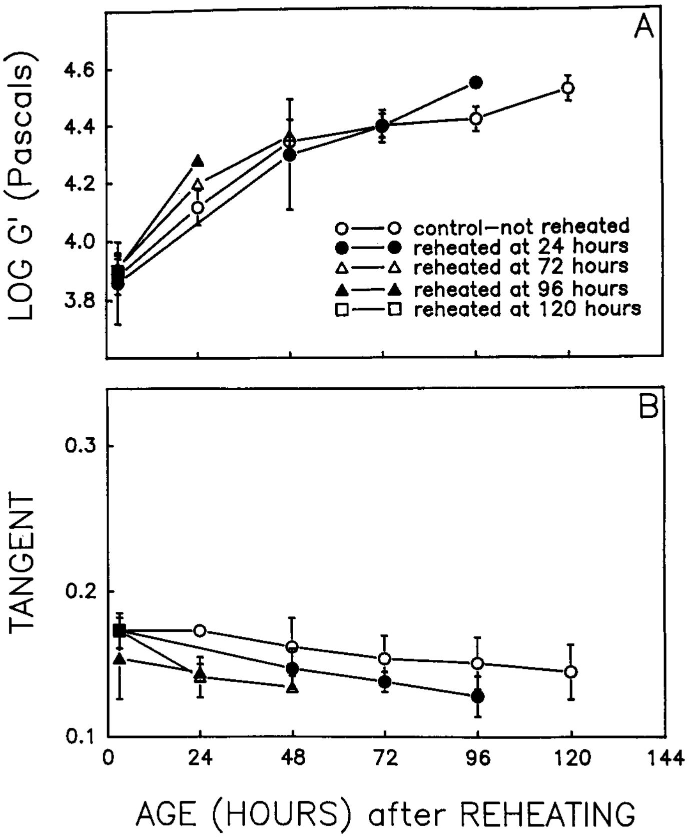

Fig. 3. Refreshing of bread crumb by conventional oven reheating. Middle slices of loaves aged to the times shown were heated to a center temperature of 80°C and further aged at 25°C. Measurements were made at 0.2% strain.

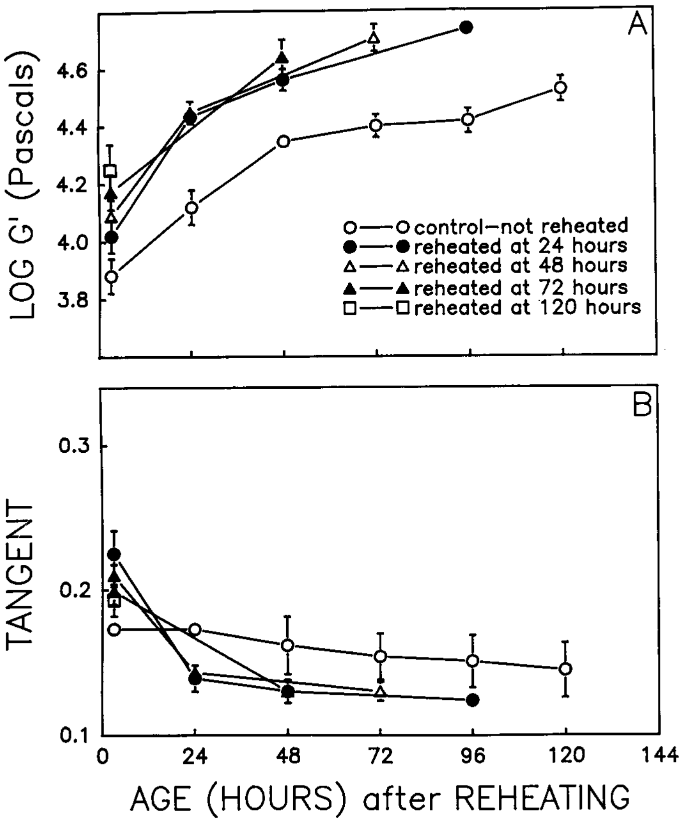

Fig. 4. Refreshing of bread crumb by microwave heating. Sample sections were heated to 80°C and further aged at 25°C. Measurements were made at 0.2% strain.

To assess the contribution of water loss because of microwave heating, the effects on crumb rheology of heating the crumb for various lengths of time (various moisture losses) were compared with the effects of air-drying alone. The relationship between microwaving time (0–20 sec) at 0.283 A and moisture lost from 48-hr-old crumb is shown in Table II. The moisture lost from the samples heated (4, 6, 8, and 10 sec.) before subsequent dynamic testing is listed in Table II. As the amount of moisture removed by air-drying increased above 2.0%, *G′* increased continuously (Fig. 5). That is, as the plasticizer (water) content of the crumb matrix was reduced, it became more resistant to deformation. Surprisingly, heating by microwave for up to 6 sec resulted in a reduction in *G′* (Fig. 5), whereas heating longer than 6 sec caused *G′* to increase and, eventually, to become higher than that of the unheated sample (Fig. 5).

Therefore, there appear to be two processes occurring simultaneously during microwave heating. Both processes affected the rheology of the crumb. The loss of moisture resulted in increased *G′* whereas heating reduced it. The effects of heating predominated for up to 6 sec of microwave exposure. At longer heating times (and regardless of the amount of moisture lost), the tangent increased rapidly (Fig. 5). On the other hand, the tangent decreased with increased moisture removal by air-drying alone (Fig. 5). Thus, the effect of the absorbed microwave radiation and not the removal of moisture was responsible for the increase in flow properties.

Effects of Surfactants

Figure 6A shows the change in *G′* during storage for samples treated with surfactants at level 1 and their controls (Table I). There were no differences in the *G′* of any freshly baked crumbs. Freilich (1948), among others, has reported the same phenomenon for firmness values obtained via static compression tests. The small differences between individual surfactant and control values may have been due to the low surfactant levels used.

Comparison of the control with samples containing both MGH and SSL (Fig. 6A) indicated that the rate of change of *G′* of

TABLE II
Moisture Lost During Microwave Heating (0.283 A)

Heating Time (sec)	H_2O Lost % Sample Wt	 % Total Moisture
0	0	0
3	0.5	1.19
4	1.20	2.84
5	2.16	5.11
6	3.20	7.57
7	4.45	10.53
8	5.40	12.77
10	7.52	17.76
15	15.84	37.43
20	18.77	44.37

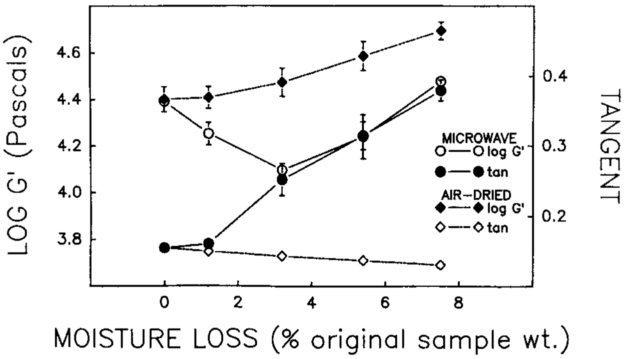

Fig. 5. Comparison of the effects of duration of microwave heating and of moisture loss by air-drying on *G′* and tangent of bread crumb. Sections from the middle slice were heated or air-dried. Measurements were made at 0.2% strain.

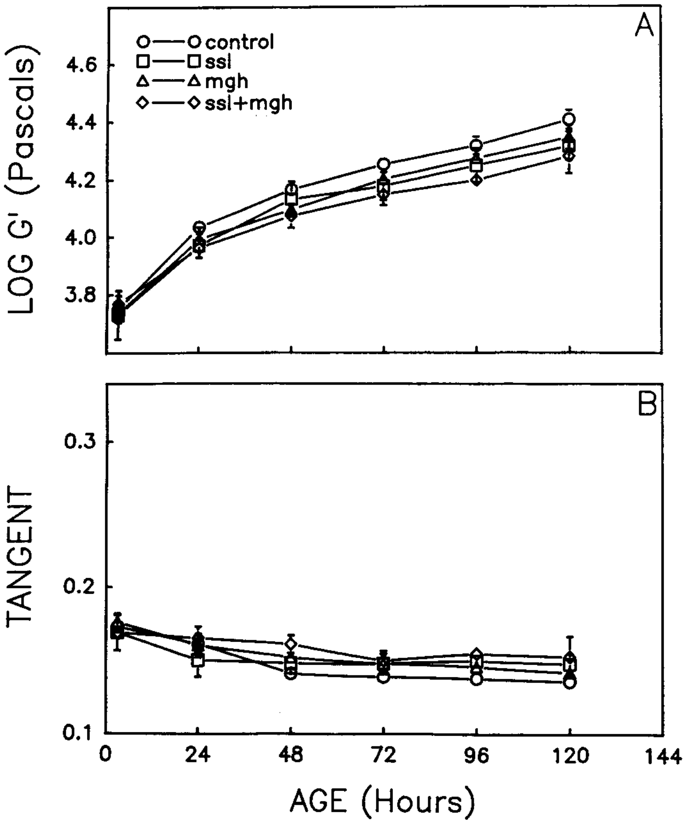

Fig. 6. Effects of surfactants (level 1) on log *G′* and tangent during aging at 25°C. Measurements were at 0.2% strain on middle slices. SSL = sodium stearoyl lactylate, MGH = hydrated monoglyceride.

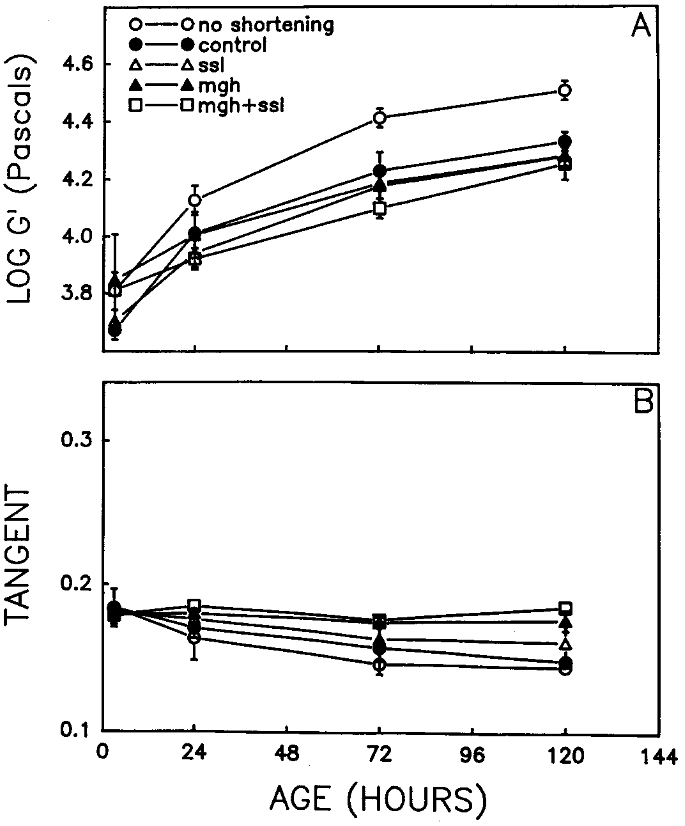

Fig. 7. Effects of surfactants (level 2) on log *G′* and tangent of bread crumb aged at 25°C. Measurements were at 0.2% strain on middle slices. SSL = sodium stearoyl lactylate, MGH = hydrated monoglyceride.

surfactant-treated crumb was significantly lower than that of the control. After 72 hr, there was a clear difference in G' between the treated (combination of SSL plus MGH) and control crumbs. A strain scan of the 72-hr-old crumb was similar to one of a freshly made bread crumb (Persaud et al 1990). However, the extent of the increase was smaller than that in fresh bread crumb. This suggests that the surfactants act by delaying the loss of viscous flow properties associated with aging of bread.

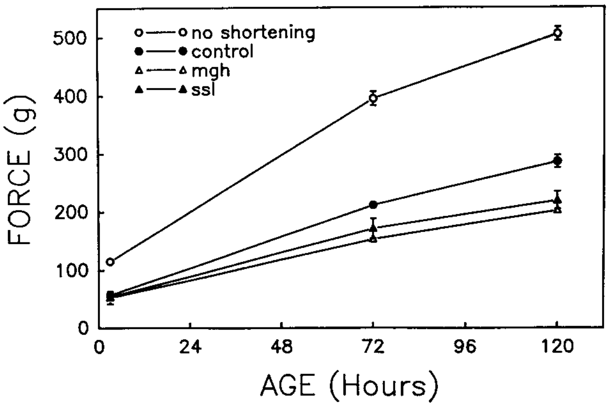

Fig. 8. Effect of surfactants (level 2) and shortening on firmness of the aged crumb (25°C) as measured by static compression. SSL = sodium stearoyl lactylate, MGH = hydrated monoglyceride.

Increased Levels of Surfactants

With surfactants present at level 2 (Fig. 7A), there was no significant difference between the single surfactant treatments and the control crumb containing 3% shortening. Furthermore, even though the combined-treatment crumb had the lowest G' after 24 hr of storage, it was no longer significantly lower than that of the control. This was surprising, because the treated loaves (especially the MGH+SSL combination) "felt" softer than the control. Several previous studies using static compression testing indicated that antifirming properties are proportional to the concentration of surfactant in the crumb (Knightly 1977).

Again from Figure 7A it can be seen that the rate and extent of change of G' of a crumb with no shortening was highest and the loss tangent was the lowest of those tested. More revealing data are seen in the plot of the sample's loss tangent (Fig. 7B). At higher treatment levels, the separation of the surfactant-treated and untreated crumb is clearer than at the lower levels (compare Figs. 7B and 6B). Throughout the aging period, crumb containing MGH+SSL had the same tangent as the fresh bread. MGH treatment resulted in a similar effect. Loss tangent of the SSL-treated crumb decreased slightly with age but was still higher than that of the control.

Voland-Stevens Analysis

To confirm that the observations made on the loaves treated with surfactant at level 2 were reflected in traditional firmness measures, static compression measurements were made on the crumb using the Voland-Stevens LFRA texture analyzer. Plots

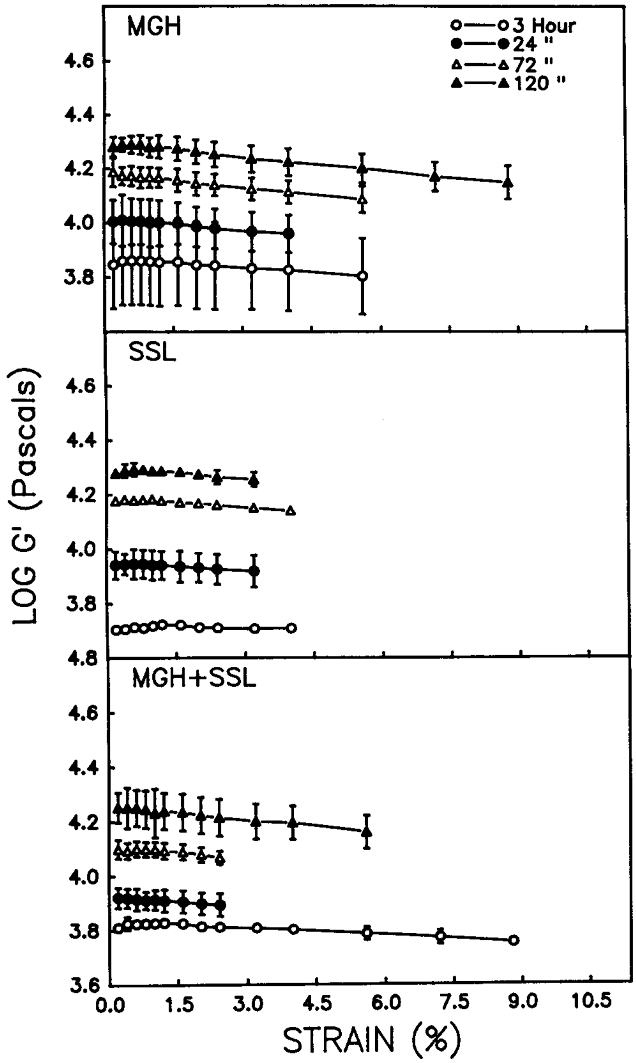

Fig. 9. Log G' vs. strain of surfactant-treated (Level 2) crumb aged at 25°C. SSL = sodium stearoyl lactylate, MGH = hydrated monoglyceride.

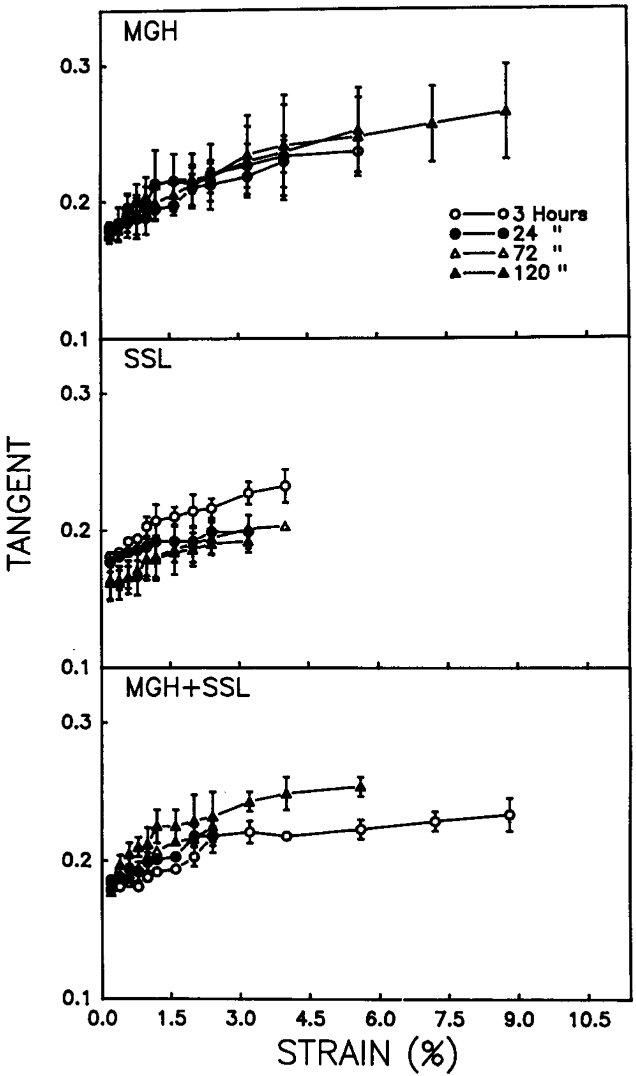

Fig. 10. Tangent vs. strain of surfactant-treated (level 2) crumb aged at 25°C. SSL = Sodium stearoyl lactylate, MGH = hydrated monoglyceride.

in Figure 8 show the change in firmness with time when compression was done parallel to the loaf's long axis, the same plane as most previously published data. The firming pattern was similar to published data for bread containing the surfactants used here (Kulp and Ponte 1981, Krog and Davis 1984). The clear separation of the shortening crumb from the no-shortening crumb and of the surfactant-treated crumb from the shortening-containing control confirms that the bread preparation procedure did not confer any peculiar behavior to the crumb. Data (not shown) for compression in the same plane (perpendicular to the loaf's long axis) in which dynamic shearing was done demonstrate that the effects of shortening and surfactants could still be differentiated.

Figure 9 shows that, for all of the surfactant treatments, G' is unaffected by strain level. This is not the case for the loss tangent, as Figure 10 demonstrates. For MGH treatment, the effect of strain on loss tangent was the same at 120 hr as it was at 3 hr. MGH+SSL treatment caused the aged crumb to have even higher values of loss tangent than when fresh. As SSL-containing crumb aged, the effect of strain was reduced. Even so, the strain effect was still greater than that for either the aged control or the no-shortening crumb samples.

Because the effect of surfactants is small on G' but large on the loss tangent, surfactants appear to have limited effects on segmental cross-linking between polymers in the crumb matrix and large effects on the maintenance of crumb's viscous properties throughout the aging period.

Tests employing static compression to large deformations between parallel plates cannot differentiate between viscous and elastic components of the response and, therefore, only give total resistance to deformation. In surfactant-containing crumb, the resulting value is lower than that for controls because of the contribution of the viscous component. Thus, although G' appears to be a good index of the rate of change and extent of the perceived firmness of the aging crumb (with or without shortening), it is not adequate to describe perceived firmness of a surfactant-treated crumb. These data also provide evidence that the mechanisms by which shortening and surfactants (especially MGH) affect firming are different.

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