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Water Loss and Structure Development in Model Cake Systems Heated by Microwave and Convection Methods[1]

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ABSTRACT

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Dynamic water loss rates, temperature profiles, and final structure of batters heated by microwave and convection methods were evaluated for three leavening conditions. Temperature gradients developed within the cake systems early in the microwave-heating process. Water loss rates increased during heating with a change in the slope of the water loss rate versus temperature curves occurring over the temperature range associated with starch and protein transformations. Only small temperature gradients were present in convection-heated cakes. Water loss rates for convection-heated batters sequentially increased initially, entered a short constant rate period, and increased rapidly until the final constant rate period was reached. The dependence of water loss rates on uniformity of structural development was demonstrated for both heating methods. Differences between systems made without and with chemical leavening were greater than differences between chemical leavening treatments.

Attention has been given to development of cereal-based foods for use in microwave ovens. Traditional formulations often result in structural development differences that affect quality.

Measurements of dynamic water loss and temperature profiles, coupled with evaluation of structure at the macro- and microstructural levels, have provided useful insights into the mechanism of heat and mass transfer during convection heating and into the role of formulation in these processes (Grider et al 1983, Cloke et al 1984, Pearce et al 1984). Although the development of structure and the cumulative water losses during heating in household types of microwave ovens have been studied (Baker et al 1990a,b), dynamic measurements of water loss and temperature profiles in batters have not been made. LePage et al (1989) and Umbach et al (1990) compared microwave and convective

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heating in gluten and bagel systems using these methods, but additional information is needed for batter systems, which contain higher water, fat, and sugar levels than those used in the LePage and Umbach studies. In the present study, these factors were taken into consideration. Variations in the type of chemical leavening systems also were introduced. Chemical leavening agents that have different heat requirements to release carbon dioxide also might be expected to contribute to differences in these profiles.

Microwave heating might be expected to place special requirements on leavening agents because of the relatively rapid heating and the potential for the development of pressure and vapor density profiles that are different from those developed during convection heating. Wei et al (1985a,b), in modeling studies using sandstone as a example of a porous medium, demonstrated such differences in profiles for microwave- and convection-heated samples.

In the present study, dynamic water loss rates, temperature profiles, and final structure of batters heated by microwave and convection methods were evaluated. Then these properties were compared under three different leavening conditions: one with no added chemical leavening agent, a "fast" chemical leavening system, and a "slow" one.

MATERIALS AND METHODS

Batter Formulation

A modified version of the lean research formula cake was used (Kissell 1959, Cloke et al 1984). One of three leavening treatments was used in each cake-baking trial: no added chemical leavening agent, sodium aluminum sulfate-phosphate (SAS-P) baking powder, or tartrate baking powder. Except for tartrate baking powder, household-grade ingredients were used. Tartrate baking powder was formulated by blending potassium tartrate (43.5%), sodium bicarbonate (43.4%), and corn starch (13.1%) (w/w).

Batter pH, Specific Gravity, and Viscosity

Specific gravity of batter and pH measurements were made immediately after preparation of batters for thermal and water loss measurements. Specific gravity of batter was measured using a 15-ml grease pycnometer (Fisher, Pittsburgh, PA).

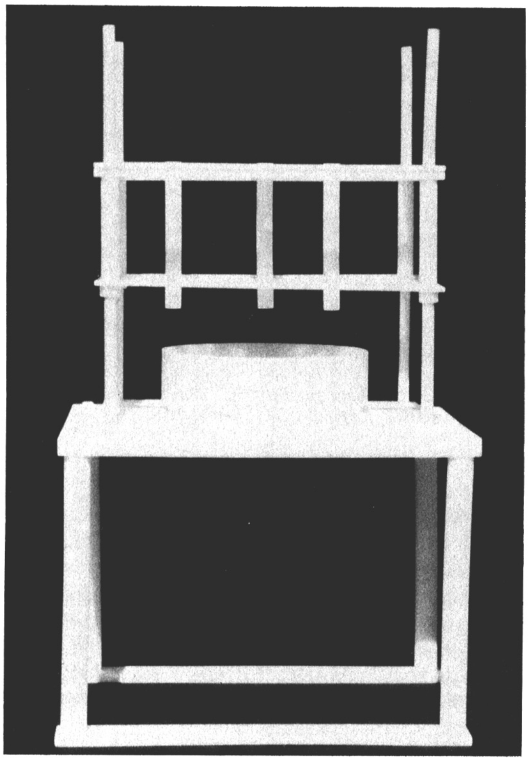

Fig. 1. Probe guides for microwave heating.

Apparent viscosity of batter was determined with a viscometer (model RVT, Brookfield, Stoughton, MA) using spindle no. 4 and a rotational speed of 20 rpm. The apparent viscosity measurement was based on three trials for each batter in a separate series, and three replications were made.

Heating Methods

Batter (220 g) was heated by either convection or microwave methods in round bake pans, 15.2 cm in diameter and 3.2 cm deep. Aluminum pans were used for convection heating, and Teflon pans (fluorinated ethylene propylene, Cole-Parmer, Chicago, IL) were used for the microwave method.

Microwave Baking

The hybrid environmental oven (Hung 1980, Zylema et al 1985, LePage et al 1989) was used for the microwave-heating trials. Operating conditions were 2,450 MHz frequency and 300 effective watts of power measured as the difference between the transmitted and reflected power. Volumetric airflow was 24.1 m^3/hr, yielding an air residence time of 1.19 min. The heating time was 10.0 min and was selected on the basis of the time needed to reach the final constant rate portion of the curves of water loss rate.

For temperature measurements, cakes were placed on a Teflon platform with guides for temperature probes (Fig. 1). Temperature measurements were made with fiber optic probes (model 750, 4 Channel Fluoroptic Thermometry System, MSA probes, Luxtron, Mountain View, CA). Probe positions are shown in Figure 2. Probes were positioned vertically at the midpoint of the batter. Temperatures were recorded at 15-sec intervals.

Water loss rates were measured gravimetrically in a separate baking series. Cakes were placed on a Teflon platform suspended from a balance placed on the top of the oven cavity. The Teflon stage that was used for the determinations of temperature profile was retained in the oven cavity to ensure that the operating conditions were similar for the temperature and water loss experimental series. Weights were recorded every 30 sec. Water loss rates for a given time (n) were calculated as the average of the water loss rates for the time intervals ($n - 1$ to n) and (n to $n + 1$) and converted to grams per minute.

The cumulative water loss during the bake period was taken as the difference between the initial weight and the weight recorded at 10 min. The loss during the 15-min period after removal from the oven also was recorded.

Convection Baking

The small-cavity environmental oven designed by Godsalve et al (1977) was used for the convection heating. Operating conditions were cavity temperature of 191 ± 1°C and volumetric air flow of 10.1 m^3/hr, which resulted in air residence time equivalent to that of the microwave oven. The heating time period was 25.0 min.

Temperature profiles and curves of water loss rate were simultaneously monitored, and measurements were taken at 1-min inter-

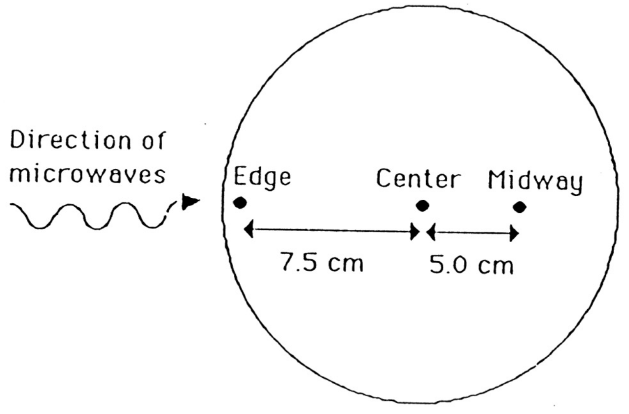

Fig. 2. Probe placement for microwave heating. Pan diameter, 15.2 cm. Probe tips centered vertically at each position.

vals. Temperature measurements were made using a thermocouple thermometer (model 650/600, Omega, Stamford, CT) equipped with copper constantan thermocouples. Temperatures were measured at the cake center and at 5 cm (midway position) and 7.5 cm (edge position) from the center. Water loss rates were psychrometrically determined from the inlet and outlet wet bulb-dry bulb temperatures. The cakes were weighed within 90 sec after removal from the oven to determine the cumulative water lost during the bake period and 15 min after removal from the oven.

Characterization of Baked Cakes

Measurements of cake cross-sectional areas using a planimeter were used as index to volume. Volume was determined by rapeseed displacement and was used to calculate specific gravity of baked cakes. Grain and contours were recorded by Xerograph prints of cake cross-sections (Kodak Ektaprint 85) at 129% enlargement.

Samples for scanning electron microscopy were taken from the edge, midway, and center positions for the convection cakes and from the hard and normal crumb regions in the microwave samples (corresponding to the center and midway regions, respectively). In each case, the samples were taken from the crumb regions midway between the top and the bottom of the cake. Each sample was placed on silver-colloid painted stubs, fixed overnight with osmium-tetroxide vapors in a desiccator containing anhydrous calcium carbonate, and coated with gold palladium before examination in a scanning electron microscope (model PSEM 500, Philips, Mahwah, NJ) operated at an accelerating voltage of 6 kV.

Statistical Analysis

Three replications of the leavening agent series were prepared for both the convection and microwave treatment groups. The order of leavening treatments was randomized within each replication. Analyses of variance were calculated for batter and cake characteristics. Duncan's multiple range test was used when results of analyses of variance indicated significant treatment differences.

RESULTS AND DISCUSSION

Batter Characteristics

Batter characteristics are summarized in Table I. The pH of the unleavened batter was 4.6, and the pH values for the tartrate and SAS-P batters were 7.0 and 7.2, respectively. The specific gravity of the unleavened system (1.009) was lower than that of either the tartrate (1.025) or the SAS-P (1.023) systems. The apparent viscosity of the unleavened batter (1,400 mPa·sec) was higher than that of either the SAS-P (907 mPa·sec) or the tartrate batters (753 mPa·sec).

Temperature Profiles

Typical temperature profiles for microwave- and convection-heated batters are shown in Figures 3 and 4, respectively. Batters baked by the microwave method developed temperature gradients early in the baking period. The temperatures at the three locations then converged as the maximum temperatures of 101–104°C were reached sequentially at center, midway, and edge positions. Because of the heating conditions and pan type used in this study, the temperatures at the center position were higher than those at the edge and midway positions. Baker et al (1990a) found that the direction of the gradients in cakes baked in a household microwave oven depended on whether the pan material was glass or metal, with the metal pan producing center to edge gradients.

Temperature gradients were smaller in the unleavened systems (Fig. 3A) than in the leavened systems (Fig. 3B). The gradients in the tartrate and SAS-P leavened systems were similar and developed early in the baking period when temperatures at the center of the pan increased more rapidly than those at the edge and midway positions. The temperatures at the edge and midway positions initially increased, then tended to increase less rapidly between 60 and 70°C, and then again increased more rapidly until the maximum temperatures were reached.

TABLE I
pH, Specific Gravity, and Viscosity of Cake Batters Made with Different Leavening Systems[a]

Leavening Agent	pH[b]	Specific Gravity[c]	Viscosity (mPa·sec)[d]
Unleavened	4.6 c	1.009 b	1,400 a
Tartrate	7.0 b	1.025 a	753 b
Sodium aluminum sulfate-phosphate	7.2 a	1.023 a	907 b

[a] Means within a column that are followed by different letters are significantly different at the 0.01 level of significance.
[b] Standard error of mean = 0.03, $n = 9$.
[c] Standard error of mean = 0.0007, $n = 9$.
[d] Standard error of mean = 66, $n = 3$.

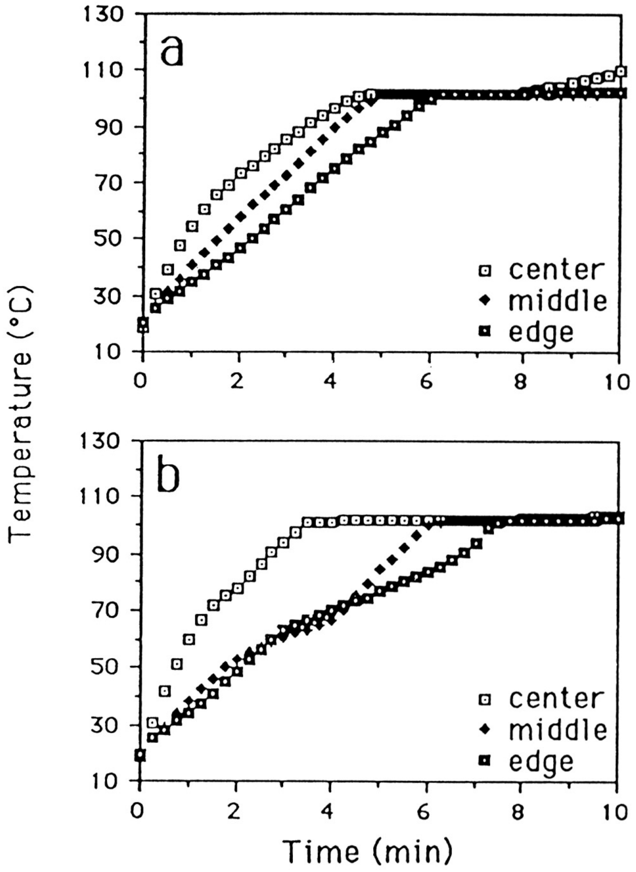

Fig. 3. Representative temperature profiles for microwave-heated cakes. **a,** Unleavened; **b,** tartrate leavened.

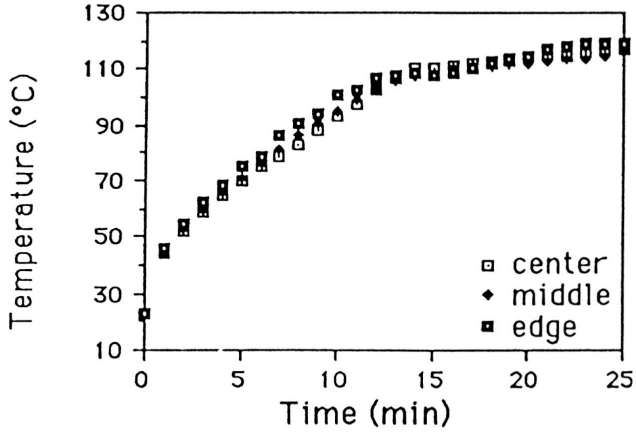

Fig. 4. Representative temperature profiles for convection-heated, unleavened cakes.

Temperature profiles were similar for all of the leavening treatments heated by convection. A typical profile is shown in Figure 4. Temperatures in all of the batters heated by convection rose rapidly in the first stages of baking and then increased more slowly or became constant toward the end of the baking period (Fig. 4). Maximum temperatures ranged from 109 to 120° C. Only small temperature gradients developed within the batters. These temperatures are typical of those found in earlier studies of cakes heated under similar conditions but with different formulation modifications (Grider et al 1983, Cloke et al 1984, Pearce et al 1984). They may be due to heat transfer from the metal pan to the partially dried cake matrix and surrounding air rather than to the limiting temperatures of concentrated sucrose solutions.

Water Loss and Structural Development

Microwave heating. Water loss rates for microwave-heated batters are shown in Figure 5. Water loss rates throughout the heating periods were higher than those for the convection method (Fig. 6), reaching a final rate of water loss of 4–5 g/min compared with that of 1.4–1.6 g/min for convection methods. Cumulative water losses immediately after baking and at 15 min also were greater for the microwave-heated cakes. Water losses measured immediately after heating ranged from 21.0 g for unleavened systems to 23.6 g for leavened batters (Table II). Cumulative losses 15 min after removal from the oven were 27.3, 29.9, and 32.4 for unleavened, SAS-P-, and tartrate-leavened batters, respectively (Table II). Cumulative water losses during heating by the convection method were similar for all of the leavening treatments, averaging 20.3 ± 1.25 g immediately after baking and 23.3 ± 1.04 g 15 min after removal from the oven.

In each of the systems heated by the microwave methods, the water loss rates increased slowly during the first 4 min of heating until the temperature in the batter reached at least 70° C. Then the water loss rates increased more rapidly until the final constant rate period was reached just before the conclusion of heating (Fig. 5). Structural development within the microwave-heated cakes was nonuniform both in the proportion of gelled and porous regions and in the bimodal contours, as shown in Figure 7. Thus, the water loss rates represent the average of losses from all of these structural regions at each stage of heating.

The bimodal contours of the microwave cakes reflect in part the effects of temperature gradients on structural development, but pressure gradients may also develop (Wei et al 1985a,b). Bimodal contours were more evident in the leavened systems than in the unleavened systems, suggesting, as would be expected, that the amount of vapor present is an additional factor in the development of the characteristic contours.

As shown in Figure 7, gellike regions predominated in the unleavened cakes, but some porosity was present. Further examination of the crumb structure using the scanning electron microscope at low magnification indicated that the structure of the porous regions was similar across all leavening treatments in microwave-heated samples (Fig. 8). Examination of the cell wall structure at high magnification (Fig. 9) showed that the swelling of starch granules and appearance of the extragranular matrix was similar for all leavening treatments. For most regions the matrix development for both heating treatments was similar and typical of that shown in Figure 9A. Some regions with a less abundant matrix and with discrete starch granules that were not

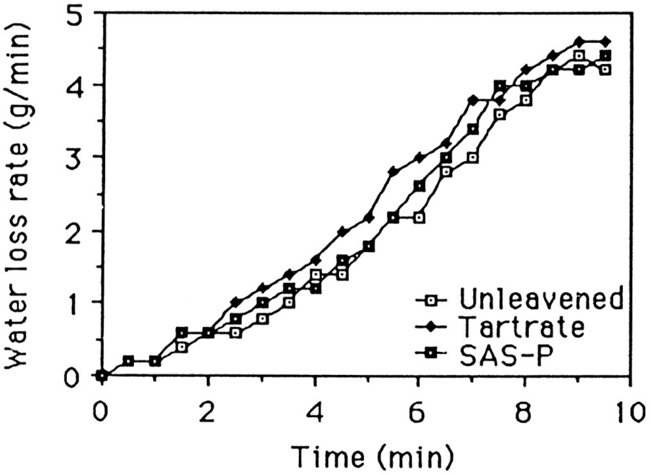

Fig. 5. Water loss rates for microwave-heated cakes. SAS-P = Sodium aluminum sulfate-phosphate.

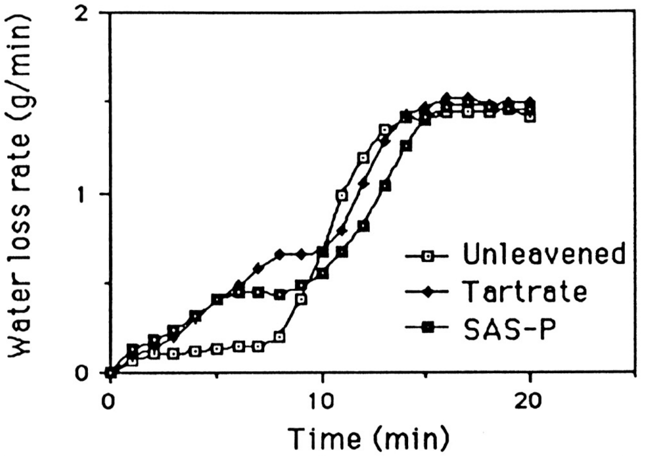

Fig. 6. Water loss rates for convection-heated cakes. SAS-P = Sodium aluminum sulfate-phosphate.

TABLE II
Cumulative Water Losses During the Microwave Bake Period and 15 Min After Removal from the Oven

Leavening Agent	Water Loss (g) During Heating[a]	Water Loss (g) After 15 Min Out of the Oven[b]
Unleavened	21.0 b	27.3 c
Tartrate	24.6 a	32.4 a
Sodium aluminum sulfate-phosphate	22.5 ab	29.9 b

[a] Means within the column that are followed by different letters are significantly different at the 0.05 level of significance; standard error of the mean = 0.60, $n = 3$.

[b] Means within the column that are followed by different letters are significantly different at the 0.01 level of significance; standard error of the mean = 0.22, $n = 3$.

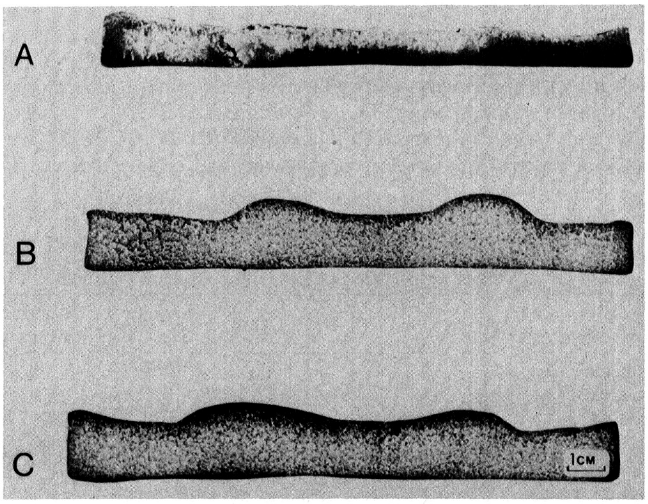

Fig. 7. Cross-sections of microwave-heated cakes. **A,** Unleavened; **B,** tartrate leavened; **C,** sodium aluminum sulfate-phosphate leavened.

greatly swollen also were found in the microwave-heated cakes (Fig. 9B). Studies by Goebel et al (1984) and Zylema et al (1985) with starch-water systems also demonstrated that no new starch structures were formed during microwave heating, but the stage of starch transformations may be different.

Convection heating. Water loss rates for convection-heated cakes (Fig. 6) showed more clearly defined regions of characteristic changes in water loss rates and greater differences among leavening treatments than those shown by microwave-heated cakes (Fig. 5). In each case, characteristic changes in water loss rates occurred when the temperatures of batters increased from 70 to 90°C.

For the early stages of convection baking, water loss rates for the unleavened cakes were lower than those for the leavened systems, but in the later stages of baking, during which the rate of water loss increased rapidly before reaching the final constant rate period, the curves were parallel. The change to the more rapid rate of water loss occurred between 70 and 90°C for all of the systems, and the final constant rate period began when the temperatures approached 100°C. The leavened systems, but not the unleavened systems, showed a short period of constant water loss rates just before the rapid increases in water loss rates. In the unleavened system, the water loss rates increased only slightly until the temperatures reached the 70–90°C range, so that the initial constant rate period encompassed the heating period up to the temperature associated with protein and starch transitions. Characteristic changes in these plateaus have been described previously for convection-heated samples in which structure development was changed by several other formulation modifications (Grider et al 1983, Cloke et al 1984, Pearce et al 1984). Cell structure and cake contours were relatively uniform in the leavened cakes, but the overall appearance of the cell structure in unleavened cakes was gellike with few pores (Fig.

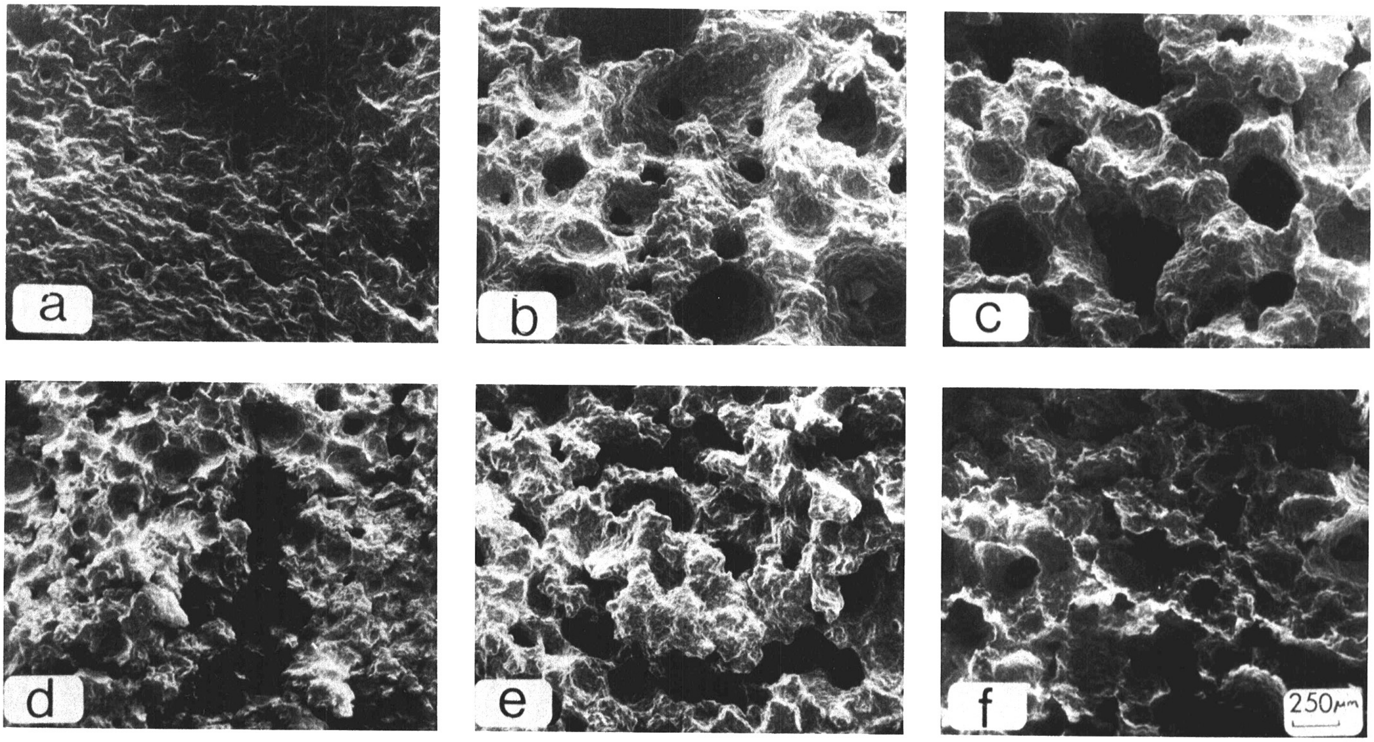

Fig. 8. Scanning electron micrographs of crumb (low magnification) from convection-heated (**a–c**) and microwave-heated (**d–f**) cakes. **a** and **d**, Unleavened; **b** and **e**, tartrate leavened; **c** and **f**, sodium aluminum sulfate-phosphate leavened.

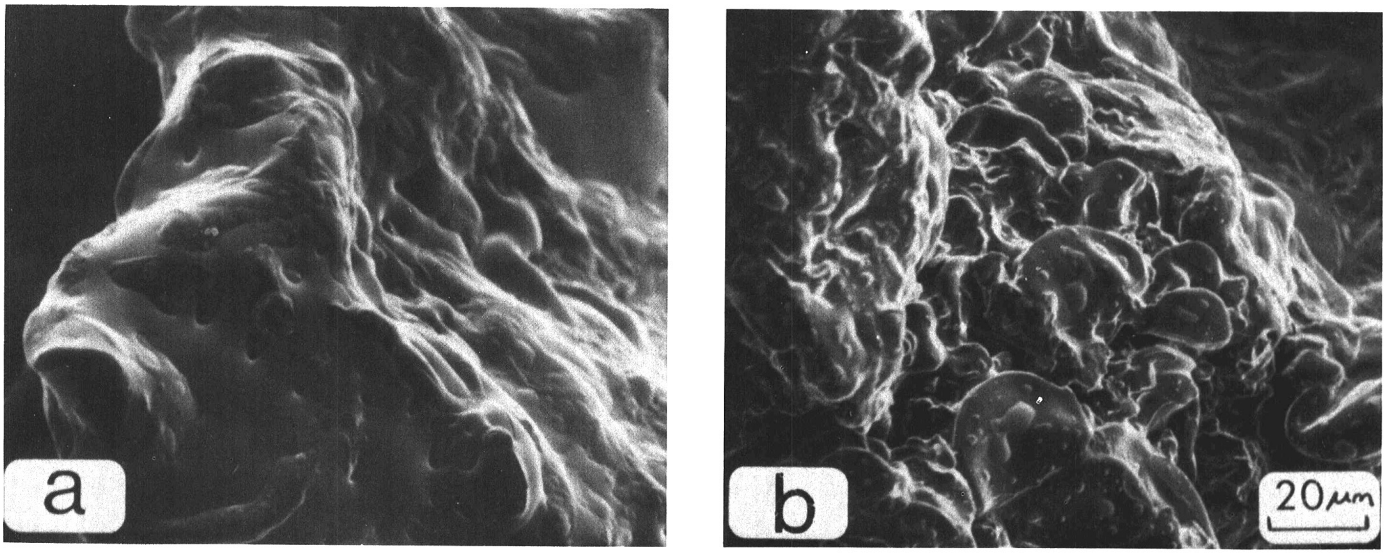

Fig. 9. Scanning electron micrographs of crumb (high magnification) from convection cakes (**a**) and microwave cakes (**b**).

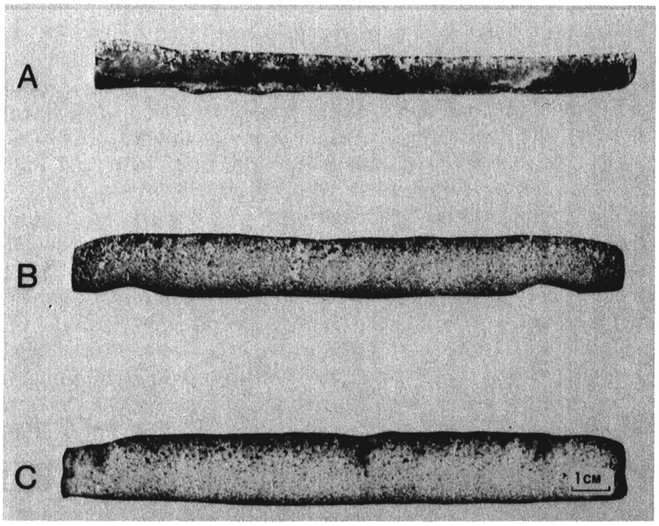

Fig. 10. Cross-sections of convection-heated cakes. **A,** Unleavened; **B,** tartrate leavened; **C,** sodium aluminum sulfate-phosphate leavened.

10). As was observed in microwave-heated cakes, some porosity could be found in all samples, but differences among the leavening treatments were greater in the convection-heated samples than in microwave heating (Fig. 8). At high magnification, more uniform granular swelling and extragranular matrix development were found for convection-heated crumb (Fig. 9A) than for microwave-heated crumb (Fig. 9B).

Comparison of Tartrate and SAS-P Leavening Systems

For most of the measurements that were made, few differences were found between tartrate and SAS-P leavened systems, and if differences were found they were smaller than those between unleavened and leavened systems. Initially, the batters made with the tartrate systems had a lower pH than those made with the SAS-P system, but specific gravities of batter and apparent viscosities were similar. Thus, the reactants had some effect on pH, but the combined gas production and retention effects were similar during batter formation. The differences between chemically leavened batters were small in comparison with the results of omission of either chemical leavening systems.

During heating by either convection or microwave methods, the characteristic temperature and water loss rate profiles were, in general, similar for the two leavening systems. In the convection-heating method, the first constant rate period of water loss for the tartrate system was slightly higher than that of the SAS-P system, but the total amounts of water lost during heating and in the 15-min period after removal from the oven were not different. However, for microwave heating, the total water lost during heating and in the 15-min period after removal from the oven was greater in the tartrate-leavened system than in the SAS-P-leavened system.

Although the cell structures of the finished cakes heated by convection and microwaves were different, low magnification scanning electron micrographs indicated few differences between the two leavening systems within each heating method. Cross-sectional areas, which were used as an index to volume, showed that SAS-P-leavened cakes had larger volumes than those of tartrate-leavened cakes, and the differences between leavening systems were greater for convection heating than for microwave heating (Table III). When the effects of weight loss and volume were combined in the measurement of specific gravity of the final cake, no differences between the leavening systems for either heating method were found, and the specific gravities of cakes made with each leavening system were similar for the two heating methods (Table III).

TABLE III
Cross-Sectional Areas and Specific Gravity of Cakes Baked by Convection and Microwave Methods[a]

Leavening Agent	Cake Cross-Sectional Area (cm^2)		Cake Specific Gravity	
	Convection[b]	Microwave[c]	Convection[d]	Microwave[e]
Unleavened	13.5 c	15.5 c	1.04 a	1.12 a
Tartrate	22.6 b	22.1 b	0.77 b	0.74 b
Sodium aluminum sulfate-phosphate	29.3 a	23.5 a	0.66 b	0.66 b

[a] Means within a column that are followed by different letters are different at the 0.01 level of significance.
[b] Standard error of the mean = 0.94, $n = 3$.
[c] Standard error of the mean = 0.34, $n = 3$.
[d] Standard error of the mean = 0.01, $n = 3$.
[e] Standard error of the mean = 0.03, $n = 3$.

Chemical leavening agents are usually classified and chosen with regard to the relative proportion of carbon dioxide released at room temperature and at elevated temperature. Given the shorter heating time required for microwave heating of batters when high power inputs are present, arguments could be made for having carbon dioxide available early in the baking period, as is the case with the tartrate system, or for a more gradual release, as is the case with the SAS-P system. However, the theoretical modeling studies for porous media (Wei et al 1985a), the experimental studies with gluten (LePage et al 1989), and the bagel system (Umbach et al 1990) have demonstrated the complexity of the interrelationships among temperature profiles, water loss rates, and development of structure. Furthermore, Evans et al (1984) demonstrated the importance of the events occurring during the transformation of the emulsion foam to the solid foam in controlling structure development in microwave-heated cakes. Therefore, it would also appear from the current study that the timing of the release of carbon dioxide was not the major factor in determining water loss rates and structure development. However, development of the porous solid foam is critical, as seen in the comparison of nonchemically leavened and chemically leavened systems.

CONCLUSIONS

The dependence of water loss rates on structure development during convection heating resulted in differences between the curves of water loss rates for nonchemically leavened and chemically leavened cakes. In each case, as the structure changed from a uniform distribution of cell types to combinations of cell structures such as gelled and porous regions, the curves of water loss rate changed also. The changes for the convection-heated cakes were most evident in the first constant rate period that occurred over the temperature range associated with starch and protein transformations.

Curves of water loss rate for microwave-heated samples were different from those for convection heating. Combinations of gelled and porous regions and bimodal contours were present, which were indicative of nonuniform heating during microwave heating. Under these conditions, no constant water loss rate period resulted for any of the variously leavened systems, and only a change in the slope of the water loss rate curve was observed.

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