Relationship of Heat Transfer and Water-Loss Rates to Crumb-Structure Development as Influenced by Monoglycerides[1]

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ABSTRACT

The relationships among heat transfer, water-loss rates, and crumb-structure development were studied in model cake systems made with different levels of saturated and unsaturated monoglycerides. Air incorporation, volume, and dispersion of lipid-containing matrix were affected by emulsifier type and amount. Total water loss during the original baking was not affected by the nature of the emulsive system. Dynamic measurements of water-loss rates and temperature during baking were related to the nature of the emulsive system and could be associated with physicochemical changes during baking and final cake structure.

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Development of cake-crumb structure is influenced by the presence of emulsifiers. The specific role emulsifiers play in altering structure depends on emulsifier chemical structure and concentration, dispersing medium, and temperature. Emulsifiers can also influence the role of water during heating. Emulsifiers can thus affect each stage of batter and structure development by changing chemical and physical transitions that occur in the lipid, protein, and starch components of batters (Davis and Gordon 1982; Cloke et al 1982, 1983; Hsu et al 1980).

The purpose of this study was to evaluate the role of different levels of saturated (SMG) and unsaturated monoglycerides (USMG) in the heat and water transport properties as related to selected physicochemical properties of the batter system. Resultant differences in heat transfer and water-loss rate data were related to initial specific gravity of batter as an index of air incorporation, cross-sectional area of the final cakes as index to volume, photographs of cross-sectioned cakes showing air-cell structure uniformity and tunneling, and scanning electron microscopy (SEM) showing starch granule and matrix swelling and lipid distribution.

MATERIALS AND METHODS

Emulsifier Incorporation into Batter

Emulsifiers were incorporated into a lean cake formulation (Kissell 1959), as shown in Table I. A modified two-stage mixing method was used. Flour and baking powder were sifted together, and the shortening and sucrose were added. The batter was mixed for 3.5 min with a mixer (KitchenAid, model K45). The distilled water was added, and the batter was mixed for an additional 3 min.

Specific Gravity

Specific gravity of the batter was determined with a pycnometer (15 ml).

Water Loss and Temperature Measurement

All cakes were baked in an aluminum pan (15.2 cm diam × 3.2 cm deep) containing 220 g of batter and placed in a specially constructed environmental oven (Godsalve et al 1977) for 25 min at 191°C and an air-flow rate of 10.1 m^3/hr.

Thermocouples were placed 0.5 cm above the pan base at four locations: center, 2.5, 5.1, and 6.9 cm radially from the center of the pan. The rate of water loss was calculated from wet and dry bulb thermometry of the airstream entering and leaving the oven (Godsalve et al 1977, Hsu et al 1980). Each treatment was replicated four times using a randomized block design.

Cake Weight, Cake Photographs, and Cross-Sectional Areas

The cakes were weighed immediately after baking. The outline of the center cross section of the cake was traced, and the area was determined from triplicate measurements on a Hewlett-Packard digitizer (model 9107a) as an index to volume. The tops of cakes were photographed as well as the cross sections of bisected cakes.

Scanning Electron Microscopy of Crumb

The crumb was sampled 2.5 cm from the outer edge, midway between the top and bottom crusts for SEM of the crumb. Wedges were cut with a razor blade and mounted on aluminum stubs with a thin layer of silver paint. Samples were placed in a desiccator and treated overnight with osmium vapors. The samples were then coated with gold-palladium and viewed in a Philips SEM 500 operated at 6 kV.

RESULTS AND DISCUSSION

Water-Loss Rates

Water-loss rates and accompanying temperature profiles as a function of time are shown in Fig. 1a and b, respectively, for the unemulsified batters. The overall shape of these curves is similar to that found in previous studies of formulation-modifications of the system (Hsu et al 1980, Gordon et al 1979). Changes in the specific features of these curves are sometimes more revealing than the absolute numerical values of a water-loss rate at a particular moment in time as one begins to change the formulation. Four periods have been identified from previous work with these types of curves. A more detailed discussion of these four regions is given in a review of food microstructure evaluation (Davis and Gordon 1982). Because the data are essentially the same for all cake formulations, only one set of curves is presented in this article (Fig. 1a and b).

Briefly, in the T_0–T_1 period (0–6 min), the water-loss rate increases from 0 to approximately 0.2 g/min. This is accompanied by a rapid increase in temperature from room temperature to 75–80°C, depending on thermocouple location from center to edge. This temperature range is in the region where SMG undergoes phase transitions and starch transformations begin (Cloke et al 1982, 1983). The T_1–T_2 period (6–11 min) shows very rapid increases in water-loss rates (0.2 to approximately 0.55 g/min) and is in a temperature range that reaches a maximum temperature at T_2 between 88–100°C from center to edge. This is the time when granule swelling begins (Cloke et al 1982). The T_2–T_3 period (11–17 min) is characterized by a significant slowing of water-loss rate differences, especially between 13 and 16 min of baking time. Maximum temperatures at T_3 of 97–107°C from center to edge are reached during the third period. This is the period when the greatest differences in water-loss rates between formulation changes are observed. Cloke et al (1982, 1983) have related this to the time when the starch granule loses its characteristic shape and is greatly affected by the presence of different kinds and amounts of emulsifiers. This is also the period when the cake is transformed from a fluid emulsion/dispersion to a

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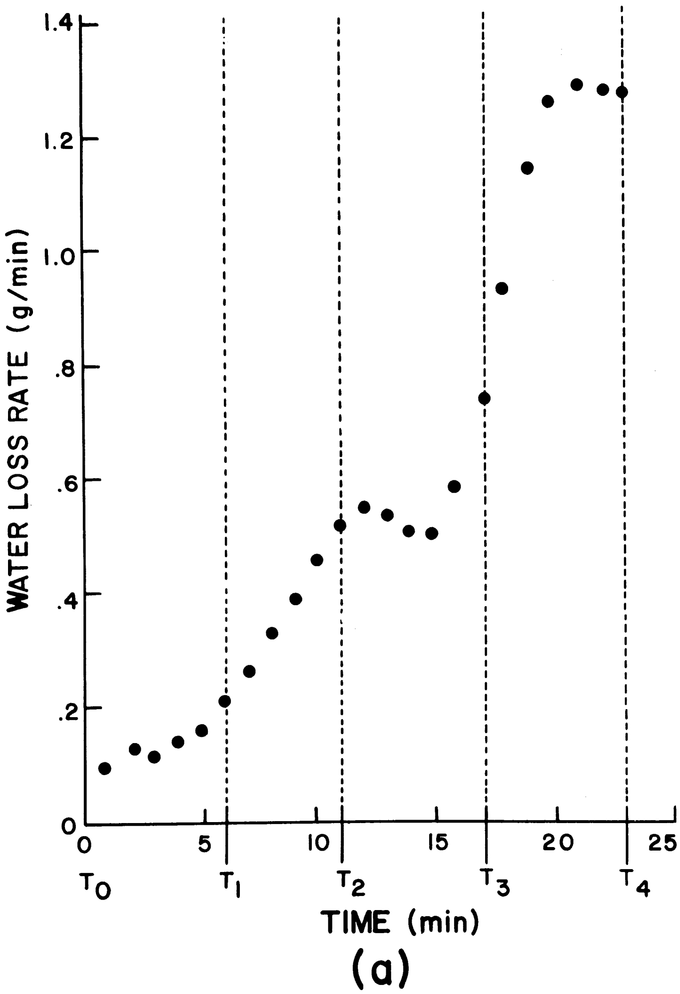
solid, porous medium. The T_3–T_4 period (17–23 min) is characterized by rapidly increasing rates of water loss similar to those seen in T_1–T_2. The temperatures range from 108 to 115°C from center to edge. Slight differences in temperature ranges between formulations are attributed to differences in final cake volume.

The T_2–T_3 period is the period most influenced by batter formulation. Within this period, a local maximum (maximum for this part of the water-loss rate curve) or stabilization of the rate of water loss developed. This was also the period during which major differences in the emulsive system appeared. Figure 2 contains stylized curve shapes taken from water-loss rate curves (which are similar to the representative curve shown in Fig. 1a) between 13 and 16 min, which included the local maxima or plateaus that characterize this period. Averaged data for all replications for centerline temperature at 13 and 16 min, batter specific gravities, and cake crumb cross-sectional areas also are shown in Fig. 2 for the entire series.

A definite plateau was present in the unemulsified batters between 13 and 16 min. Plateaus extending over the 3-min time were present in batters containing up to 2% of the SMG emulsifier. As the emulsifier level was increased up to 5%, the duration of the plateau became progressively smaller. At the 5% level, there was no true plateau, although the rate of increase in water loss slowed at 13 min and then increased again between 15 and 16 min. Plateaus were present at the 7.5 and 10% levels, although they were not as large as those found at the lower concentrations.



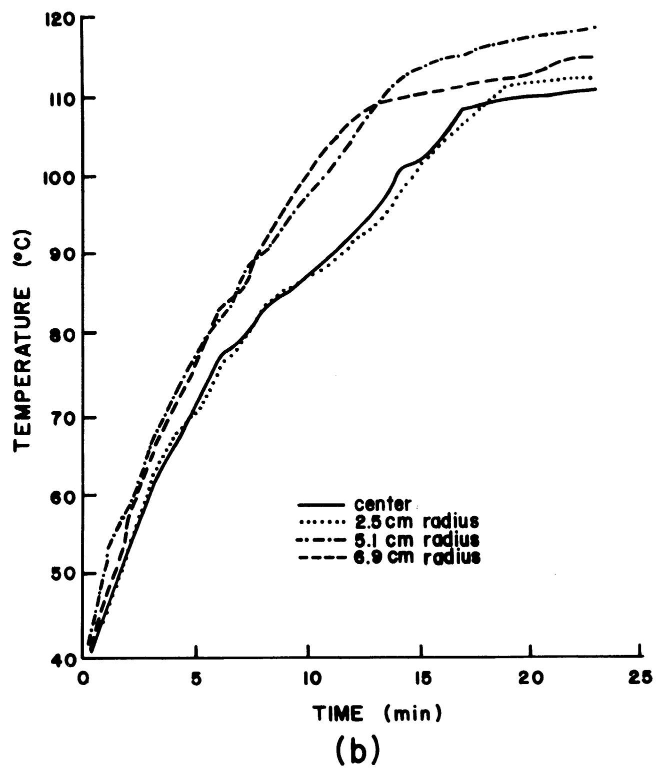
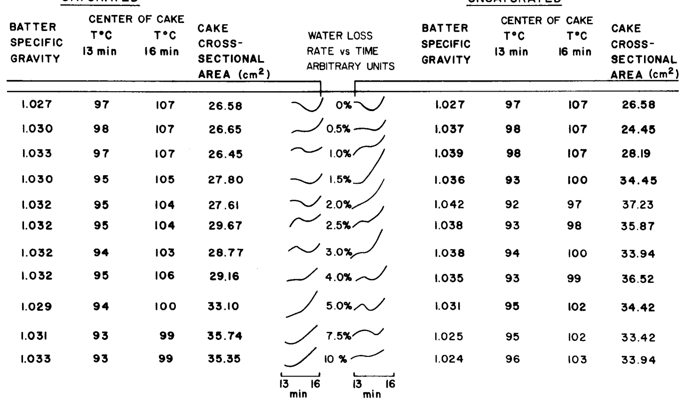


Fig. 1. Water-loss rate. **a**, temperature profiles; **b**, unemulsified cake during baking at 191°C. Dashed lines delineate different periods of baking.

TABLE I
Test Formula

Ingredient	Quantity (g)	Percent	Percent (flour basis)
Cake flour[a]	150.0	25.3	100
Baking powder[b] (sodium aluminum sulfate-phosphate)	7.1	1	5
Shortening (corn oil[c] and monoglyceride)[d,e]	41.8	7.1	27.9
Sucrose solution			
Sucrose	167.4	28.2	111.6
Distilled water	107.0	38.2	151.0
Additional distilled water	19.5 + 100.0		

[a]Softasilk, General Mills.
[b]Calumet, General Foods Corporation.
[c]Mazola, Best Foods.
[d]Dimodan PV, Grinsted Products: 85–90% glycerol monostearate and 10–15% glycerol monopalmitate (referred to as SMG). When SMG was used, it was heated to 60°C in 19.5 g of water and allowed to cool to room temperature before being incorporated into the batter.
[e]Dimodan O, Grinsted Products: 70% glycerol monooleate (USMG). When USMG was used, it was heated to 60°C in 19.5 g of oil and allowed to cool to room temperature before being incorporated into the batter.



SATURATED Batter Specific Gravity	Center of Cake T°C 13 min	Center of Cake T°C 16 min	Cake Cross-Sectional Area (cm²)	Water Loss Rate vs Time Arbitrary Units	UNSATURATED Batter Specific Gravity	Center of Cake T°C 13 min	Center of Cake T°C 16 min	Cake Cross-Sectional Area (cm²)
1.027	97	107	26.58	0%	1.027	97	107	26.58
1.030	98	107	26.65	0.5%	1.037	98	107	24.45
1.033	97	107	26.45	1.0%	1.039	98	107	28.19
1.030	95	105	27.80	1.5%	1.036	93	100	34.45
1.032	95	104	27.61	2.0%	1.042	92	97	37.23
1.032	95	104	29.67	2.5%	1.038	93	98	35.87
1.032	94	103	28.77	3.0%	1.038	94	100	33.94
1.032	95	106	29.16	4.0%	1.035	93	99	36.52
1.029	94	100	33.10	5.0%	1.031	95	102	34.42
1.031	93	99	35.74	7.5%	1.025	95	102	33.42
1.033	93	99	35.35	10 %	1.024	96	103	33.94

Fig. 2. Stylized plots of the T_2–T_3 water-loss rate period of heating including temperatures at center of cake at 13 and 16 min of baking, specific gravity of batter and cake crumb cross-sectional areas.

As the stylized plots in Fig. 2 show, plateaus cannot be seen in the USMG series for batters with emulsifier concentrations between 1 and 4% but were present at concentrations between 0.5 and 1.0, and between 4 and 10%. Our data showed that the rate of water loss during the plateau tended to be slightly higher (about 0.05 g/min) in the USMG batters than in the SMG batters. However, all were close to 0.60 g/min, as shown in Fig. 1a.

The temperatures (Fig. 2) at 13 min varied from 92 to 98° C and at 16 min from 97 to 107° C. Within the SMG series, the temperatures for the higher concentrations of emulsifier (5.0–10.0%) were lower and the range smaller than those for lower levels of emulsifiers. In the USMG series, the reverse was true: the temperatures for the 1.5–4.0% levels were lower than those for either the very low or the very high levels of emulsification. In general, in either series, definite plateaus in water-loss rates tended to be associated with the higher temperatures.

More importantly, in each series the transitions in the nature of the plateau during the T_2–T_3 period, as the concentration of emulsifier was increased, were associated with changes in crumb. Lack of uniformity in final crumb structure was documented in photographs (Fig. 3A,B) at the 5–10% level of SMG emulsifier and the 1–3% level of USMG emulsifiers. Those emulsifier level ranges produced cakes with large tunnels and air cavities. In most cases, the presence of tunnels and large cavities was reflected in large cross-sectional areas (Fig. 2). For these reasons, there was not agreement between initial batter specific gravity and final cake cross-sectional area (Fig. 2). Since analysis of variance of specific gravities had shown that the F values for emulsifier type, concentration, and interaction of emulsifier with concentration were all highly significant ($P < 0.01$), it had been believed that some relationship of specific gravity to final cake structure would exist. The rates of water loss in the T_2–T_3 period for tunneled cakes from either series shows only very short periods of constant rate during the T_2–T_3 period that were attributed to nonuniformity in the porous media (crumb structure). The temperatures of the tunneled cakes at the beginning of this period were also among the lowest in the series. This may be due to the air within the tunnels inhibiting heat transfer. Also, emulsifiers may shift the loss of fluidity of the batter to an earlier time, and the water-loss plateaus may be more related to structural reasons and less to the heat associated with starch gelatinization. This loss of fluidity need not be related to earlier gelatinization but to general immobilization of water. This will be discussed later. Since initial air incorporation does not seem to be related to tunneling, this suggests that air-cell stability is the more important factor. The 4% level in each series was the optimum level for that series, in absence of tunneling (Fig. 3).

Thus, the relationship between heat and water transfer has some features that are best contrasted within the same emulsive system, but other features at this stage are best contrasted as a function of common structural characteristics from one system to the next, as might be expected if heat and water transfer is determined by the macroscopic character of the emerging porous structure that develops at this stage of baking and is not necessarily due solely to starch gelatinization. To substantiate this idea, theoretical and experimental studies of heat and water transport in rigid porous media (not developing porous structure from a fluid) conducted by Wei et al (1984) indicated that water loss is mainly controlled by capillary suction pressure. This corresponds to the T_2–T_3 period of heating of the cake study. The same plateau is present even though no chemical reaction is occurring. Thus, the rate of water loss cannot be controlled solely by the result of chemical reaction. Interestingly, however, cakes lost between 17.0 and 17.5 g of total water during baking, and differences were not statistically different across all formulations.

Microscopic Evaluation

Scanning electron microscopy observations of crumb structure (Figs. 4–7) further substantiate the more macroscopic observations (Fig. 3) and help to interpret why initial air incorporation was not directly related to water-loss rate data and final crumb structure. Also, differences in appearance of batter components were observed in relationship to final cake structure.

The distribution of air cells as viewed by SEM at low magnification is shown in Fig. 4. In the unemulsified cakes (Fig. 4a), the air cells are small and the crumb appears very "knobby". Before fixation, the texture of the crumb was observed to be rubbery. All cakes with emulsifier appeared to be less rubbery, but those with the SMG were always tough and heavy. In the SMG emulsifier series, the air cells became progressively larger until tunnels began to form above the 5% level (Fig. 4c) and continued to become larger as the emulsifier concentration increased. The USMG (Fig. 5) cakes showed tunneling at low concentrations, but as the concentration was increased, the air cells became smaller and the crumb structure more fragile. The air cells generally give the impression of being spherical, shallow depressions. The size of the air cells and the number of tunnels obviously have a profound effect on the final volume of the cake.

The dispersion of the starch and lipid components, which could be seen at higher magnifications (Figs. 6 and 7), also appeared to be affected by the nature of the emulsive system, and influenced final cake tunneling. Starch granules and lipid droplets on the surface or embedded in the air-cell wall of the final crumb structure are shown in Figs. 6 and 7. In SEM studies of this type, the degree of swelling of starch granules is difficult to assess because of the limited number of granules viewed, the random orientation of the granules, the wide range of initial sizes, and the presence or absence of leached materials.

All the cakes have a globular material dispersed on the side walls of the air cells. These droplets are seen as lighter areas because of heavy metal fixation and are, therefore, likely to be lipid or at least to contain lipid. Possibly some emulsifier and some protein or solubilized starch are associated with them, but it is not possible to do an analysis of individual droplets after fixation for SEM.

In the unemulsified cakes (Fig. 6a), the lipid or oil droplets had a wide range of sizes and shapes, from small to spherical to large and elongated. The droplets were lodged on top of the granules or in the depressions between granules. The oil droplets in the unemulsified cakes were more beam sensitive than those in the emulsified cakes, suggesting a difference in droplet composition. It was generally easier to detect starch granules in the SMG monoglyceride cakes (Fig. 6) than in the unemulsified cakes. At the higher concentrations of the SMG emulsifier, the lipid pools tended to elongate and gather at the boundaries of the starch granules. This dispersion has the potential to surround and stabilize air cells. In addition to the pools, very small spherical droplets were observed. In the unemulsified cakes the larger droplets remained spherical, whereas in the cakes with saturated emulsifiers the bigger lipid pools were elongated and ropelike. Major differences in the lipid dispersion pattern were observed within the USMG series (Fig. 7). There was a higher proportion of small lipid droplets in these cakes than in the SMG cakes (Fig. 6). In the 2.5% USMG cakes (Fig. 7b), there were some large oil pools, but many of these were in thin strands around the starch granules. In the micrograph for the 5% USMG cake (Fig. 7c), the oil droplets delineated the starch granules clearly. With greater concentration of USMG, there was an increase in the number of very tiny oil droplets. Thus, the nature and concentration of emulsifiers influenced the dispersion of lipid containing matrix in the cake. According to Shepherd and Yoell (1976), a finer fat dispersion in the batter and in the finished cake results in greater crumb softness and friability in the mouth.

Based on earlier freeze-etch transmission electron microscopy studies, granule swelling has been observed in the temperature range, which is encompassed by the T_2–T_3 period (Cloke et al 1982). The swelling order in the freeze-etch studies at 90° C was observed to be: unemulsified > 5% USMG > 10% USMG > 5% or 10% SMG. As the batter reached higher temperatures, all the granules were observed to undergo similar swelling.

The earlier observations using freeze-etch (Cloke et al 1982) found that SMG also undergoes a series of transformations or phase changes when it associates with oil or water upon heating. The phase changes affect the mobility of water during the baking period and influence batter fluidity. The USMG as such was not distinguishable by the freeze-etch technique, but it is dispersed throughout the system because of its close association with oil.

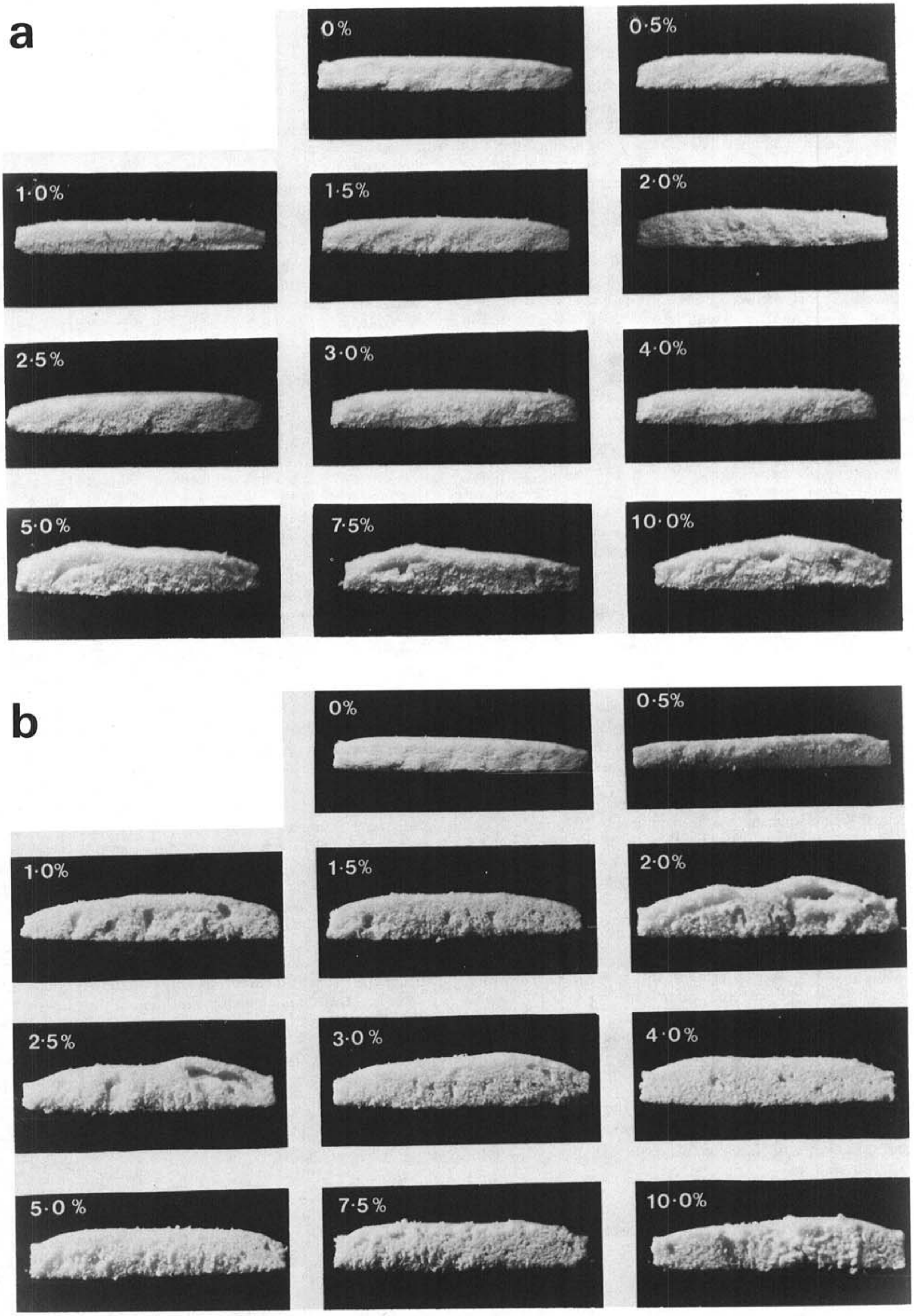


Fig. 3. Cake cross sections. **a,** cakes with saturated monoglycerides; **b,** cakes with unsaturated monoglycerides.

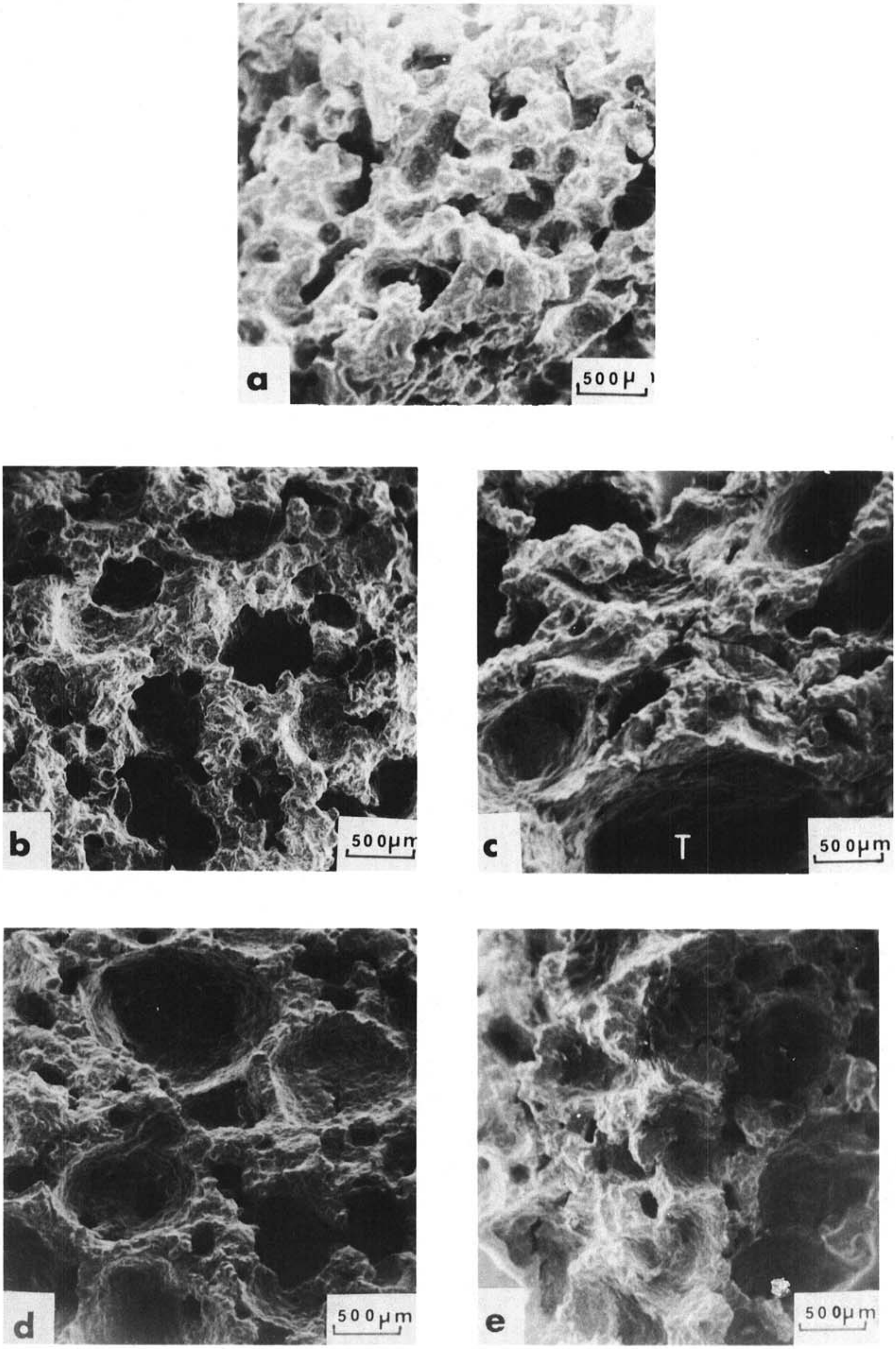


Fig. 4. Photomicrographs (scanning electron microscopy at low magnification) of cakes containing **a,** no emulsifier and of cakes containing **b,** 2.5%; **c,** 5%, **d,** 7.5%; and **e,** 10% saturated monoglyceride. T = tunnel.

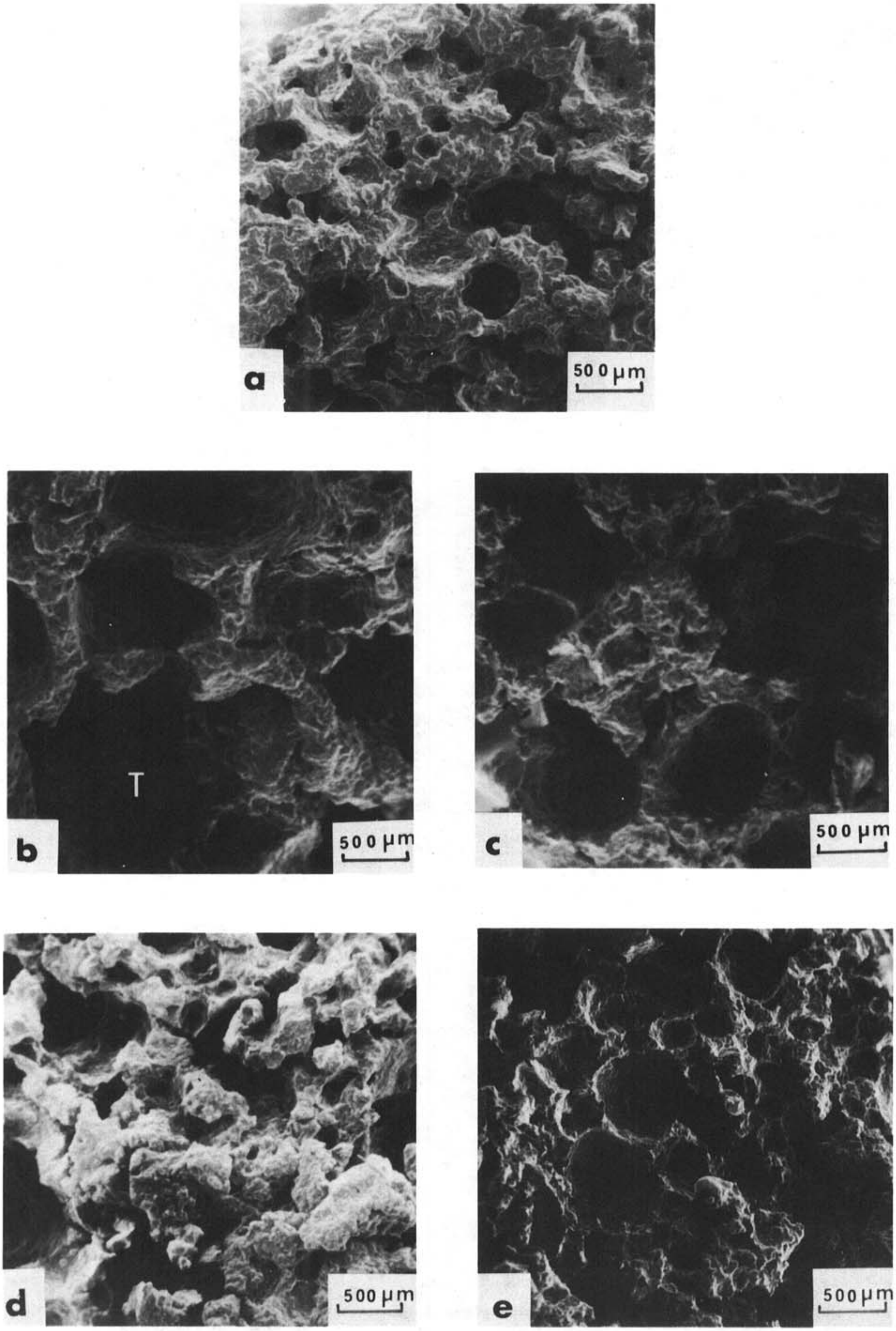


Fig. 5. Photomicrographs (scanning electron microscopy at low magnification) of cakes containing **a**, no emulsifier and of cakes containing **b**, 2.5%; **c**, 5%; **d**, 7.5%; and **e**, 10% unsaturated monoglyceride. T = tunnel.

Because swelling of the starch granule and phase transitions of SMG may each require mass transport of water into the respective crystalline structures, water available for evaporation decreases, and water-loss rates, as seen during this period, decrease correspondingly. Although part of the differences in water-loss rates within the series are due to chemical differences in starch swelling and emulsifier transitions, they are also strongly associated with the more macroscopic physical aspects of crumb structure that control water movement by capillary pressure, as Wei et al (1984) evaluated in their model system studies. Therefore, it was concluded that emulsifiers can influence air-cell water mobility, air-cell stability, air-cell size, and starch granule swelling, which collectively contribute to development of the solid, porous crumb structure.

CONCLUSIONS

The interrelations of initial air incorporation in cake batters are not necessarily directly related to optimal final cake volume, since resulting tunneling and uneven cell structure of crumb adversely affect final cake quality. Microscopic studies show that emulsifiers

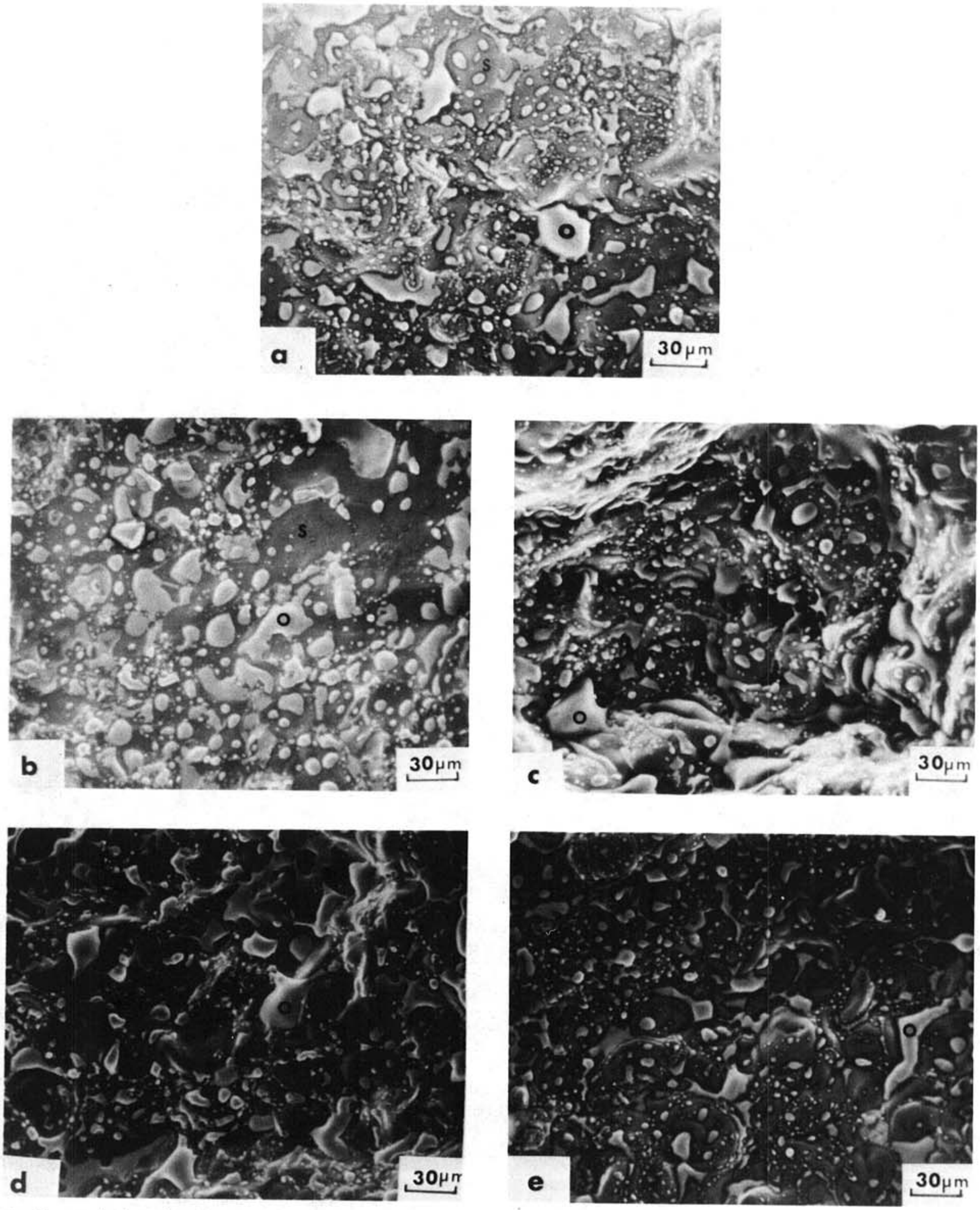


Fig. 6. Photomicrographs (scanning electron microscopy at higher magnification) of air-cell wall of cakes containing **a,** no emulsifier and of cakes containing **b,** 2.5%; **c,** 5%; **d,** 7.5%; and **e,** 10% saturated monoglyceride. 0 = oil, S = starch granule.

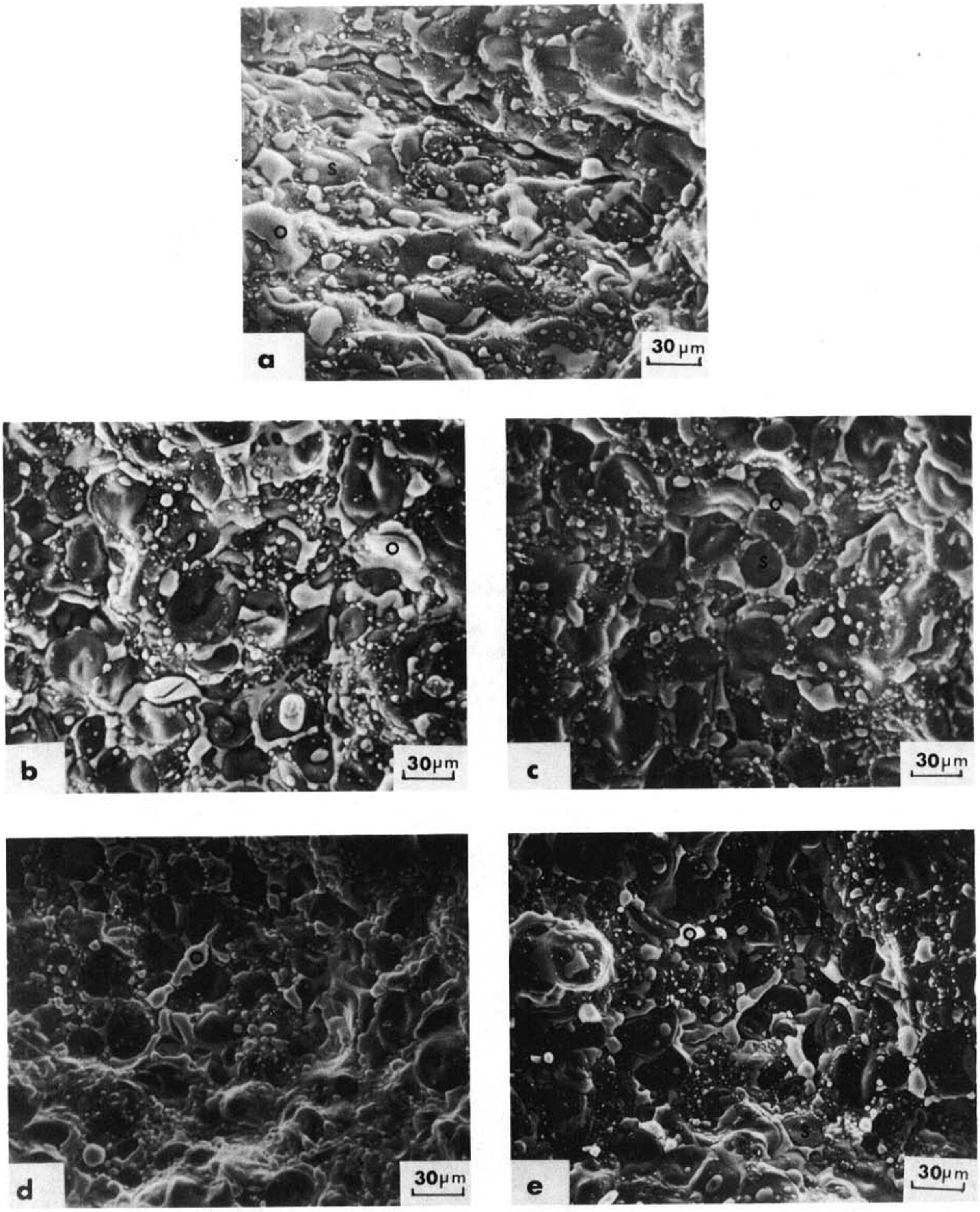


Fig. 7. Photomicrographs (scanning electron microscopy at higher magnification) of air-cell wall of cakes containing **a,** no emulsifier and of cakes containing **b,** 2.5%; **c,** 5%; **d,** 7.5%; and **e,** 10% unsaturated monoglyceride. 0 = oil, S = starch granule.

influence air-cell stability during baking by irregular pooling of lipid. Crumb air-cell size is influenced by starch granule swelling as well.

The dynamics of water loss throughout baking are the results of all these factors and are erratically affected when tunneling results, even though total water loss is statistically not different among formulations.

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