

# The Dynamics of Cake Baking as Studied by a Combination of Viscometry and Electrical Resistance Oven Heating<sup>1</sup>

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## ABSTRACT

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A combination of resistance oven heating and continuous oscillatory rod viscometry was used to monitor changes in cake batter viscosity during baking. This procedure measured the viscosity without degrading the batter by shear-thinning. Batter viscosity versus temperature plots illustrated a decrease in viscosity early in heating and a subsequent rapid increase, which was determined to be due to starch gelatinization. Major formula ingredients affected batter viscosity during the course of heating but in different ways. Sugar type and concentration affected the onset temperature of starch gelatinization and thereby the rapid viscosity

increase; sucrose was more effective than glucose or fructose. Shortening increased the viscosity at ambient temperature and decreased the rate of rapid viscosity increase but did not affect onset temperature. Egg white increased the viscosity of batter at ambient temperature and during heating. Fresh egg white produced higher minimum viscosities of heated batters and better cake volumes than dried egg white. The primary effect of hydrocolloids was maintenance of higher minimum viscosities of batters during heating but before starch gelatinization. Emulsifiers increased single-stage batter viscosity at ambient temperature and during heating.

Cake batters are complex fat-in-water emulsions with four bulk phases (aqueous, fat, gas, and solid starch granules). The physical properties of these batters play a large part in determining the characteristics of the resulting cakes. Among the physical properties of interest, viscosity appears to be particularly important, because it undergoes large changes during the baking process.

Differences in cake flour quality are not always manifested by differences in their batter properties at ambient temperature. This implies that the changes the batter undergoes during heating are critical. Many studies investigated the changes that occur during baking—in physical properties such as batter volume and bubble size, in the chemical components of starch and protein (Bell et al 1975, Dunn and White 1939, Handleman et al 1961, Miller and Derby 1964, Mizukoshi et al 1979, Mizukoshi et al 1980), and in rheological properties (Voisey 1979, Paton et al 1981, Mizukoshi 1985, Ngo et al 1985, Miller and Trimbo 1965, Gaines and Donelson 1982, Christianson et al 1981).

A problem associated with previous research on batter rheology during heating has been the shear-sensitive nature of the batters (Atwell 1986) and the existence of extreme temperature gradients within the product during conventional (conduction) baking (Gordon et al 1979). Resistance oven baking (Moore and Hosenev 1986, Dreese et al 1988) offers the possibilities of heating the entire batter mass uniformly and of reducing or eliminating temperature gradients. Likewise, recently developed viscometric techniques, which impose exceedingly small oscillatory strains at high frequency, are capable of measuring viscosity without degrading the batter (Shelke et al 1988, 1989).

The following study reports on the combined use of these two techniques in studying the effects of ingredients and additives on the dynamics of cake baking.

## MATERIALS AND METHODS

### Materials

The materials and their sources were as follows: dried egg white, Monark Egg Corp. (Kansas City, MO); cake flour (8.3% protein and 0.36% ash, 14.0% mb; pH 4.68), Mennel Milling Co. (Fostoria, OH); 6X sugar, Amstar Sugar Corp. (New York, NY); nonfat dry milk, Breddo, Inc. (Kansas City, KS); double-acting baking

powder, ADM Arkady (Olathe, KS); sodium chloride (reagent grade), Fisher Scientific Co. (Kansas City, KS); shortening, D10 (a partially hydrogenated mixture of soybean, palm, and cottonseed oils), Durkee Industrial Foods Corp. (Cleveland, OH); and emulsified shortening (Richtex), Kraft Industrial Foods Group (Memphis, TN). Hydrocolloids were commercial food grade samples of xanthan (Keltrol, Kelco Co., San Diego, CA), guar (Supercol U, Henkel Corp., Minneapolis, MN), and carboxymethylcellulose (CMC) (7HF, Hercules, Inc., Wilmington, DE). Reagent grade sucrose, glucose, and fructose (Fisher Scientific) were used. Emulsifiers used were propylene glycol monostearate (PGMS, PROMOPAN SP), Grindsted Products, Inc. (Industrial Airport, KS); lecithin (ADM Arkady, Olathe, KS); and mono- and diglycerides (Durkee, Cleveland, OH). Fresh eggs were obtained from the Department of Animal Science, Kansas State University, Manhattan.

### Methods

Cake batters were prepared using either the AACC approved method 10-90 (1976) or the single-stage, laboratory-scale method of Lee and Hosenev (1982) and Lee et al (1982). Absorptions for all cakes were adjusted using the control formulations (single-stage and AACC) in preliminary trials to produce an optimum cake. This level was maintained for all subsequent formulations. Ingredients and their incorporation levels in the AACC formula were as follows on a flour weight basis (fwb): surfactants—PGMS 4.00%, lecithin 0.81%, mono- and diglycerides 3.00%; shortening—30, 50, or 80%; sugar (sucrose, glucose, or fructose)—75, 100, 140, 175, or 200%; egg white—dried 9.00%, or fresh (solids) 9.00%; xanthan, guar, or CMC—0.10, 0.50, or 1.00%. Ingredients were substituted or varied one at a time.

Batter specific gravity (in grams per cubic centimeter) was determined as the ratio of the weight of a standard container filled with batter to that of the same container filled with water (specific gravity, 1 g/cm<sup>3</sup>). Standard deviation for all determinations was 0.016 g/cm<sup>3</sup>.

Batter viscosity (in centipoise) was determined using the Nametre Oscillating Rod Viscometer (model 710, Nametre Co., Metuchen, NJ) as specified by the manufacturer's operating instructions. Instrument operation was checked using viscosity standards (S200, S600, and S2000, Cannon Instrument Co., State College, PA). Standard deviation for the determination of batter viscosity at ambient temperature was 100 cP. Averages of triplicate trials are reported.

### Temperature Measurement During Baking

Batter temperatures during conventional oven baking were obtained at three points (center, wall, and half-radius) in an AACC cake batter (8-in. diameter cake pan, 375°C oven) by thermistors connected to a digital readout (Thermolyne Corp., Dubuque,

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IA). The temperature profile at the center position was used to establish the heating profile of the resistance oven (see below).

### Electrical Resistance Oven Baking

The electrical resistance oven (ERO) technique described by Moore and Hosoney (1986) for bread baking was modified for use with batter systems. Grooves at the opposite walls of the  $16.8 \times 10.3 \times 6.0$  cm (i.d.) Plexiglas container held two  $16.8 \times 6.3 \times 0.1$  cm steel plates. Cake batter (800 g) was poured between the plates and alternating current (controlled by a variable transformer) was applied. By virtue of its electrical resistance, the batter heated and was baked into a cake in  $20 \pm 3$  min. Heating rates were adjusted with the variable transformer to match the temperature profile at the center of conventionally baked cakes.

Cake specific volume (expressed in cubic centimeters per gram) was determined by weighing a known volume of the cake. The averages of triplicate trials are reported. Standard deviation for specific volume determinations was  $0.2 \text{ cm}^3/\text{g}$ .

### Viscosity Measurement During ERO Baking

The ERO was filled with the batter, and the viscometer and temperature sensor probes were inserted at a constant depth midway between the steel plates as shown in Figure 1. The viscometer was turned on and allowed to stabilize prior to ERO heating. Temperature and viscosity were recorded continuously

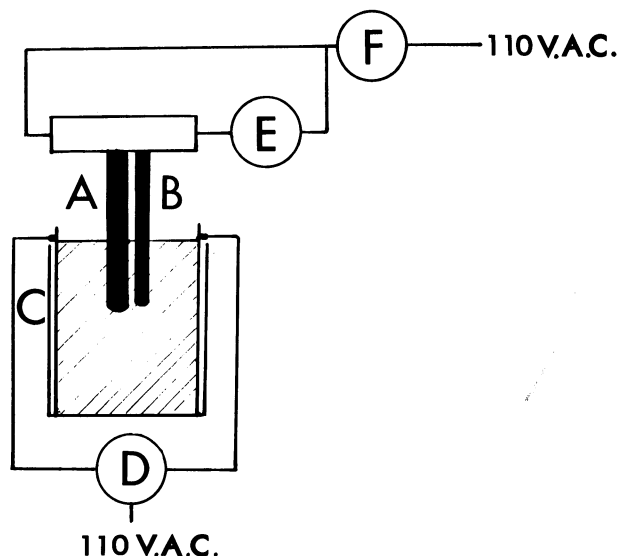


Fig. 1. Schematic diagram of the oscillatory viscometer and electrical resistance oven combination. Viscometer probe (A), temperature probe (B), electrical resistance oven (C), auto transformer (D), isolation transformer (F), two-pen recorder (E).

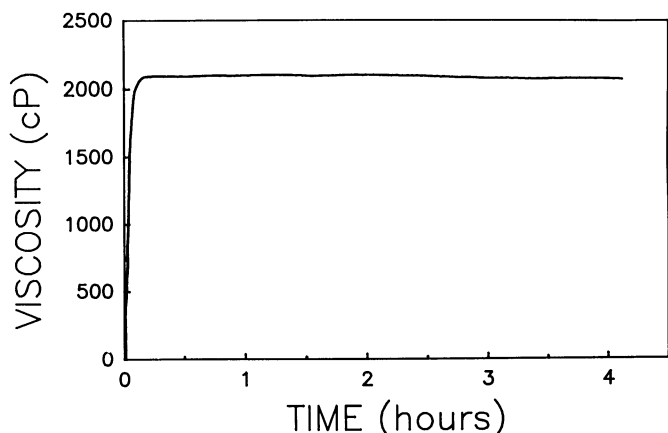


Fig. 2. Cake batter viscosity measured using the oscillatory rod viscometer at ambient temperature over an extended testing period (4 hr).

with a two-pen recorder. An isolation transformer was used to separate the electrical circuits of the viscometer from that of the ERO, to prevent interference by other electrical sources during heating. A constant level of batter in contact with the probe was maintained during heating and expansion by allowing the expanding batter to overflow the ERO chamber.

## RESULTS AND DISCUSSION

### Effect of Measurement Conditions

To be useful, viscosity should be measured without causing significant changes in the rheological properties of the batter. Figure 2 illustrates a viscosity versus time trace resulting from the continuous analysis of an AACC cake batter at ambient temperature over an extended (4-hr) period. The minimal change in batter viscosity illustrates the ability of the instrument to measure batter viscosity without the loss of viscosity that often accompanies empirical, high-shear testing techniques (e.g., capillary and rotational viscometers).

### ERO Cake Characteristics

The temperature versus time curves for points in the resistance oven AACC cakes (Fig. 3) were sigmoidal and peaked at less than  $100^\circ\text{C}$ . These results, obtained by adjusting the potential applied to the plates in the ERO, are in close agreement with those obtained by Mizukoshi et al (1979) for sponge cake baking. There were no differences (gradients) between the center and edge temperatures during heating.

Although ERO cakes did not brown, their interior crumb characteristics were similar to those of a conventional cake. Table I compares the specific volumes of cake batters and the final products baked in the conventional oven and in the ERO.

### Batter Viscosity During Heating

The viscosity of a typical AACC formula batter system as it heats is shown in Figure 4. As batter temperature increased from ambient to  $60^\circ\text{C}$ , batter viscosity decreased to a minimum value approximately 10% of that at ambient temperature. Continued heating above  $60^\circ\text{C}$  resulted in a rapid increase in viscosity.

TABLE I  
Specific Volumes ( $\text{cm}^3/\text{g}$ ) of Cake Batters and Final Products Baked in Conventional and in Electrical Resistance Ovens

| Sample                 | Batter | Cake Baked in     |                            |
|------------------------|--------|-------------------|----------------------------|
|                        |        | Conventional Oven | Electrical Resistance Oven |
| AACC white layer cake  | 1.1    | 4.7               | 4.5                        |
| Commercial yellow cake | 1.4    | 3.3               | 3.2                        |
| Pound cake mix         | 1.5    | 3.2               | 3.2                        |

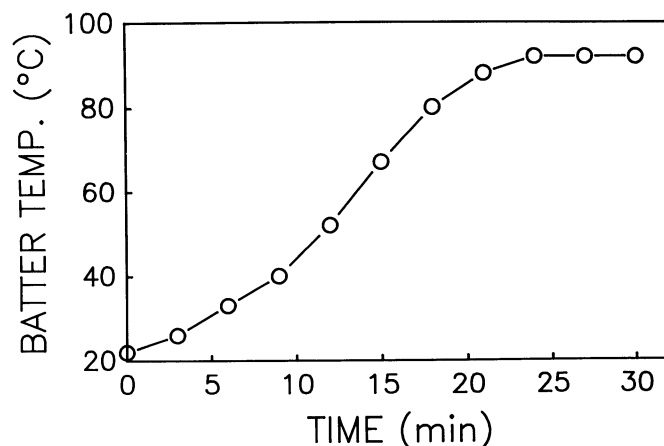


Fig. 3. Temperature profile of the AACC cake batter during electrical resistance oven heating.

Extrapolation of this portion of the curve to the baseline showed that the onset of the rapid increase in viscosity was at approximately 83°C (Fig. 4). To assess whether the rapid increase in batter viscosity could be attributed to starch gelatinization, aliquots of the batter were taken at regular intervals during heating and viewed microscopically under regular and polarized light (Fig. 5). Partial and complete loss of starch granule birefringence at 80 and 83°C, respectively, corresponded to the change in viscosity and confirmed that starch gelatinization was responsible for the change. These data are in agreement with values reported for starch gelatinization temperature in cake systems (Miller and Trimbo 1965, Howard et al 1968).

Viscosity versus temperature plots clearly showed the rate at which viscosity changes occurred during baking. Thus, such plots should be helpful in understanding the role of various ingredients and solving problems associated with cake baking.

### Ingredients

**Shortening.** The effect(s) of increasing levels of emulsified (mono- and diglycerides) shortening on viscosity and temperature profiles of AACC white layer cake batters are shown in Table II. Control batters contained 50% (fwb) shortening. Batter viscosity at ambient temperature increased with increased levels of shortening in the batter. Conversely, minimum viscosity of heated batter decreased with increased shortening levels.

The onset temperature of the rapid viscosity increase (starch gelatinization) was not affected significantly by shortening level. However, the rate of the viscosity increase decreased with increased shortening levels.

Increasing shortening levels in the AACC cake formulation decreased end product volume (Table II). Lower viscosity during heating, coupled with reduced rates of viscosity increase during setting, explains the phenomenon. Shortening is reported to limit

starch swelling (Ghiasi et al 1982). The reductions in the rate of viscosity increase reflected restricted starch swelling and were in agreement with previous reports of Ghiasi et al (1982) and D'Appolonia (1972).

**Surface-active agents.** High-ratio, single-stage cakes require the presence of surfactants to achieve acceptable volumes. In particular, the use of PGMS (or similar compounds) is required to facilitate incorporation of sufficient air in the aqueous phase of batters during mixing (Wootton et al 1966). Table III compares the viscosities of single-stage cake batters made with shortening with and without surfactants (PGMS, lecithin, mono- and diglycerides). The presence of emulsifiers had a significant positive effect on viscosity at ambient temperature. This reflects their ability to promote air incorporation in the batter, as is shown by specific gravity measurements of the same batters (Table III).

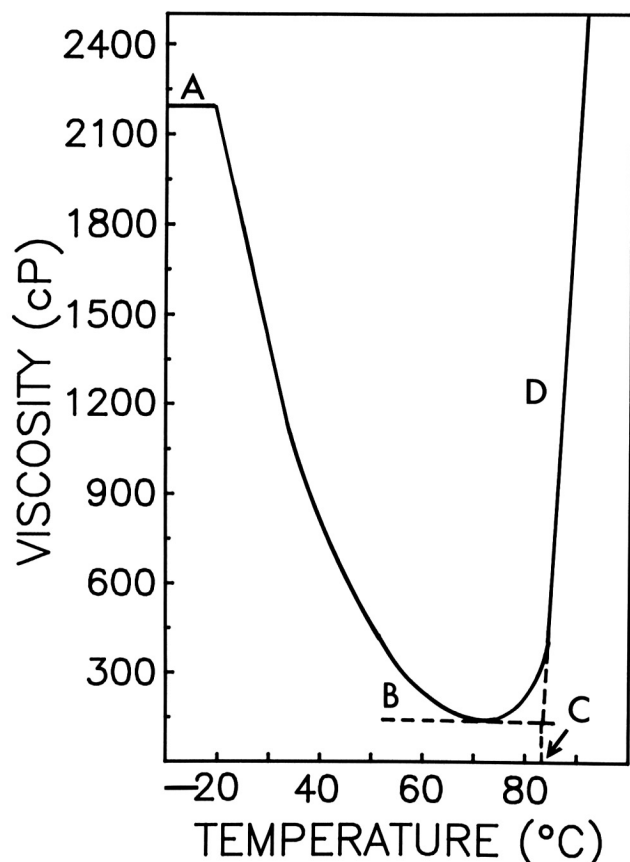
Batters containing surfactants maintained higher viscosities

**TABLE II**  
The Effect of Increasing Levels of Emulsified Shortening on AACC White Layer Cake Batters

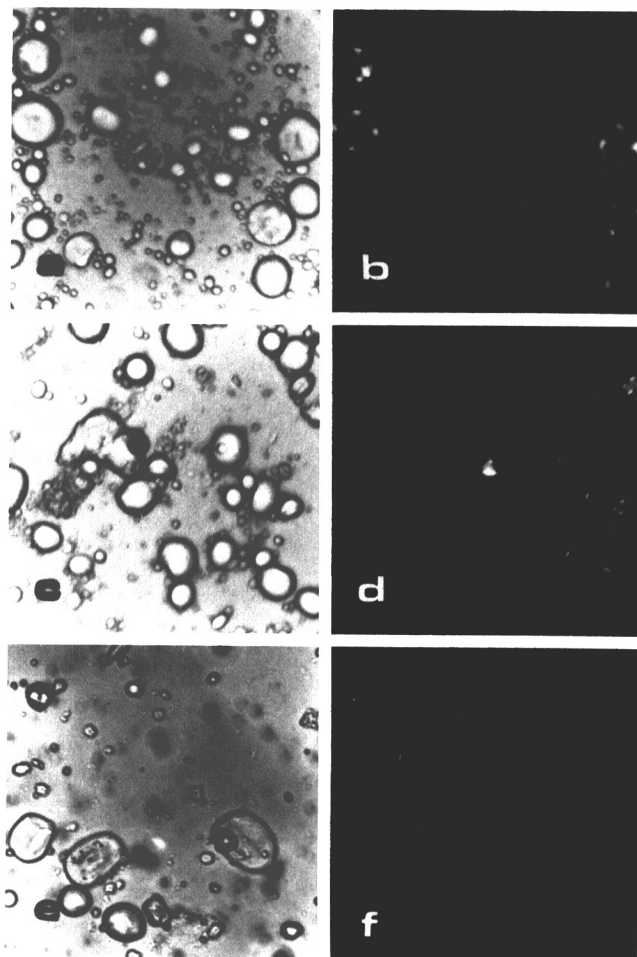
| Shortening (% fwb) | Viscosity (cP)      |                            | Onset Temperature (°C) | Onset Slope (cP/°C) | Onset Volume (cm <sup>3</sup> ) |
|--------------------|---------------------|----------------------------|------------------------|---------------------|---------------------------------|
|                    | Ambient Temperature | Heated Batter <sup>a</sup> |                        |                     |                                 |
| 30                 | 1,540 ± 20          | 108 ± 5                    | 83 ± 0.5               | 81                  | 995 ± 10                        |
| 50 <sup>b</sup>    | 1,950 ± 25          | 85 ± 5                     | 83 ± 0.5               | 56                  | 955 ± 10                        |
| 80                 | 2,250 ± 25          | 50 ± 5                     | 83 ± 0.5               | 43                  | 875 ± 05                        |

<sup>a</sup>At the minimum point.

<sup>b</sup>Control.



**Fig. 4.** Viscosity-temperature profile of the AACC cake during heating. Viscosity at ambient temperature (A), minimum viscosity of heated batters (B), onset temperature of rapid viscosity increase (C), and rapid viscosity increase (D).



**Fig. 5.** Photomicrographs, under regular and polarized light, of starch granules taken from AACC cake batter during heating in an electrical resistance oven at 75°C (a and b), 80°C (c and d), and 83°C (e and f).

throughout the heating process, particularly at the point of minimum viscosity (Table III). Surfactant presence had no significant effect on the onset temperature of the rapid increase in viscosity but did reduce the rate of viscosity increase after the onset.

Taken together, the data suggest that surfactants function in single-stage batters by increasing the air incorporated in the batter and maintaining a higher minimum batter viscosity during heating. The higher viscosities during the heated batter stage prevent coalescence, migration, and loss of air cells before the batter sets.

**Sugars.** Sugars can increase the temperature at which starch gelatinization occurs (Bean and Yamazaki 1973, Ghiasi et al 1982, Spies and Hoseney 1982). For comparison of the effects of sugars, the sucrose in the AACC cake formula (140% fwb) was adjusted to 75, 100, 175, and 200% (fwb) (Table IV), and replaced with glucose and fructose at these levels (data not shown). Batter viscosity at ambient temperature increased as sugar concentration increased. The batter contained a higher ratio of solids at ambient temperature than during heating because not all of the sugar was dissolved prior to heating. As batter temperature increased, the sugar dissolved, resulting in greater total volume and reduced viscosity. These changes explain the greater decrease in minimum viscosity with increased sugar content (Ghiasi et al 1982).

The onset temperature for the AACC formulation was 83°C, which is the characteristic starch gelatinization temperature in high-ratio cakes. This temperature increased with increased sugar

TABLE III  
Effects of Emulsifiers on Single-Stage Cake Batters

| Emulsifiers <sup>a</sup> | Specific Gravity (g/cm <sup>3</sup> ) | Cake Volume (cm <sup>3</sup> ) | Viscosity (cP)      |               | Onset Temperature (°C) |
|--------------------------|---------------------------------------|--------------------------------|---------------------|---------------|------------------------|
|                          |                                       |                                | Ambient Temperature | Heated Batter |                        |
| Present                  | 0.879                                 | 1,015 ± 05                     | 2,350 ± 20          | 128 ± 10      | 76.5 ± 0.5             |
| Absent                   | 1.124                                 | 765 ± 10                       | 1,670 ± 25          | 55 ± 5        | 77.0 ± 0.5             |

<sup>a</sup>Surfactants used were propylene glycol monostearate, lecithin, and mono- and diglycerides.

TABLE IV  
The Effect of Different Levels of Sucrose on Viscosity and Onset Temperature of AACC Cake Batters

| Sucrose (% fwb)  | Viscosity (cP)      |                            | Onset Temperature (°C) |
|------------------|---------------------|----------------------------|------------------------|
|                  | Ambient Temperature | Heated Batter <sup>a</sup> |                        |
| 75               | 1,400 ± 30          | 115 ± 5                    | 76.0 ± 1.0             |
| 100              | 1,500 ± 25          | 100 ± 5                    | 78.0 ± 0.5             |
| 140 <sup>b</sup> | 1,950 ± 20          | 85 ± 5                     | 83.0 ± 0.5             |
| 175              | 2,150 ± 25          | 70 ± 5                     | 91.0 ± 0.5             |
| 200              | 2,285 ± 30          | 60 ± 5                     | 93.0 ± 0.5             |

<sup>a</sup>At the minimum point.

<sup>b</sup>Control.

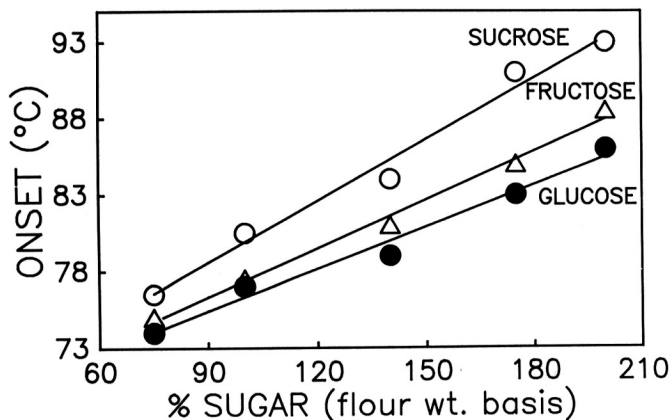


Fig. 6. Effect of increasing levels of sucrose, glucose, or fructose on the onset temperature of rapid viscosity increase. AACC cake batter was measured during heating in an electrical resistance oven.

concentration (Table IV).

Replacement of sucrose with glucose or fructose showed similar trends. The effects of sucrose, glucose, and fructose on viscosity during heating are compared in Figure 6. Onset temperature is plotted as a function of sugar concentration (fwb). All three sugars increased the onset temperature, but at equal concentrations sucrose was most effective.

**Egg white.** Because they can be beaten into stable protein foams that set with heating, egg whites might be expected to have large effects on batter viscosity during heating. Table V compares the viscosities of AACC white layer cake batters prepared without egg whites or with dried or fresh egg whites. With no egg white in the formula, both viscosity at ambient temperature and minimum viscosity during heating were significantly lower than control values. Both viscosities were higher in batter containing fresh egg white than in that containing dried egg white. Neither the presence nor the type of egg white in the formula had any effect on the temperature of rapid viscosity onset (starch gelatinization). The higher viscosities of the fresh egg white batter produced better cakes, as confirmed by conventional baking results (data not shown).

TABLE V  
Comparison of AACC White Layer Cake Batters Prepared With and Without Egg Whites

| Egg White     | Viscosity (cP)      |                            | Onset Temperature (°C) | Cake Volume (cm <sup>3</sup> ) |
|---------------|---------------------|----------------------------|------------------------|--------------------------------|
|               | Ambient Temperature | Heated Batter <sup>a</sup> |                        |                                |
| Dried control | 1,950 ± 20          | 85 ± 5                     | 83.0 ± 0.5             | 955 ± 10                       |
| Fresh         | 2,200 ± 25          | 110 ± 5                    | 83.0 ± 0.5             | 990 ± 05                       |
| None          | 1,600 ± 20          | 50 ± 5                     | 83.0 ± 0.5             | 835 ± 10                       |

<sup>a</sup>At the minimum point.

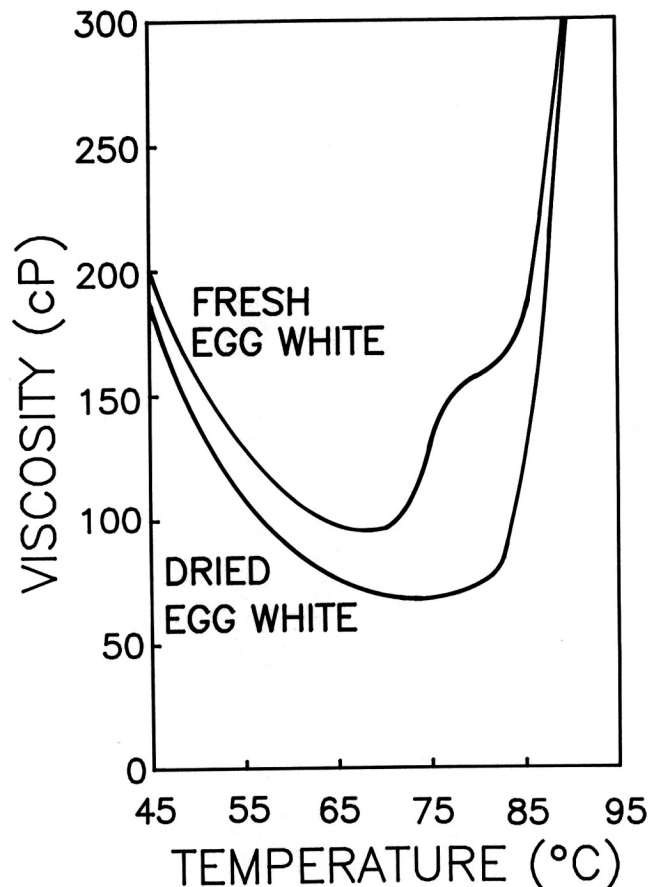


Fig. 7. Viscosity-temperature plots of the minimum viscosity stage of heated AACC cake batters containing no, fresh, and dried egg whites.

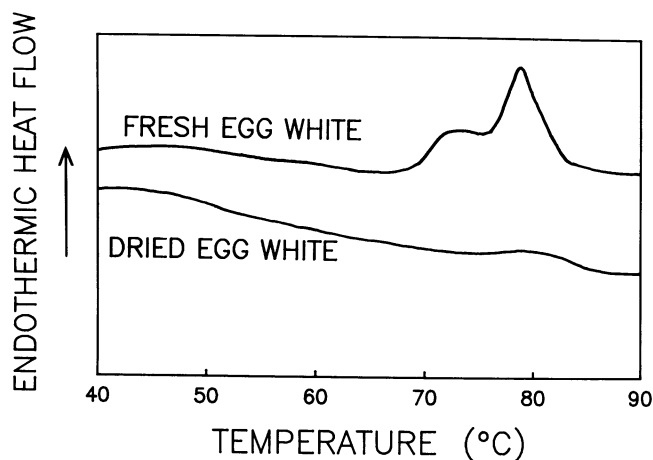


Fig. 8. Differential scanning calorimetric scans of fresh and rehydrated dried egg whites.

Additional differences between fresh and dried egg whites are evident from inspection of their viscosity versus temperature plots (Fig. 7). The discontinuity or shoulder at 70°C, present in fresh but absent in dried egg whites, was assumed to be caused by the denaturation of egg white protein in the batter. DSC analyses (Fig. 8) of fresh and rehydrated dried whites confirmed the presence of a peak at 70°C for fresh whites that was absent from scans of rehydrated, dried egg whites.

**Hydrocolloids.** Although not present in the AACC formulation, hydrophilic gums (hydrocolloids) are frequently added to cake batters to improve final product crumb grain and volume. The effects of incorporating increasing levels of three common hydrocolloids (xanthan, guar, and CMC) on batter viscosity are presented in Table VI. As might be predicted, the presence of the hydrocolloid increased batter viscosity at ambient temperature over control values. The largest difference between the control and the hydrocolloid-containing batters was for minimum viscosity of heated batter. At this point, xanthan was able to maintain higher batter viscosities than guar or CMC when present at equivalent levels. Higher viscosity during heating would give the batters greater capacity to retain expanding air nuclei and resist settling of starch granules, thereby improving both cake volume and crumb grain.

The hydrocolloids affected the rate of rapid viscosity increase during heating (Table VI). At the highest concentration tested, xanthan slowed the rate of viscosity increase slightly. Conversely, the highest level of guar (1.0%) increased the rate of viscosity increase by roughly 20%. This was also the case for CMC.

## CONCLUSIONS

The combination of oscillatory viscometry and electrical resistance heating techniques was applicable to the continuous observation of the cake baking system and could be used to follow the effects and roles of various ingredients on batter viscosity and cake quality during heating.

The viscosity of the batter during heating decreased to a minimum, then increased rapidly at 80–85°C. The setting of the batter coincided with the gelatinization of starch in the system. Of the ingredients studied, sugars, emulsifiers, shortening, egg white, and gums significantly affected batter viscosity. The course of gelatinization in cake batters was affected greatly by several ingredients. Sugars increased the onset temperature of the rapid viscosity increase, with sucrose being more effective than glucose and fructose. Shortening did not affect the onset temperature but affected the rate at which the rapid viscosity increase occurred. Cake volume was greater with fresh egg white, which gave higher batter viscosities both at ambient and higher temperatures. Hydrocolloids improved cake volume and texture by substantially increasing the viscosity of the batter at all points during heating. In a single-stage cake-mix type formulation, emulsifiers increased

TABLE VI  
The Effects of Xanthan, Guar, and CMC<sup>a</sup> on Batter Viscosity, Onset Temperature, and Volume of AACC White Layer Cake

| Hydrocolloid (% fwb) | Viscosity (cP)      |                            | Onset Temperature (°C) | Onset Slope (cP/°C) | Cake Volume (cm <sup>3</sup> ) |
|----------------------|---------------------|----------------------------|------------------------|---------------------|--------------------------------|
|                      | Ambient Temperature | Heated Batter <sup>b</sup> |                        |                     |                                |
| Control              |                     |                            |                        |                     |                                |
| 0                    | 1,950 ± 20          | 85 ± 5                     | 83.0 ± 0.5             | 81 ± 3              | 955 ± 10                       |
| Xanthan              |                     |                            |                        |                     |                                |
| 0.1                  | 2,180 ± 25          | 110 ± 5                    | 83.0 ± 0.5             | 75 ± 5              | 985 ± 05                       |
| 0.5                  | 2,245 ± 25          | 145 ± 5                    | 83.0 ± 0.5             | 67 ± 3              | 990 ± 05                       |
| 0.8                  | 2,285 ± 20          | 170 ± 5                    | 83.0 ± 0.5             | 65 ± 5              | 1,005 ± 10                     |
| 1.0                  | 2,350 ± 30          | 195 ± 5                    | 83.0 ± 0.5             | 58 ± 3              | 1,015 ± 05                     |
| Guar                 |                     |                            |                        |                     |                                |
| 0.1                  | 2,000 ± 20          | 90 ± 5                     | 83.0 ± 0.5             | 81 ± 3              | 975 ± 05                       |
| 0.5                  | 2,195 ± 20          | 110 ± 5                    | 83.0 ± 0.5             | 98 ± 3              | 990 ± 10                       |
| 1.0                  | 2,285 ± 25          | 120 ± 5                    | 83.0 ± 0.5             | 105 ± 5             | 1,005 ± 05                     |
| CMC                  |                     |                            |                        |                     |                                |
| 0.1                  | 2,195 ± 20          | 95 ± 5                     | 83.0 ± 0.5             | 85 ± 3              | 980 ± 05                       |
| 0.5                  | 2,250 ± 25          | 115 ± 5                    | 83.0 ± 0.5             | 93 ± 3              | 995 ± 10                       |
| 1.0                  | 2,350 ± 35          | 135 ± 5                    | 83.0 ± 0.5             | 105 ± 5             | 1,000 ± 10                     |

<sup>a</sup>Carboxymethylcellulose.

<sup>b</sup>At the minimum point.

viscosity at ambient temperature and, perhaps more importantly, increased minimum viscosities during heating.

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