Model Studies of Cake Baking. V. Cake Shrinkage and Shear Modulus of Cake Batter During Baking

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ABSTRACT

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A relationship between cake shrinkage and structural development of cake batter during baking was investigated. Sugar concentration markedly affected cake batter expansion, cake volume, and cake shrinkage. A shear modulus measurement of cake batter during model baking revealed that sugar retards structural development of batter. Cake shrinkage after baking decreased linearly with increasing shear modulus of degassed cake. Shear modulus of baked cake decreased with increasing amounts of air bubbles incorporated in the cake. An equation was developed to compare shear modulus and cake porosity.

Cake shrinkage, collapse, or dipping is one of the most undesirable faults in cake making. Few studies of the mechanism of cake shrinkage have been reported. Kissell and Marshall (1962) and Kissell (1967) reported that a high baking powder ratio or a high sugar to water ratio causes dips in cakes. Ohtsubo et al (1978) reported that a mechanical shock to the cake immediately after baking was sufficient to prevent shrinkage as the cake cooled. Clements and Donelson (1982a,b) studied the effect of flour treatment on cake batter expansion and shrinkage after baking.

To clarify the mechanism of cake shrinkage, it is desirable to measure the rheological properties of cake batter during baking to understand the contribution of mechanical properties to cake structure. Miller and Trimbo (1965) studied the association between cake quality and structural development and found it coincided with starch gelatinization. Russo and Doe (1970) observed chlorinated and unchlorinated flours and starches in a buffered slurry containing sugar and heated in an amylograph. Frazier (1974) measured the gel strength of flour and water slurries and compressed cake crumb from chlorinated and untreated flours. Voisey et al (1979) and Paton et al (1981) studied the cohesive force developed in the cake during baking. Mizukoshi et al (1979) studied viscosity changes simultaneously with starch gelatinization and protein coagulation in a model system. Gaines and Donelson (1982) used a modified viscograph to measure viscosities of cake batters during heating.

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Other papers concerning cake baking mechanisms have examined starch gelatinization and protein coagulation (Mizukoshi et al 1979), batter expansion and heat setting (Mizukoshi et al 1980), cake foam stability (Mizukoshi 1983a), and foam drainage (Mizukoshi 1983b). This study reports the effects of sugar concentration on batter expansion during baking and cake shrinkage after baking. A well-defined and universal rheological unit, shear modulus, is introduced to measure the structural development in cake batter during baking. Finally, shear modulus is used to describe the mechanism of cake shrinkage and the development of the porous structure of cake.

MATERIALS AND METHODS

Cake ingredients, cake formulation, preparation of cake batter, and a model baking method have been reported previously (Mizukoshi et al 1979, 1983a). The standard cake formulation used was cake flour (400 g), sugar (480 g), whole egg (600 g), foaming agent (emulsifier) (20 g), and water (80 g). To measure the effect of sugar on baking expansion, seven cake batters containing 0, 40, 80, 120, 160, 200, and 240% sugar (flour basis) were prepared. Cake heights at center and edge were monitored during baking by the method of Clements and Donelson (1981). The approximate batter volume during baking was calculated by the equation: $V = (h_1 + h_2)\pi r^2/2$, where V = batter volume (ml), h_1 = center height (cm), h_2 = edge height (cm), π = 3.14, and r = cake pan radius (9 cm). The volume of baked cake was determined by rapeseed displacement. All actual and model baking data are the means of duplicate measurements.

Measurement of Shear Modulus

All cake ingredients were mixed for 0.5 min at 58 rpm and 3 min at 116 rpm under 3 cmHg pressure with a vacuum mixer (type 5DMV, Shinagawa Kōgyōsho Co., Ltd.) to avoid incorporation of gas bubbles in the cake batter. Eight grams of cake batter was weighed in a stainless steel sample cell (1.5×2.5 cm at the base) and covered with a polyvinylidenechloride film bag (40 μm thick). A rectangular stainless plate (2.5 × 3.5 × 0.1 cm) attached with a steel pin was placed in the center of the sample cell (Fig. 1). The sample cell was placed in a water bath for the viscosity measurements of the model baking system (Mizukoshi et al 1979). After the sample cell was heated for 50 min, or to the desired temperature, it was immediately placed in ice water for 5 min to quickly bring the contents to 20°C, then in another water bath for 15 min at 20°C. Temperature changes of the water baths and the center of the cake batter in the sample cell were recorded continuously. The polyvinylidenechloride bag was removed before measurement of shear modulus.

Shear modulus measurements were made with a Tensilon tensile tester (model UTM-III-100) and recorder (SS-207D-ZA) from Toyo Baldwin Co., Ltd. The elastic limit of a gel was never exceeded so that a single specimen was used in each experiment to eliminate errors due to sample preparation. A crosshead speed of 0.4 cm/min and chart speed of 20 cm/min were used, and tensile strength at 0.1 cm of sample was measured. Shear modulus was calculated by the following equation (Nakagawa 1978):

$$G = (PH/2Sd) \quad (1)$$

where G = shear modulus (dyne/cm^2), P = tensile strength (dyne), H = thickness of the gel on both sides of the plate (1.2 cm), S = area of the plate immersed in the gel (cm^2), and d = distance of shift of the plate (0.1 cm). All data of shear modulus are the means of triplicate measurements.

To investigate the effect of the porosity of cake on shear modulus measurements, eight cake batters having various specific gravities were prepared by adjusting the vacuum in the mixer from 76 to 3 cmHg. From each vacuum treatment 5 g of cake batter was placed in a sample cell. Cake porosity was calculated by the following equation:

$$\phi = 1 - (W_1/V_1)/(W_2/V_2) \quad (2)$$

where ϕ = porosity (volume fraction pores), W_1 = weight of sample gel (g), V_1 = volume of sample gel (ml), W_2 = weight of degassed gel (g), and V_2 = volume of degassed gel (ml).

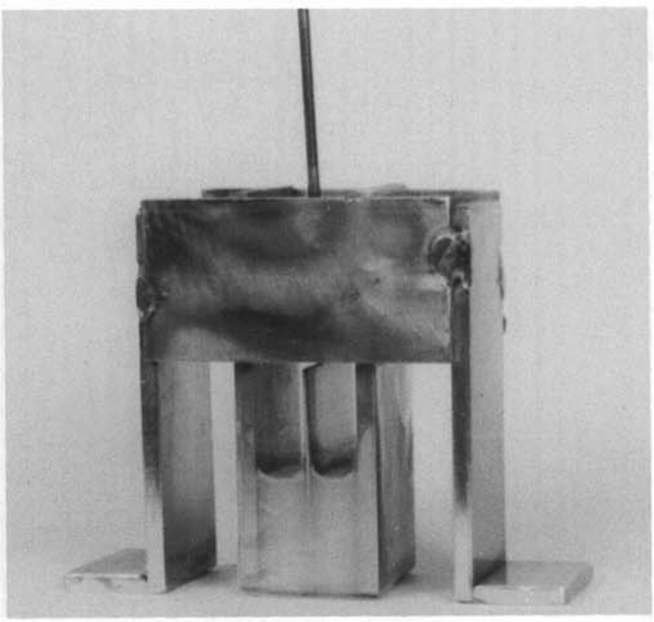

Fig. 1. Sample cell used to measure shear modulus.

RESULTS AND DISCUSSION

Oven Baking

The approximate batter volume during baking of batters containing seven sugar levels (0, 40, 80, 120, 160, 200, and 240%) are

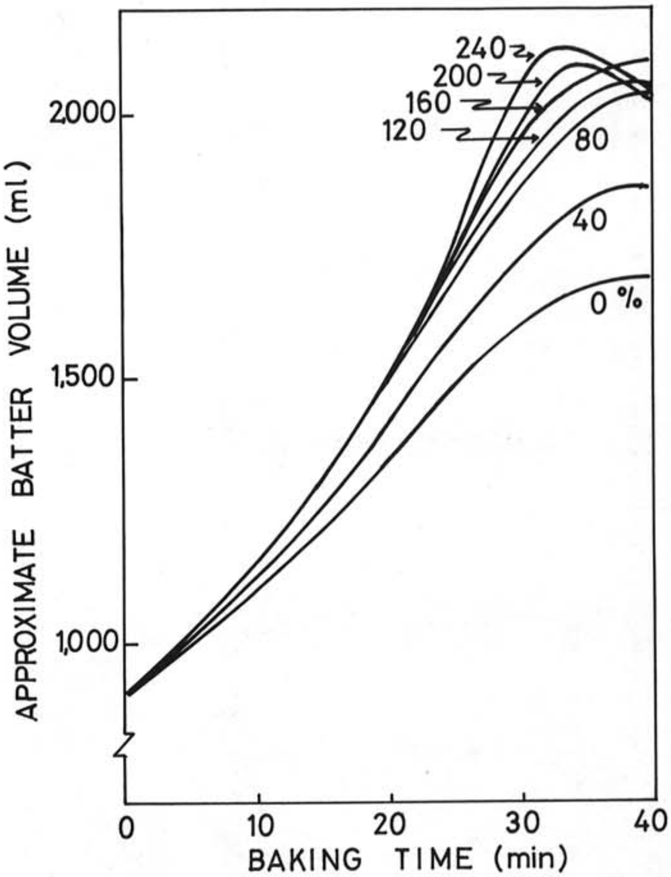

Fig. 2. Approximate expansion of cake batters containing 0–240% sugar (flour basis) during oven baking.

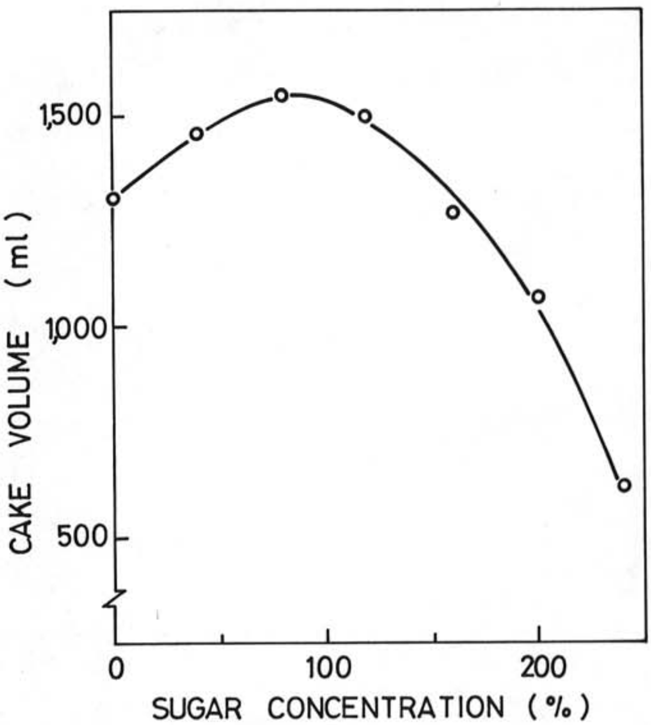

Fig. 3. Relationship between cake volume and sugar concentration.

shown in Figure 2. Though the batter expansion increased with increasing sugar concentration and increasing baking time, expansion of batters containing 200 and 240% sugar decreased during the final baking stage. The relation of cake volume after cooling to sugar concentration is shown in Figure 3, and cross-section photographs of cakes are shown in Figure 4. Maximum cake volume was attained at the 80% sugar level. These data indicated that the sugar concentration of cake batter markedly affected the batter expansion, cake volume, and shrinkage during cooling.

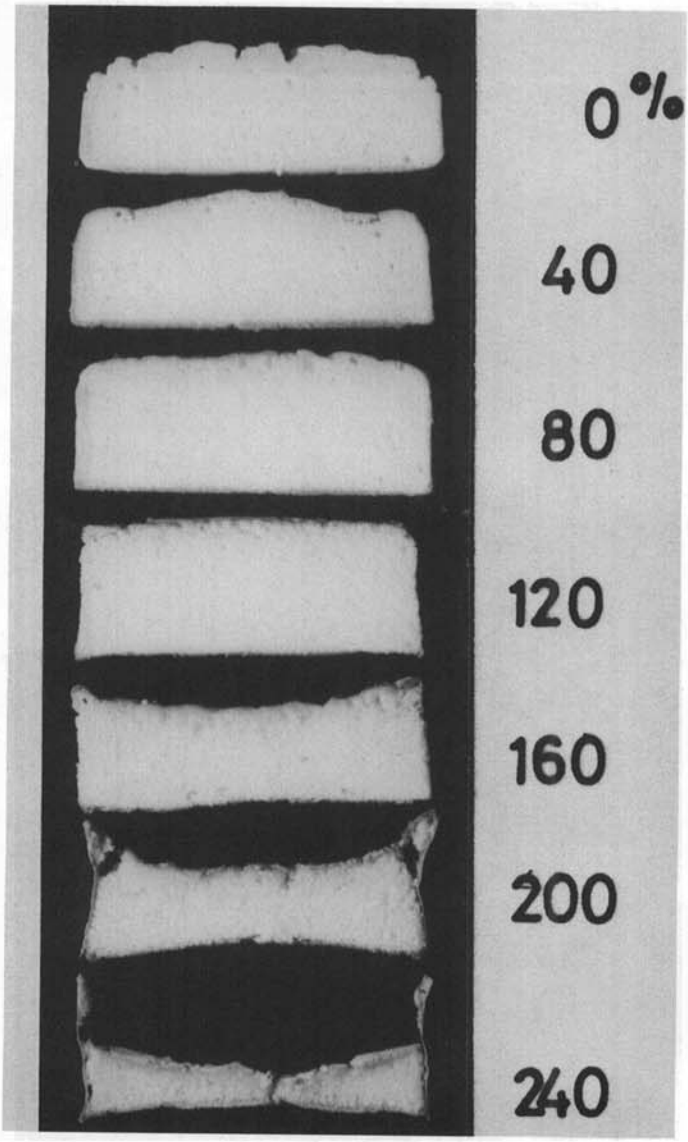

Fig. 4. Cross sections of cakes made from cake batters containing 0–240% sugar (flour basis).

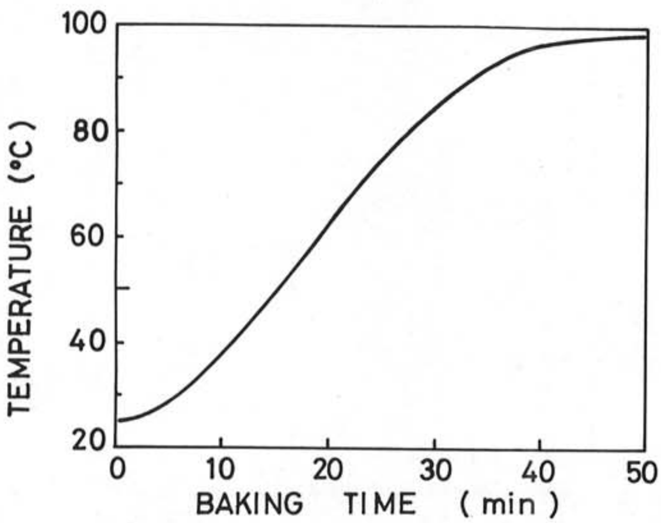

Fig. 5. Temperature profile for the shear modulus measurement of a batter during model baking.

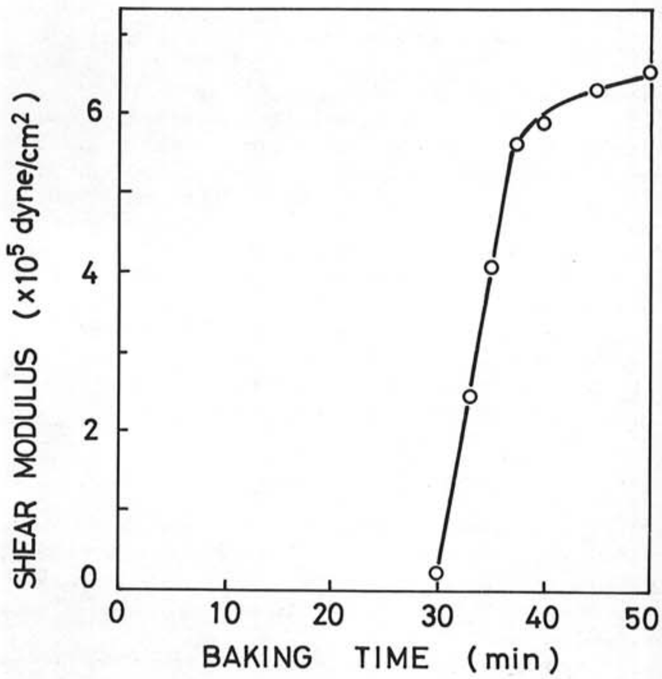

Fig. 6. Shear modulus changes of cake batter during model baking.

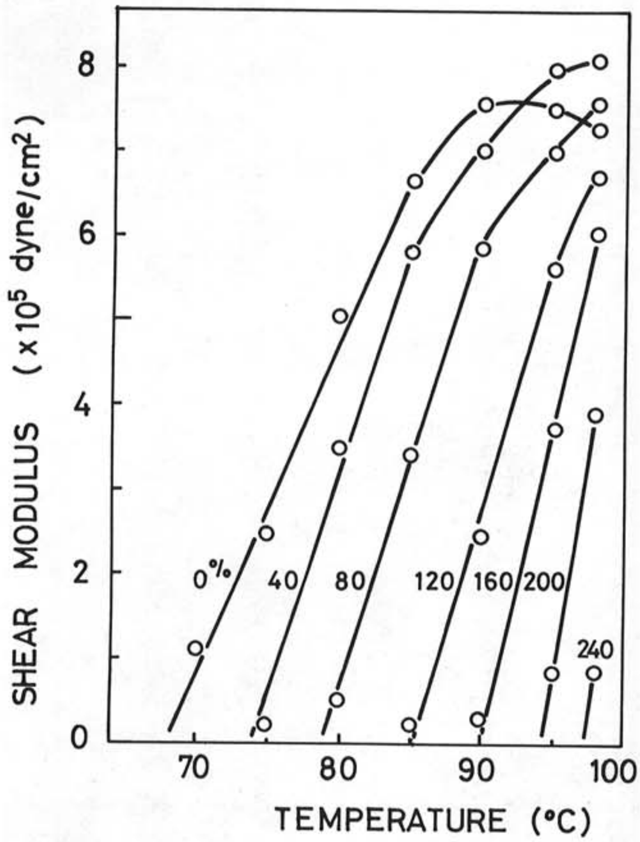

Fig. 7. Shear modulus changes of cake batters during model baking containing 0–240% sugar.

Temperature and Shear Modulus Changes During Model Baking

Temperature changes at the center of cake batter in a sample cell for shear modulus measurement during model baking are shown in Figure 5. The temperature of cake batter increased with baking time in the early and middle stages of baking. After 30 min the temperature was about 85° C, gradually increased to 97° C after 40 min, and finally reached 98° C at the end of baking. After 30 min of baking, shear modulus increased linearly with baking time and was finally asymptotic to 6.7×10^5 dyne/cm^2 during the final stage of baking (Fig. 6). Early structural development has been attributed to starch gelatinization and final structural development to protein coagulation in cake batter (Mizukoshi et al 1979).

Effect of Sugar Concentration on Structural Development

Increasing sugar levels retarded structural development (Fig. 7). The initial temperature of structural development increased from 68° C with no sugar to 97° C with 240% sugar. Maximum shear modulus was observed at the 40% sugar level, and higher sugar levels decreased shear modulus (Fig. 8).

Cake Shrinkage and Shear Modulus

Cake shrinkage (the difference between the maximum calculated volume of batter during oven baking and cake volume after cooling) and shear modulus were linearly related (Fig. 9). The coefficient of correlation for cake shrinkage and shear modulus was −0.972. The regression equation was: cake shrinkage = 1,538 − 0.00142 shear modulus. These data reveal that cake shrinkage is a balance between the shrinking force exerted by the decreasing inner pressure of gas bubbles as they cool and the resistance to this force, expressed in this study as a shear modulus of gel (crumb) strength surrounding the bubbles. It may therefore be said that a cake producing a low shear modulus has greater shrinkage during cooling.

Cake Porosity and Shear Modulus

The effects of porosity on mechanical properties have been investigated by many authors working in other fields (Dewey 1947, MacKenzie 1950, Coble and Kingery 1956, Okano 1962, Fryxell and Chandler 1964, Uemura and Takayanagi 1966).

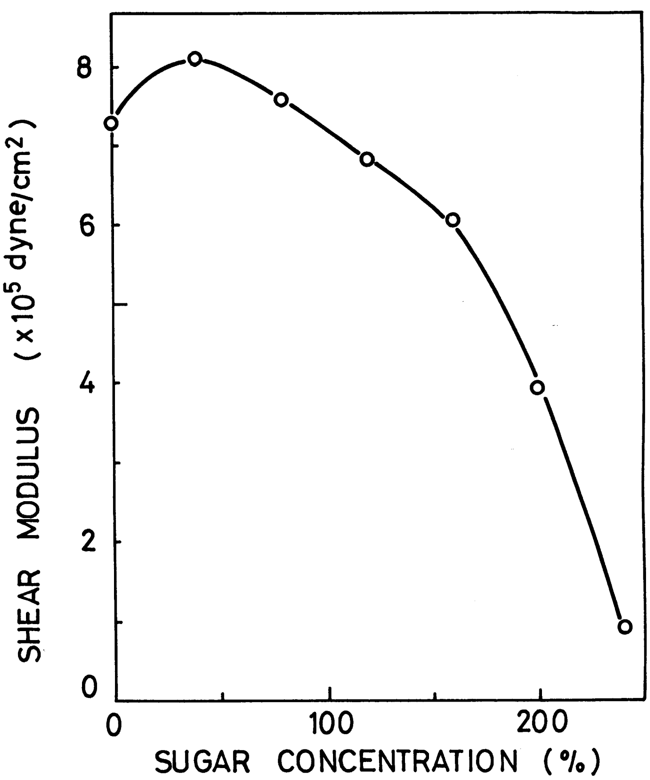

Fig. 8. Relationship among shear modulus measurements of batter temperature (at 98° C) and sugar concentration during model baking.

MacKenzie (1950) proposed the following equation for the effect of porosity on shear modulus:

$$G = G_o\,[1 - 5(3K_o + 4G_o)\phi/(9K_o + 8G_o) - A\phi^2] \quad (3)$$

where G = shear modulus of real material (dyne/cm^2), G_o = shear modulus of medium (dyne/cm^2), K_o = bulk modulus of medium (dyne/cm^2), ϕ = porosity (volume fraction of pores), and A = constant.

Poisson's ratio is presented by the following equation:

$$\delta_o = (3K_o - 2G_o)/(6K_o + 2G_o) \quad (4)$$

where δ_o = Poisson's ratio of medium.

From equations 3 and 4:

$$G = G_o[1 - 15(1 - \delta_o)/(7 - 5\delta_o)\,\phi - A\phi^2]. \quad (5)$$

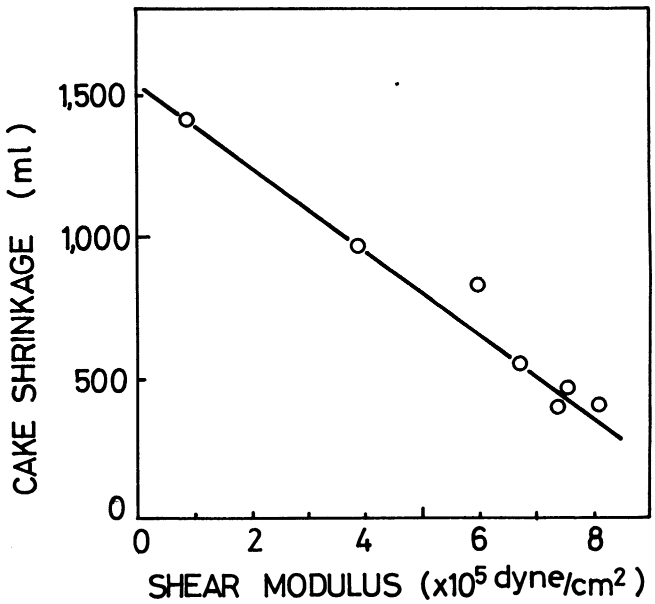

Fig. 9. Relationship between cake shrinkage during cooling and shear modulus.

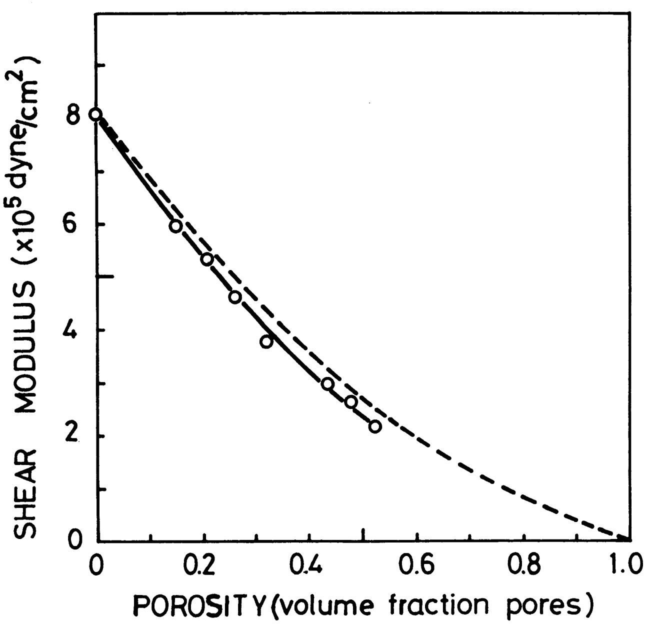

Fig. 10. Relation between shear modulus and porosity of cake. Dashed line is from calculated values.

It can be determined semiempirically that A is −0.67 by setting $G/G_0 = 0$ at $\phi = 1$ and $\delta_0 = 0.5$. Finally, the following equation was derived for this cake system:

$$G = G_0(1 - 1.67\phi + 0.67\phi^2) \qquad (6)$$

The relationship between shear modulus, the observed values of porosity, and those values calculated by equation 6 are shown in Figure 10. Although MacKenzie's equation indicated a slightly larger value of shear modulus than was observed, it appears to be a good estimator for cake systems. Shear modulus was strongly affected by cake porosity as long as the same component (sugar) was changed systematically. Therefore, when a relationship exists between a mechanical property, such as shear modulus, and a formulation change, it is important not to neglect the overall structural properties of the system. For this reason, the experiments to observe the effect of sugar on shear modulus were conducted on cakes containing no gas bubbles, that is, $\phi = 0$.

These results lead to the following conclusions: 1) sugar concentration of cake batters markedly affected batter expansion, cake volume, and cake shrinkage; 2) shear modulus measurements revealed that sugar retarded the structural development of cake batter during baking; 3) cake shrinkage after baking was closely related to the shear modulus of degassed cake; and 4) the effect of the porosity of cake batter was strongly correlated to shear modulus values, making it necessary to measure the shear modulus of cake batter at zero porosity (degassed).

The shear modulus measurements described in this study have been shown to be useful for the investigation of cake structural development. This method may be applicable to the study of other formulated and processed cereal and protein-based foods.

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