

Tools and Theories to Understand Cake Baking— Focus on Foam-to-Sponge Conversion

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ABSTRACT

Worldwide the food industry is under pressure to reduce caloric values of sweet bakery products such as cakes. In addition, there is a need to optimize baking processes so that both energy consumption and waste generation can be reduced. Irrespective of the product, understanding fundamental mechanisms behind the changes occurring during processing is key. This article presents tools to study the behavior of cake batters during baking, generating knowledge on batter stabilization mechanisms and foam-to-sponge conversions. Cake batter stability is generally favored by low air bubble velocity, small bubble diameter, and high batter viscosity. Unfortunately, temperature gradients during baking negatively affect each of these variables, resulting in coarser cake structure. Changes in these physicochemical variables were studied using dynamic viscosity and rheological techniques. Foam-to-sponge conversion is a key stage in which the transformation of liquid cake batter (foam) into the solid and aerated cake structure (sponge) takes place. Substantial viscosity changes occur during baking that are highly affected by ingredients such as flour type and sugar content. These factors were studied using various imaging techniques, such as photography and dynamic or static computerized tomography (CT) scanning. By combining physicochemical and imaging techniques, information on fundamental aspects of the system were obtained.

Many different varieties of cakes are produced worldwide. Per country, desired product qualities differ, resulting in many different formulations and preparation methods. One traditional type is a pound cake, containing equal quantities by weight of flour, sugar, fat, and egg. This cake is popular for home baking but does not contain enough sugar to provide the long mold-free shelf life required for retail sale. Increasing the sugar level in a pound cake tends to cause structural collapse because of the inability of the flour to support the extra liquid required when sugar levels increase. Heat-treated and chlorinated flours provide solutions to this problem. In Europe, heat-treated flour is used to stabilize the structure when higher sugar and associated liquid levels are required. These cakes are known as high-ratio cakes because sugar is incorporated at a higher level than flour. Alternatively, there are sponge cakes, which do not contain added fats, and angel cakes, which are made with egg whites rather than whole eggs (4). These are just a small selection of the many cake types produced worldwide.

While bread is a basic product that people consume on a daily basis, cake is an indulgent product that should be eaten in lower quantities. Despite its indulgent character, however, British con-

sumers purchase on average 107 g of cakes and pastries per week (Weekly UK Household Consumption of Cakes, Buns, and Pastries, 2018/2109, available online at www.statista.com/statistics/698176/weekly-uk-household-consumption-of-cakes-buns-and-pastries, accessed 6-02-2020, 2020). As a result, cake products are under pressure within the United Kingdom with respect to sugar reduction to reduce the caloric intake of U.K. consumers. In addition, the whole food supply chain faces increasing pressures as consumers and governments ask for reduced energy consumption and waste generation, while using sustainably sourced ingredients that preferably have a clean label. The desire for “free-from” products is creating additional challenges.

Irrespective of the type of cake product, obtaining a fundamental understanding of the changes that occur during the baking process is key to creating an optimal product. During the cake baking process, all cake batters go through a “foam-to-sponge” conversion (7). A thermodynamically unstable foam-like cake batter converts itself to a solid and thermodynamically stable cake foam (1). This stable structure can be stored for a period of time and consumed at a later date. In this article, we outline the basic structural changes that take place during cake baking and demonstrate tools that can be used to increase our understanding of the changes and the effects of ingredients on these changes. The research tools described can be extrapolated to other food products and assist in development of more sustainable, yet indulgent, products.

Cake Batters

All types of cakes are prepared from liquid batters that can essentially be described as foams (7). The aim of cake batter preparation is to combine the ingredients into a homogeneous batter and introduce air into the system. It is critical that the air bubbles be stabilized by the cake ingredients throughout the batter preparation and baking processes. The exact mechanism of air stabilization depends on the type of cake and the mixing method used (8). Batter stability during baking is essential to maintain as many of the air bubbles as possible and to let these grow during the heating phase of the baking process. Air bubbles contribute to the formation of highly aerated and texturally soft products. There are a variety of factors contributing to the stability of bubbles within the cake batter. This is described by the Stokes relationship:

$$v = \Delta\rho g d^2 / 18\eta \quad (\text{Eq. 1})$$

in which v is the velocity ($\text{m}\cdot\text{sec}^{-1}$) of the air bubble; $\Delta\rho$ is the difference in density ($\text{kg}\cdot\text{m}^{-3}$) between the continuous phase (cake batter) and dispersed phase (air); g is the gravitational force ($\text{m}\cdot\text{sec}^{-2}$); d is the air bubble diameter (m); and η is the viscosity of the batter ($\text{Pa}\cdot\text{sec}$). By studying the relationship, one observes that a low bubble velocity is achieved mostly by small bubble diameters and high batter viscosities. These factors are

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critical for preventing the bubbles from rising and either coalescing or escaping from the batter surface. The ingredients and mixing method used both contribute to the quantity of air bubbles entrained in the batter and their range of diameters.

During mixing, air is entrapped in the system, forming a foam in which the interfaces between air and water are stabilized by solid fat crystals (e.g., pound cake) (8), egg proteins, and surface-active components originating from egg yolk and emulsifiers (6). The surface-active components help to reduce the surface tension of the aqueous phase and assist in breaking up the air bubbles to reduce their size (reduce d^2) and distribute them evenly throughout the batter. Sugar and flour both contribute to water absorption and increase batter viscosity (η). The increase in batter viscosity contributes to batter stability by reducing the velocity (v) at which the bubbles rise through the batter.

Cake Baking

The Rapid Visco Analyser (RVA) and rheometer are valuable tools to study and understand cake setting. The RVA can be used to measure the viscosity of batter systems during the heating and cooling regimes. It is traditionally used to study starch gelatinization but can be adapted for cake batters by using a different spindle. The RVA profiles of high-ratio cake batters containing heat-treated flour at two different levels of sugar—80% as in a low-ratio cake and 130% as in a high-ratio cake—are shown in Figure 1. The graph shows that batters have a high starting viscosity that decreases as temperature rises due to increased molecular mobility and melting of solid fat. From around 80°C, the viscosity of the lower sugar batter (80%) increases while viscosity of the higher sugar batter (130%) increases from around 92°C. Additionally, viscosity rises much more sharply in the 80% batter than in the 130% batter. The rise in viscosity is related to egg protein denaturation and starch gelatinization, which occur at lower temperatures and at higher rates in the lower sugar batter.

While the RVA provides information on changes in viscosity, the rheometer provides additional information on the viscoelastic properties of the batter, measuring the elastic modulus (G'), viscous modulus (G''), and phase angle (ratio between G' and G''). During the early stages of baking, the strength of both moduli decreases, while the phase angle increases as a result of increased batter mobility (data not shown). A decrease in phase angle at later stages of baking reflects batter setting and starts at higher temperatures at higher sugar levels. Trends observed with

the rheometer are similar to those observed in RVA data but allow further quantification of physicochemical parameters.

It is hypothesized that foam-to-sponge conversion coincides with these setting events (2), which implies that sugar levels are critical for controlling bubble movement (Eq. 1). During cake expansion and structure setting, the pressure on the air bubbles increases as CO_2 from baking powder and steam from evaporated water move into the bubbles. Late in the baking process the individual bubbles burst, creating an open sponge containing one large interconnected bubble. The cake needs to be sufficiently set for this event to take place without catastrophic structural collapse.

The exact setting temperature depends on the cake formulation, more specifically water content and sugar levels. Elevated sugar levels contribute to a delay in starch swelling and gelatinization (Fig. 1) and, therefore, a delay in the cake setting temperature (5). Initially, increased sugar levels allow for increased cake expansion due to the delay in setting. At excessive levels, however, cake setting is delayed to such high temperatures that setting would not occur in a conventional oven, with the result that foam-to-sponge conversion cannot take place. When the conversion does not take place, individual bubbles are still present. These bubbles shrink in size when the cake is taken from the oven as the bubble temperature and pressure decreases. The absence of sufficient foam-to-sponge conversion is hypothesized to cause collapse in high-ratio cakes made with plain rather than heat-treated flour (2). The starch in plain flour is less capable of absorbing water relative to heat-treated flour, which limits the quantity of sugar that can be added. In industrial cakes, high sugar levels are desired to achieve a long mold-free shelf life: sugar assists in water binding and decreases water activity. Without sugar levels greater than 100% on a flour weight basis, it is not possible to achieve a sufficient mold-free shelf life for the retail supply chain. In situations where high sugar levels are present, the semisolid system created during baking of high-ratio cakes with plain flour is insufficiently stable to avoid structural collapse, and the foam-to-sponge conversion is insufficient.

When cakes are baked in tins, structure setting starts from the bottom and sides as the metal from the tins conducts heat efficiently to the batter. Temperature gradients are created from the outside toward the center. It could be hypothesized, therefore, that the foam-to-sponge conversion events follow these temperature gradients, starting from the outer regions and migrating toward the inner regions and top surface.

Monitoring Foam-to-Sponge Conversion

To investigate foam-to-sponge conversion events, structurally invasive methods might be required. Initially, researchers used time-lapse photography (3) to study baking processes from the outside. However, time lapses do not provide quantitative information on the internal structure during that time. This can be followed in real time using medical computerized tomography (CT) scanners (7) that simultaneously monitor changes in product density and dimensions (Fig. 2). The time points at which batter density significantly decreases are related to steam formation and contribute to setting. The use of medical scanners may not be the most straightforward method as it involves the expense of paying for use of the scanner and designing an oven that fits into the scanner (7).

Alternatively, photography and static micro-CT can be used together to provide insights into structure formation and foam-to-sponge conversions. Cross-sections cut from a high-ratio cake

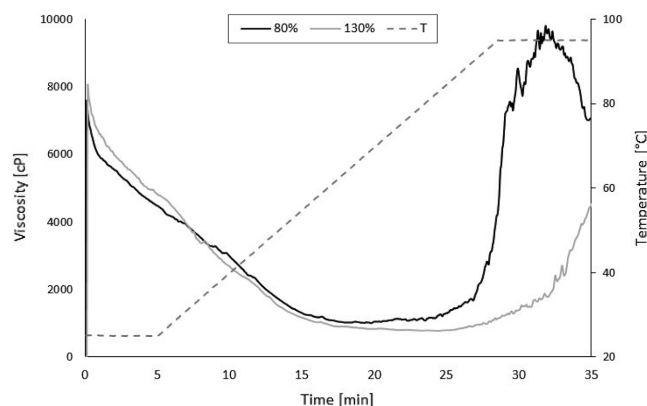


Fig. 1. Rapid Visco Analyser (RVA) profile of high-ratio cake batters containing heat-treated flour and different sugar levels (expressed as percent on a flour weight basis). T: temperature (°C).

removed from the oven at different time points are illustrated in Figure 3. The differences in internal temperature distributions result in visible changes in bubble structure that can be studied using simple photography.

During the study, high-ratio cakes prepared using heat-treated flour and 110% sugar on a flour weight basis were removed from the oven at different times. At each time point, the core temperature was measured using a digital thermometer (Fig. 3). When cakes were removed before 19 min, insufficient structure setting had occurred to be able to remove cakes from their tins.

- After 19 min, the internal temperature was 80°C, and the batter was not fully set, but the partially baked cake could be removed from the tin. The top surface was pale and contained holes, while the center had not yet risen and appeared dense. This demonstrated that structure setting started from the outside.
- After 23 min, most of the cake batter had set, apart from the top middle region, but the foam-to-sponge conversion was not complete.
- After 25 min, the cake had reached its maximum height, all batter had set, and the cakes contained more holes and bubbles.
- After 27 min, the holes had grown larger, but the cake had shrunk slightly. It was hypothesized that the foam-to-sponge conversion was completed between 23 and 27 min, as holes were formed at the expense of a slight decrease in volume. The volume decreased as water vapor and air escaped when the bubbles became interconnected into one

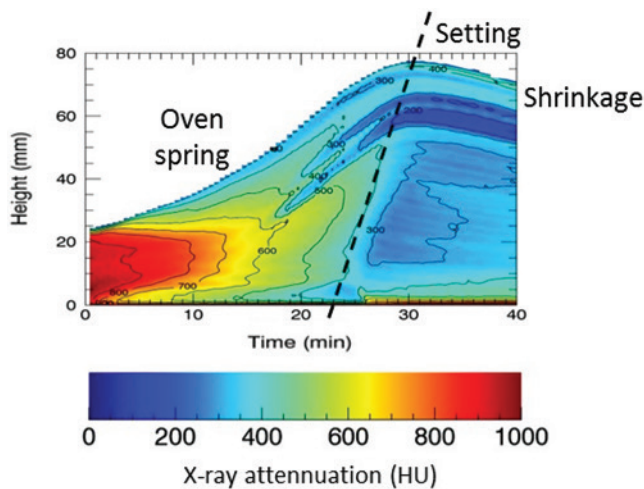


Fig. 2. Density profiles during baking of a high-ratio cake. Data obtained from medical computerized tomography (CT) scanning.

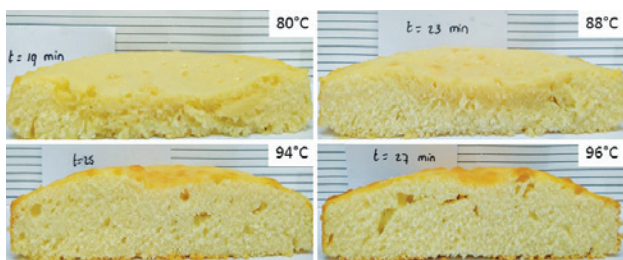


Fig. 3. Crumb structures and internal temperatures of high-ratio cakes after 19, 23, 25, and 27 min of baking. Temperatures reflect core temperatures determined immediately after removal from the oven.

large bubble, and the internal pressure equilibrated to atmospheric pressure.

Micro-CT can provide further detail as 3D images of products can be constructed by scanning them in a horizontal direction. Cake batters must be set sufficiently to be cut, positioned in the sample holder, and scanned. Micro-CT images of the same cakes shown in Figure 3 are shown in Figure 4. During early baking, the holes are smaller and less elongated, with fewer tunnels present. As the batter decreases in viscosity during early baking, air bubble coalescence can occur, forming larger air bubbles in the structure that will inflate further due to the activity of the baking powder. In these locations, the stabilization of gas bubbles by egg proteins, egg phospholipids, and emulsifiers may not be sufficient to withstand the decrease in viscosity during baking, resulting in batter drainage and air bubble coalescence.

An additional theory about the formation of tunnels relates to the rate of structure setting. When the rate of structure setting is low, bubbles can increase in size in all directions. The upward driving force is increased, as shown in Equation 1, allowing the bubbles to move upward slowly but without drastic shape change. When the rate of structure setting is high, the structure resists an increase in bubble size. This forces the bubbles to deform their shape upward into the batter with lower viscosity caused by structure setting from outside regions. This phenomenon can lead to tunnel formation, as is often seen in high-sugar muffins that set their structure late in the baking process (7).

In addition to imaging food structures in 3D, micro-CT can also be used to determine structural elements in a quantitative manner. One can look at the distribution of wall thickness (Fig. 5) and air structures (structure separation) (Fig. 6). Analysis of structure separation allows quantification of the air pockets and interconnections between these pockets. After 19 min of baking, average wall thickness was the highest, and there was a wide range of cell wall thicknesses (Fig. 5). These features are also visible when looking at the structure separation data; shorter baking times produced wider distributions of bubble sizes and more separation (Fig. 5). The distribution in both wall thickness and structure separation decreased as baking continued, reaching narrow distributions after 25 min when the cakes went through their foam-to-sponge conversion. The results indicate that, at the foam-to-sponge conversion, the formation of steam

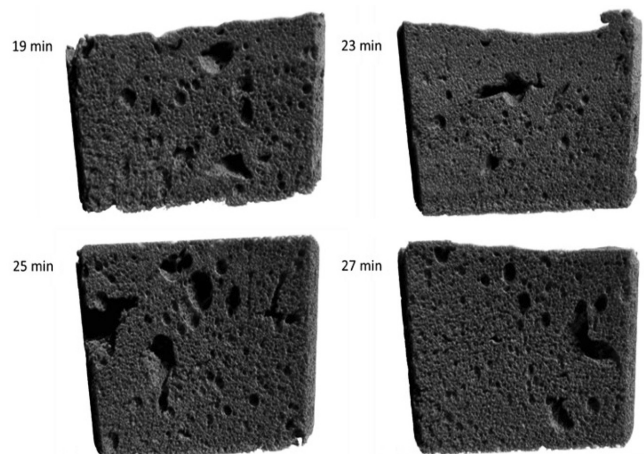


Fig. 4. Micro-computerized tomography (CT) cross-sections of high-ratio cakes after 19, 23, 25, and 27 min of baking.

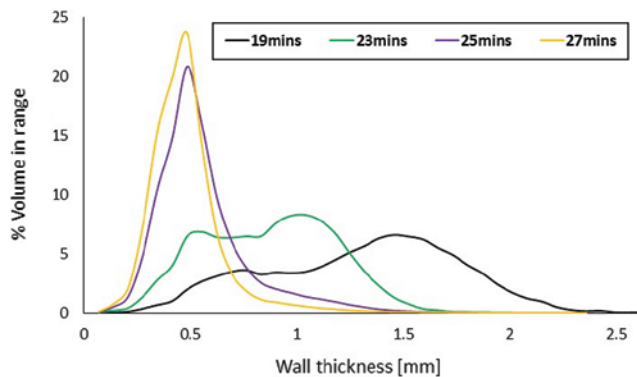


Fig. 5. Wall thickness distribution determined by micro-computerized tomography (CT) for high-ratio cakes baked for various times.

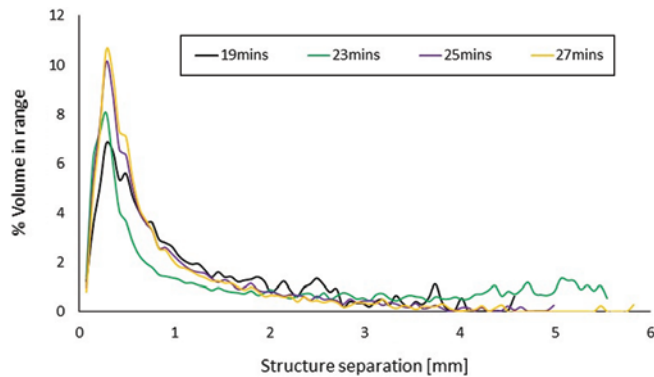


Fig. 6. Air bubble size determined by micro-computerized tomography (CT) for high-ratio cakes baked for various times.

stretched the bubble walls, decreasing wall thickness, and the bursting of individual bubbles decreased separation between individual air bubbles.

The data indicate that the foam-to-sponge conversion is an event that migrates through the cake, driven by temperature gradients, as hypothesized previously. The foam-to-sponge conversion follows cake structure setting from the outside inward. Steam formation toward the later stages of baking provides further lift to the structure and raises the internal gas pressure to a level that breaks each bubble and converts the structure from a foam to a sponge. In the examples presented here, the conversion was completed after 23 min, when raw batter was no longer part of the cake structure (Fig. 3).

Conclusions

Foam-to-sponge conversion is a crucial part of the cake baking process and is influenced by batter preparation, ingredients used, and heat transfer processes in the oven. With advances in available analytical techniques, the process is now better understood and can be used to guide optimization of cake formulations and processes.

While cake was used as an example to illustrate the potential of select analytical techniques, other products that go through heat processing, converting from raw to cooked systems, could be studied. Choosing the right research tool for a specific system allows for development of optimal products, contributing to efficient use of ingredients and lower environmental impact.

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Gary Tucker is the technical development ambassador at Campden BRI and has worked for the company since 1989. Prior to his current role, he managed the Cereal and Baking Department and the thermal processing work at Campden BRI for 18 years. Gary studied chemical engineering at Loughborough University and is a chartered chemical engineer. He holds an M.Phil. degree for work in the measurement of rheological properties of foods and a Ph.D. degree for work related to time–temperature integrators.



Sarab Sahi is the manager of the Rheology and Texture section of the Product Innovation Department at Campden BRI. Sarab studied biochemistry at Salford University followed by a Ph.D. degree in physical chemistry at Reading University attained studying physicochemical properties of sucrose esters. He joined FMBRA in 1989 after a couple of MAFF-funded postdoctoral positions at Reading investigating lipid systems at air–water interfaces and has been working in cereal science and technology at Campden BRI since 1996.

His current areas of interest include methods to measure and characterize the functionality of key ingredients in bakery systems, such as proteins, starches, enzymes, and emulsifiers, as well as the functionality of plant-based ingredients.