Cakes are complex baked goods in which the chemical leavening system is a critical functional ingredient. One part of the leavening system is the sodium bicarbonate (baking soda), which releases carbon dioxide (CO$_2$) when it reacts with an acid. The acid is the more diverse component in chemical leavening systems and can have a variety of compositions that determine when the CO$_2$ gas is released. The production of CO$_2$ influences the expansion of the cake batter (a hydrated flour–sugar matrix) during mixing and baking and determines the final properties (i.e., volume, texture, color) of the baked cake.

The influence of specific ingredients on batter and baked cake properties has been investigated. Shelke et al. (6) measured the effects of different emulsifiers and sugar sources on batter viscosity as temperature increases. Plots showed a decrease in batter viscosity as the temperature increased during baking followed by increasing viscosity with changes in macromolecular structures (starch gelatinization). The results demonstrated that emulsifiers positively effect the ability to incorporate air in cake batter. Wilderjans et al. (9) examined the main components of flour (starch and gluten) by altering their proportions and measuring cake and batter properties. They also measured viscosity and clearly demonstrated the influence of gluten, which provides the structure necessary to resist collapse. Whitworth (7) attributed crumb collapse in high-ratio cakes to a lack of structure and found the rate of setting is important for cake crumb structure and cell size. Research was performed by Wilderjans et al. (8) to evaluate temperature profiles across the depth of a cake during baking to determine when the structure is set (occurrence of macromolecular transitions). The starch source was the flour, and the protein sources were the flour (gluten) and egg. In a study by Psimouli and Oreopoulou (4) examining the replacement of the fat in a cake system with a variety of ingredients, batter properties related to starch gelatinization and their connections with aeration of the cake revealed a complicated relationship. When the onset temperature increased, theoretically allowing more time for expansion, there was no increase in final cake volume; other parameters (such as flow behavior and specific gravity) contributed to final volume. Detailed analysis of the macromolecular changes during baking was performed. During the mixing of cake ingredients, in addition to CO$_2$ gas production by the chemical leavening system, air is physically incorporated to decrease batter density (5). Rodríguez-García et al. (5) demonstrated the importance of maintaining consistency in batter preparation due to its influence on cake volume and texture properties.

Chemical Leavening Systems

The effect of each component on baked cake properties demonstrates how important it is to keep each ingredient and preparation step consistent. There are many acids that can be used for chemical leavening in cakes. Sodium acid pyrophosphate (SAPP) has been used for more than 80 years (2) and is usually associated with a number that corresponds to the quality testing that is performed. For example, the designation SAPP-28 indicates $\approx$28% of the available CO$_2$ is released within 8 min of hydrated mixing, and the other 72% will be released later (typically in the pan during baking). The designation SAPP-40 indicates $\approx$40% of the available CO$_2$ is released within 8 min of hydrated mixing, with the remaining 60% released in the oven. SALP-M is a double-acting blend of monocalcium phosphate (MCP) and heat-activated sodium aluminum phosphate (SALP). Calcium acid pyrophosphate (CAPP) is a newer commercial leavening acid developed for reduced-sodium applications. Two forms were evalu-
ated in this study: CAPP-S (slow acting) and CAPP-D (double acting). The term double acting is used to describe systems that produce gas at two separate times—typically in the mixing bowl and in the oven during baking.

Since the 1960s, leavening acids have been evaluated using a dough rate of reaction (DRR) system that adds the water to the dry ingredients in a sealed vessel maintained at a constant temperature and records the change in pressure as the CO$_2$ is released (3). CO$_2$ production by different acids in a model cake batter system (57 g of flour, 70.7 g of sugar, 6.9 g of nonfat dry milk, 1.7 g of soda [3.0% based on flour weight], and amount of acid required to neutralize the soda) is shown in Figure 1. Ingredients were mixed for 3 min after 60 mL of water was added; the water bath temperature was 27°C for the duration of the test.

CAPP-S released little CO$_2$ gas after 25 min, whereas SAPP-28 rapidly released CO$_2$ gas during mixing, followed by slow, steady, continuous gas production. The graph line for SAPP-40 has the same shape as that of SAPP-28, but at a higher level of initial gas production. The SALP-M graph line shows increasing gas production resulting from the reaction of the MCP for ≈18 min, after which the line is flat (no gas production for the rest of the test). The SALP did not react at 27°C. The double-acting nature of CAPP-D is evidenced by the two distinct parts of the graph line: a steep line for ≈10 min, followed by continuous gas production at a lower rate for the rest of the test.

Cake preparation included 5 min of mixing followed by a couple of minutes to weigh the batter into the baking pans. As a result, it was ≈8–10 min (Fig. 1) before the batter was placed in the oven. During the 8–10 min prebake period the amount of CO$_2$ released was as follows: CAPP-D ≥ SAPP-40 > SAPP-28 > SALP-M > CAPP-S. The rest of the sodium bicarbonate reacted and formed CO$_2$ during baking concurrently with the macromolecular changes that determine set. Volume, texture, and color may have been influenced by the leavening acid used, and these cake properties can be quantified for comparison.

Because baking soda is the main source of CO$_2$ gas in a cake, it was of interest to determine whether more soda would result in a cake with a greater volume. Three levels of soda were tested. Each of the acids tested was added in an amount that would neutralize the level of soda (Table I) in the cake formula. The neutralizing value used to calculate the amount of acid needed to neutralize the soda is provided. As part of the study, the amount of batter in the pan was also a factor. The results for 325 g of batter (middle amount) are discussed, because this amount was found to be optimal; however, statistical analysis (linear least squares regression) was performed using the entire data set.

![Fig. 1. Carbon dioxide production by different leavening acids in a model cake batter system. CAPP: calcium acid pyrophosphate; SAPP: sodium pyrophosphate acid; SALP: sodium aluminum phosphate.](image1)

![Fig. 2. Specific gravity of cake batters made with five leavening acids and three levels of soda. SALP: sodium aluminum phosphate; SAPP: sodium pyrophosphate acid; CAPP: calcium acid pyrophosphate.](image2)

![Fig. 3. Size and shape of cakes made with 3.0% soda (flour basis) and five leavening acids. SALP: sodium aluminum phosphate; CAPP: calcium acid pyrophosphate; SAPP: sodium pyrophosphate acid.](image3)

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<td>68</td>
</tr>
</tbody>
</table>

a SALP: sodium aluminum phosphate; SAPP: sodium pyrophosphate acid; CAPP: calcium acid pyrophosphate.
Test Cake Formulas

A simple yellow cake formula was used to study the effects of five chemical leavening systems (ingredient amounts are provided in percentages based on flour weight): 100% cake flour; 124.04% granulated sugar; 12.09% instant nonfat dry milk; 2.40% table salt; 0.83% xanthan gum; 7.15% emulsifier blend of propylene glycol ester, mono- and diglycerides, and soya lecithin; 106.00% tap water; 70.65% liquid whole egg with 0.15% citric acid; and 33.23% corn oil. Formulas were run twice in random order. For each batter preparation the ingredients were incorporated as follows: the dry blend, leavening acid, and baking soda were weighed and combined (total weight 798 g); the emulsifier (23.25 g) was weighed and added, followed by 3 min of mixing on speed 1 with a paddle in a mixer (Hobart); the water (344.5 g) and egg (230 g) were added and mixed for 1 min on speed 1; and the oil (108 g) was added and mixed for 1 min on speed 1. The blended batter was mixed for another 2 min at speed 2. The bowl was scraped after each separate mixing time. The batter (325 g) was weighed into prepared pans (8 in. round aluminum pans lined with parchment) and baked for 18 min at 177°C in a reel oven (Reed).

Cake Volume

To measure the amount of gas in the batter, cake batter was weighed in a standard volume cup and compared to the weight of water to calculate the specific volume of the batter. A lower number indicates more gas (less mass) in the batter in the cup. At the lowest level of soda (Fig. 2) all batters were the same, with little CO₂ gas dissolved. As soda level increased, some differentiation between the acids occurred, with CAPP-D and SAPP-M producing the most dissolved gas.

Photos of cakes formulated with the middle amount of soda (3%) (Fig. 3) show some differences in size, shape, and tunneling; all cakes were considered acceptable. To quantify the size and shape of the baked cakes, AACC Approved Method 10-91.01 was used (1). Indexes are calculated from the height values taken at three locations: volume is the sum; symmetry is two times the center value minus each of the side values; and uniformity is the absolute value of the difference between the two side values.

The cakes formulated with 1.4% soda had the smallest volumes (60–85) (Fig. 4); volume increased for cakes formulated with 3.0% soda. When the soda level was increased further to 4.6%, volume decreased for cakes made with SALP-M and SAPP-28 and stayed the same for those made with CAPP-D and SAPP-40. CAPP-S was the only acid that produced a slight increase in cake volume with the highest level of soda.

When designing chemical leavening systems, one approach is to have some gas produced during mixing and some produced later during baking to give the best volume. A strong negative correlation between the height of the baked cake and the amount of CO₂ liberated before the cake was placed in the oven was observed (Fig. 5). In other words, the more unreacted CO₂ there was in the batter prior to baking, the greater the height of the baked cake. For this combination of ingredients, it appears that gas produced in the batter was lost; when the majority of the gas was produced in the oven, it was retained. It is possible that the emulsifiers or xanthan gum contributed to greater volume, because the gas was produced at the right time to be trapped in the cake structure during bake. It is also possible that the CAPP molecule helped set the structure and provide gas retention.

When the data were analyzed statistically, the volume data had $R^2$ values ranging from 91.9 to 97.8% for the leavening acids. The high $R^2$ values indicate that almost all of the variation in cake volume was accounted for by level of soda and amount of batter. The model for each leavening acid is depicted in Figure 6. Each acid was a maximum volume that could be obtained. Most cakes made with higher levels of soda decreased in volume because there was too much gas for the system to retain it all. Of the five acids tested, CAPP-S produced the cake with the greatest volume and leveled out in size with increasing soda, rather than declining in volume like cakes containing the other four acids. SALP-M and SAPP-28 produced cakes that were nearly identical in size; their gas production curves were very similar for this batter system, with a maximum volume at ≈3% soda and a sharp decline in volume with increasing amounts of leavening. CAPP-D and SAPP-40 also were most similar, with more gas production during mixing, leading to an overall lower volume and slightly higher amounts of soda and acid required to achieve maximum volume.

The symmetry index for the cake quantifies the shape of the cake. At the smallest amount of leavening, SALP-M and CAPP-S produced cakes with nice rounded shapes. These two acids produced the least amount of gas during mixing, suggesting CO₂ production in the oven moved from the outer region of the cake toward the center and was trapped by the matrix as it set. The other three acids produced essentially flat cakes; there was not enough gas produced during baking to expand the shape properly. At the medium leavening level (3.0% soda), there was more similarity between the results for the five acids; all produced cakes with the desired round shape (values between 3.5 and 9.5). When the highest level of soda (4.6%) was used, a large dip was observed in the shapes of cakes made with SALP-M and SAPP-28. Either these acids produced more gas than the structure could support or the timing of gas production did not coin-

![Fig. 4. Volume index for cakes made with five leavening acids and three levels of soda (1.4, 3, and 4.6%, flour basis). SALP: sodium aluminum phosphate; CAPP: calcium acid pyrophosphate; SAPP: sodium pyrophosphate acid.](image)

![Fig. 5. Relationship between cake volume and gas production in batters made with 3.0% soda (flour basis) and five leavening acids. DDR: dough rate of reaction system.](image)
cide with the setting of the structure so the gas produced was lost. This dip would explain the lower volume index determined for these same cakes. Cake made with CAPP-D was flat at the highest amount of leavening, whereas cakes made with SAPP-40 and CAPP-S had positive symmetry indexes at the highest amount of leavening.

The uniformity index indicates whether the two sides of a cake are of equal height. The 15 cakes produced were all fairly uniform, with a maximum difference between two sides of ≈3 mm; most of the cakes had height differences of <1.5 mm.

**Cake Texture**

**Hardness.** The textural properties of a cake are affected by ingredient variations and can be quantified using a texture analyzer and texture profile analysis test. The hardness parameter quantifies the amount of force required to compress a cake by 10 mm. The biggest difference between acids was found for cakes with smaller amounts of leavening; cakes made with SAPP-40 were the hardest, and those made with CAPP-S were the softest (Table II). As leavening amount increased, the hardness values decreased and became more similar among the five acids; there was no apparent influence of acid composition on this texture parameter. SAPP-40 and CAPP-D had similar DRR, with rapid CO$_2$ production, and produced cakes with similar volumes; it is unknown if the rate of gas production is related to texture or if this was a coincidence.

The hardness results could be modeled using the design variables, and $R^2$ values ranged from 82 to 95%. Statistical analysis indicated the amount of soda had a stronger effect than the amount of batter. A plot of the model results for hardness versus soda level for cakes is provided in Figure 7. For all acids, as the amount of soda increased (and thus the amount of leavening acid required for neutralization), the cakes become softer until a soda level of 3.0% was reached, at which point all acids produced cakes with approximately the same hardness values. The hardest cake was made with SAPP-40 at the lowest soda level. CAPP-S and SALP-M had nearly identical hardness values over the range of soda levels, and SAPP-28 was very similar. Hardness results could be modeled using the design variables, and $R^2$ values ranged from 82 to 95%. Statistical analysis indicated the amount of soda had a stronger effect than the amount of batter. A plot of the model results for hardness versus soda level for cakes is provided in Figure 7. For all acids, as the amount of soda increased (and thus the amount of leavening acid required for neutralization), the cakes become softer until a soda level of 3.0% was reached, at which point all acids produced cakes with approximately the same hardness values. The hardest cake was made with SAPP-40 at the lowest soda level. CAPP-S and SALP-M had nearly identical hardness values over the range of soda levels, and SAPP-28 was very similar. Hardness results could be modeled using the design variables, and $R^2$ values ranged from 82 to 95%. Statistical analysis indicated the amount of soda had a stronger effect than the amount of batter. A plot of the model results for hardness versus soda level for cakes is provided in Figure 7. For all acids, as the amount of soda increased (and thus the amount of leavening acid required for neutralization), the cakes become softer until a soda level of 3.0% was reached, at which point all acids produced cakes with approximately the same hardness values. The hardest cake was made with SAPP-40 at the lowest soda level. CAPP-S and SALP-M had nearly identical hardness values over the range of soda levels, and SAPP-28 was very similar. Hardness results could be modeled using the design variables, and $R^2$ values ranged from 82 to 95%. Statistical analysis indicated the amount of soda had a stronger effect than the amount of batter. A plot of the model results for hardness versus soda level for cakes is provided in Figure 7. For all acids, as the amount of soda increased (and thus the amount of leavening acid required for neutralization), the cakes become softer until a soda level of 3.0% was reached, at which point all acids produced cakes with approximately the same hardness values. The hardest cake was made with SAPP-40 at the lowest soda level. CAPP-S and SALP-M had nearly identical hardness values over the range of soda levels, and SAPP-28 was very similar.
ness values for cakes made with CAPP-D were in-between at lower soda levels. At soda levels greater than or equal to \(\approx3\%\), all cakes had similar low hardness values.

**Cohesiveness.** The textural parameter cohesiveness is a measure of how well the cake crumb holds together (or conversely, falls apart). In our tests, each acid and soda level appeared to influence cake cohesiveness (Table II). CAPP-S stood out as producing the most cohesive cake crumb at three leavening amounts. High \(R^2\) values (between 82 and 95%) allowed the data to fit the model (Fig. 8). At lower levels of soda, there were bigger differences between the acids. As soda level increased, the cake crumbs became more cohesive until a maximum was reached, at which point higher leavening amounts resulted in a decrease in cohesiveness values. The data for cohesiveness aligned with the low volume and dip in symmetry found for cakes made with SALP-M and SAPP-28. The exception was SAPP-40, which did not result in a decrease in cohesiveness at higher soda levels.

**Springiness.** Springiness is defined as the measure of the degree to which a deformed sample springs back to its undeformed condition after the deforming force is removed. A value of 1 would indicate a cake was at exactly the same location at the start of each of the two compressions. Springiness values for the 15 cakes had a high average and a very small range (0.97 ± 0.03), indicating all of the cakes sprung back to nearly their original height after the first compression.

**Cake Color**

The color of the cake crust (surface) was measured using a handheld colorimeter (Minolta). \(L^*\) values are a measure of the lightness of the crust: 0 = black; 100 = white. For each of the acids (Table II), as more leavening was used the crust became darker (lower \(L^*\) value). CAPP-S produced cakes with the darkest crusts. The results for SAPP-28, SAPP-40, and SALP-M were similar.

The models indicated that soda level had a strong effect on \(L^*\) value, and the \(R^2\) values ranged from 86 to 93%. The graph shows that as leavening amounts increased, \(L^*\) values decreased (the crusts became darker) (Fig. 9). The model clearly shows differences between the acids, which were greater at higher soda levels; CAPP-D produced the lightest crusts, and CAPP-S produced the darkest crusts.

Positive \(a^*\) values for color indicate increasing red tones; negative \(a^*\) values indicate green tones. As the amount of leavening increased, red tones increased in cake crusts. SAPP-28 and SAPP-40 produced similar results (Table II). CAPP-S was the most unique of the five acids, with predominately positive \(a^*\) values arising from the brown color of the cake crust (and decreasing \(L^*\) values).

Positive \(b^*\) values for color indicate increasing yellow hues. For all the cakes, the range of \(b^*\) values was between 20 and 30 (Table II); thus, this parameter was not greatly affected by the variables measured in this study.

**Conclusions**

For the three different amounts of soda tested, the cakes with the largest volumes were made with the middle level of soda (3.0%). At the lowest amount of leavening, there was not enough gas to expand the batter. When the highest amount of soda was used, cake volume was not larger, and the structure collapsed forming an undesirable dip in the middle of the cakes made with SALP-M and SAPP-28.

The five leavening acids studied produced somewhat different results for cake volume, texture, and color. The volume index was inversely correlated with gas production in a model cake system. CAPP-S produced the largest cakes at all soda levels; these cakes were also the most symmetrical. All leavening acids and soda levels produced uniformly shaped cakes. Cake crumb was harder at lower leavening amounts, and differences between acids were observed. At high leavening amounts, hardness was consistently low for all five acids. The acids also affected crumb cohesiveness, with CAPP-S producing the crumb with the greatest cohesiveness. All cakes had similar springiness. Higher amounts of leavening produced cakes with darker crusts that had more red tones. We were able to model the data for volume index, hardness, cohesiveness, and \(L^*\) color value.

**References**


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