# Factors Controlling Gas Cell Failure in Bread Dough[1]

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## ABSTRACT

Stress relaxation in the wall of a gas bubble, as measured by the alveograph, was used to study surface tension at the gas-dough interface of doughs from flours producing differing bread crumb grains. The surface tensions in the various wheat flour doughs were not different. Dough rheological properties, as measured by both dynamic oscillatory rheometry and lubricated uniaxial compression, were not different for doughs made from wheat flours that gave breads with different crumb grains. However, when the effect of starch granule size on gas cell wall stability was tested, the presence of a greater proportion of large starch granules in wheat flour dough was sufficient to result in gas cell coalescence and open crumb grain in the final baked product. This suggests that starch granule size is at least one of the factors that affects the crumb grain of bread.

In their classic article on the origin of the gas cell in bread dough, Baker and Mize (1941) showed that yeast was incapable of originating gas cells in the dough. Therefore, air must be incorporated during mixing. They also showed that punching and molding did not introduce any new gas cells but instead created a greatly increased number of cells by subdividing the cells already present.

Hayman et al (1998a) established that the stability of the gas cell in bread dough undergoes critical changes during the early stages of baking. However, the mechanism by which the gas cell walls fail is not yet clear. Because bread dough is a viscoelastic foam, established theories for foam systems can be applied to the bread dough system to provide some insight into those mechanisms. The two theories for gas cell destabilization that can be applied to bread dough systems are: disproportionation (Ostwald ripening) and coalescing of the gas cells (Walstra 1987, Van Vliet et al 1992). The latter authors concluded that Ostwald ripening would tend to result in fewer and larger gas cells in bread dough. This would produce a more open crumb grain but would have minimal effect on gas retention. Coalescing of the gas cells could account for the variation in gas cell wall stability and gas retention.

### Coalescence Caused by Surface Tension

According to the theory of Vrij (1966) for the coalescence of foams, the interfacial film is unstable if:

$$(d^2 G_{\text{int}} / dh^2) + 2\Pi^2 \gamma/a^2 < 0$$

where $G_{\text{int}}$ is the colloidal interaction energy between two spherical particles at a surface-to-surface separation $h$, and $a$ is the diameter of the gas bubble. This theory indicates that film rupture and coalescence are promoted by a weak repulsion between droplets, a low interfacial tension ($\gamma$), and a large cell diameter (large droplets or gas cells). The predicted dependence on $\gamma$ is considered unlikely, because a lower $\gamma$ means less of a decrease in surface free energy upon coalescing and, consequently, a lower driving force for the coalesence. Fine, dispersed gas cells have an increased surface tension or surface free energy. This creates a driving force or a need to reduce the surface free energy of the system. Reducing the surface area of the gas cells through coalescence will reduce the surface free energy and make the system more thermodynamically stable. However, the activation free energy, not the ultimate free energy gain, governs the rate of coalesence (Walstra 1987).

This analysis suggests that the factors worth investigating with regards to gas cell coalescence in a bread dough system are $a$, $h$, and $\gamma$. Hayman et al (1998b) already has established that pressure and temperature have effects on gas cell stability. If these are the external factors that govern the internal factors $a$, $h$, and $\gamma$, then the effect of manipulating the internal factors should be determined.

Because of the complex, heterogeneous nature of bread doughs, direct study of surface tension is difficult. Consequently, most experimental approaches have been indirect. Mita et al (1977) attempted to apply basic foam theory and methodologies to a bread dough system but used only surface-chemical investigations of gluten protein foams as a model system for fermented doughs.

### Surface Tension and Excess Pressure

Surface tension in the gas-dough interface is one factor that may affect the behavior of gas cells dispersed in a continuous dough phase (Carlson and Bohlin 1978, Bloksma 1981). According to Bloksma (1990), excess pressure (i.e., that above atmospheric) in the gas cells of bread dough is the result of surface tension and viscous resistance. Carlson and Bohlin (1978) suggested that surface tension in the gas-dough interface contributes to the elastic resistance of bread doughs. However, Bloksma (1981) concluded that the contribution of surface tension to the elastic modulus of dough is much smaller than previously predicted and is of little importance.

Although surface tension at the gas-dough interface contributes a major part of the excess pressure in the gas cell, the excess pressure is small, relative to atmospheric pressure (Bloksma 1990). He suggested that the surface tension is important when dough viscosity is small and the number of gas cells per unit volume is large.

### Dynamic Rheological Testing

Dynamic oscillatory rheometers operating at small amplitudes are useful in the study of the rheological properties of wheat flour dough, especially when temperature-induced changes occur during testing (Chang et al 1990). This methodology can be used to calculate the storage modulus ($G'$) and the ratio of the loss modulus to the storage modulus (tangent) ($G''/G'$) from experimental data. When testing highly viscous or nonhomogeneous materials like wheat flour dough, a dynamic oscillatory rheometer with parallel plate geometry is favored. The wide gap between the plates minimizes any error that might occur if the sample expands during testing.

If, in fact, the rheological properties of the gas cell walls in the bread dough do control their coalescing, those properties of the dough system probably should be measured in the temperature range at which the gas cells are most susceptible. According to He and Hoseney (1991b), the crumb grain structure of the bread sets after 8 min of baking in a conventional oven. The temperature of the bread's core (center) at that time is ≈70°C.

### Strain Hardening

The dough around a growing gas cell will expand tangentially in two directions: parallel to the surface of the gas cell, and radially

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perpendicular to the surface. Excess pressure in the gas cell is responsible for the latter type of expansion (Luyten 1988, Akkerman et al 1990). This interaction might explain the effect of pressure on crumb grain reported earlier (Hayman et al 1998b).

As the gas cell grows, expansion creates a strain in the wall. Doughs exhibit strain hardening (Van Vliet et al 1992), a phenomenon whereby the stress increases more than proportionally to the strain (at a constant strain rate). Van Vliet et al (1992) suggested that the persistance of strain hardening at higher strain levels indicates increased resistance to biaxial extension. This, in turn, will prevent premature failure of the cell wall. Therefore, if localized thinning occurs in the expanding gas cell wall, doughs that are more prone to strain hardening will provide the gas cell wall with greater stability against coalescence and better gas retention. This suggests that a dough exhibiting greater strain hardening might result in a final product with fine crumb grain. Therefore, wheat flour doughs producing bread of fine crumb grain would be expected to exhibit more strain hardening than wheat flour doughs that produce bread of open crumb grain.

The resistance to biaxial extensional flow of doughs can be characterized by determination of a biaxial extensional viscosity (Chatrei et al 1981). Lubricated uniaxial compression experiments can be used to characterize biaxial extensional parameters or to observe the strain hardening phenomenon (Chatrei et al 1981; Bagley et al 1986, 1988; Campanella et al 1987).

### Effect of Inclusions on Gas Cell Wall Stability

The presence of starch granules that are larger than the thickness of a gas cell wall in dough is thought to induce instability in the wall (Van Vliet et al 1992). When the gas cell wall is thick compared with the size of large wheat starch granules (25–40 μm), the wall will be stabilized against coalescence.

### Particle Size Distribution of Wheat Starch

In wheat starch, small granules have a diameter of <10 μm, and the large granules are ≈15–40 μm in diameter. The large starch granules contribute 3–4% of the total number of granules but 50–75% of the total weight of the wheat starch. Although the two groups of starch granules are referred to as separate entities, a gradation in size occurs from small to large granules (Lineback and Rasper 1988).

### Image Analysis of Crumb Grain

The rapid advances in computer imaging has made it possible to use these systems to evaluate the crumb grain of bread (Zayas 1993, Sapirstein et al 1994, Rogers et al 1995). The work of Sapirstein et al (1994) is particularily pertient as they were able to resolve a number of features of crumb grain including mean cell area and cell count. The purpose of this study was to determine which factors control the stability of gas cells in bread doughs.

## MATERIALS AND METHODS

### Cell Wall Thickness, Diameter, and Surface Tension

Bread doughs were prepared according to the sponge-and-dough procedure. Because differences in proof times should affect *a* (gas cell diameter), and *h* (gas cell wall thickness), three dough proof times were tested: 30 min (underproofed), 55 min (control), and 90 min (overproofed). A fourth treatment added a surfactant, sodium stearoyl lactylate (SSL), to the dough to alter $\gamma$ (surface tension) of the system.

### Surface Tension and Excess Pressure

To study surface tension and excess pressure in a wheat flour dough system, flour-water doughs were tested using the standard alveograph (Seedburo Equipment Co., Chicago, IL) dough mixing procedure (Faridi and Rasper 1987). Because the alveograph mixing procedure does not necessarily mix the doughs to optimum development, flours also were tested using optimum water and mixing. The bubble inflation time was 2.88 with a prefix multiplier of 0.1. To prevent drying of the dough bubble surface during relaxation, the inside surface of a 400-mL heat-resistant beaker was moistened with water, and the beaker was placed over the dough piece before inflation. Pressure drop, as a measure of stress relaxation in the gas bubble, was monitored for 45 min.

### Dynamic Rheological Tests

Dynamic rheological testing was performed using the dynamic oscillatory rheometer described by Faubion et al (1985) and the heating technique described by He and Hoseney (1991a). The rheometer was fitted with a rectangular, parallel-plate heating cell operated at 1.0% strain and a frequency of 5 oscillations/sec. The rheological properties ($G'$, $G''$, and tan $\Delta$) of wheat flour doughs that produce bread of differing crumb grains were measured over a temperature range of 25–95°C.

### Lubricated Uniaxial Compression

The lubricated uniaxial compression procedure as described by Cullen-Refai et al (1988) was modified for use in this study. Doughs were mixed to optimum and tested under lubricated uniaxial compression. A texture analyzer (TA.XT2) was used to deform a 2.5-cm diameter cylindrical dough piece to 75% strain. Crosshead speeds of 0.1 and 1.0 mm/sec resulted in initial biaxial strain rates of 5.0 × $10^{-3}$ $\text{sec}^{-1}$ and 5.0 × $10^{-2}$ $\text{sec}^{-1}$, respectively. Data were obtained on compressive stress as a function of biaxial strain for wheat flour doughs that produce bread of different crumb grains.

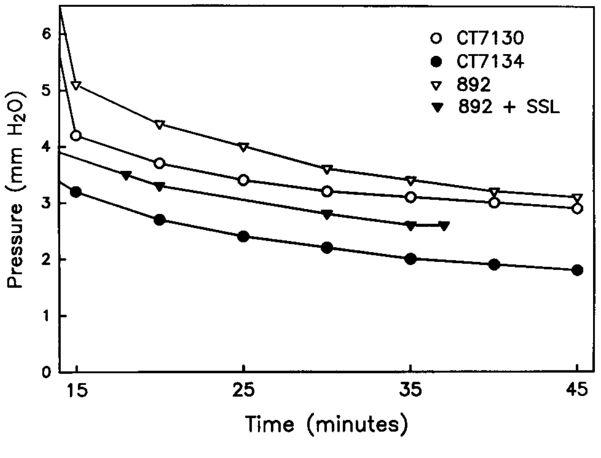

**Fig. 1.** Pressure drops (stress relaxations) in dough gas bubbles in the alveograph for wheat flour doughs mixed according to standard procedures.

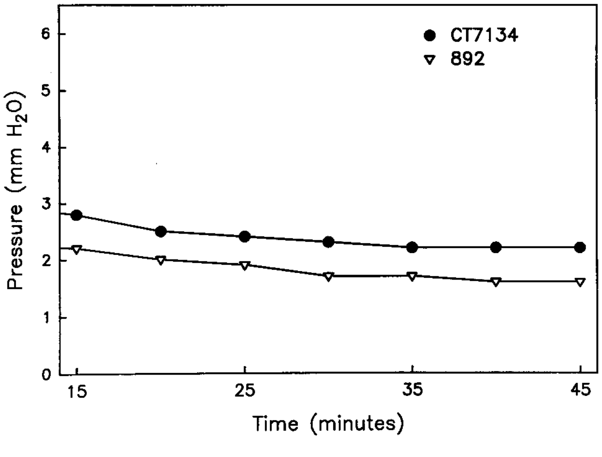

**Fig. 2.** Pressure drops (stress relaxations) in dough gas bubbles in the alveograph for different wheat flour doughs mixed to optimum.

## Gas Cell Wall Inclusions

To determine the effect of starch granule size on crumb grain, blends of 893 wheat flour with commercial wheat starch and gluten or potato starch and wheat gluten were tested. The wheat flour and starch + gluten blends were tested at levels (flour weight basis) of 95-5%, 90-10%, 75-25%, and 50-50%. Bread doughs were prepared from those blends as described in Approved Method 10-10B (AACC 1995).

## Separation of Starch Granules

A bread flour (Cargill, Wichita, Kansas) was fractionated using the gluten washing procedure modified from Approved Method 38-10 (AACC 1995). Flour (700 g) was mixed in a Hobart mixer (North York, Ontario) with 55% distilled water (≈6 min). The dough was washed in excess distilled water to separate the starch and gluten fractions. The starch slurry was passed through a 30 wire screen and a 10XX flour cloth. The starch slurry then was centrifuged at 500 × *g* for 30 min. The water-soluble fraction was discarded. The sedimented layers were separated into the tailings containing the small starch granules (top layer) and the prime starch containing the large starch granules (bottom layer). The large starch granules (bottom layer) were resuspended in an Oster blender and centrifuged at 1,000 × *g* for 15 min. This was repeated a second time. Between the centrifugations, the layers were separated by scraping with a metal spatula, and the large granules were resuspended and recentrifuged. The top layers were added to the tailings portion of the original centrifugation.

The tailings were resuspended, centrifuged, and separated in the same manner as the large starch granules. The top layer of the centrifuged slurry was made up of cell-wall fragments, water-insoluble pentosans, and damaged starch. The white pellet remaining as the bottom layer was the small granule fraction. The gluten, large granules, and small granules were lyophilized. The fractions were ground in a coffee grinder and a mortar and pestle.

The isolated large and small starch granule fractions were analyzed for particle size using a centrifugal automatic particle analyzer (CAPA-300, Horiba, Kyoto, Japan). The dispersion medium was sucrose solution with a viscosity of 2.85 cp and a density of 1.4 g/cm$^3$. The analysis procedure is based on Stokes' sedimentation law.

## Image Analysis

A computer imaging program developed at Kansas State University (Shen 1996) was used for objective evaluation of the crumb grain. Two slices from each acceptable loaf (those without extremely large holes that would allow light to leak and distort the image) were analyzed. A TV camera (Panasonic, Matsushita Communications Industrial, Ltd.) attached to monitors for focusing, and a central processing unit were used to view the crumb structure. The analysis gave an average number of cells in the 450 × 450 pixel area. It also evaluated the bread for size of the cells, perimeter of the cells, and cell roundness.

## RESULTS AND DISCUSSION

Underproofed doughs should possess lower *a* (cell diameter) and higher *h* (wall thickness) values than those proofed to optimum because of less expansion. The reverse should be the case for overproofed doughs. The 892 flour (poor crumb grain flour) produced open crumb grains in breads baked following underproofing, optimum proofing, or overproofing (data not shown). This suggests that manipulating *a* and *h* over the ranges attainable by extended proofing did not affect gas cell stability. Addition of SSL to the formula improved the crumb grains of breads made with 892 flour. Presumably, SSL affects crumb grain by altering the interfacial tension ($\gamma$) of the dough system. However, this does not clarify whether inherent differences in the $\gamma$ of different doughs are sufficient to affect gas cell coalescence.

If Bloksma (1990) is correct, and the excess pressure in the gas cells of bread dough is due to surface tension and viscous resistance, then a dough system that has undergone complete relaxation should have a viscous resistance of zero, and any excess pressure in the gas cell over atmospheric pressure would be due to the $\gamma$ of the dough system.

With the Chopin alveograph's relaxometer, the flow of air can be stopped at a chosen bubble volume and the decay of pressure recorded. This corresponds to a measurement of stress relaxation (Bloksma and Bushuk 1988). Thus, the relaxometer should be useful to measure the $\gamma$ of dough. If the pressure in the gas bubble reaches equilibrium, any pressure over atmospheric remaining in the bubble could be attributed to $\gamma$ because viscous resistance is zero.

Addition of SSL to the 892 flour dough resulted in a lower residual pressure when compared with the 892 flour dough without SSL. This is the expected result, if SSL alters surface tension of the gas-dough interface.

Figure 1 shows stress relaxation curves from doughs mixed by the standard alveograph procedure. The results indicate that CT7130, the flour that produces bread of fine crumb grain, relaxed to a higher residual pressure than did CT7134, the flour that produces bread of open crumb grain (Table I). If all viscous resistance in the dough had dissipated after 45 min, this would indicate a higher surface tension in the dough that produces bread of fine crumb grain. The results indicate, as well, that the dough from 892 flour relaxed to a higher residual pressure than the doughs from both the CT7130 and CT7134 flours. These results did not confirm our hypothesis, because no consistent relationship existed between inter-

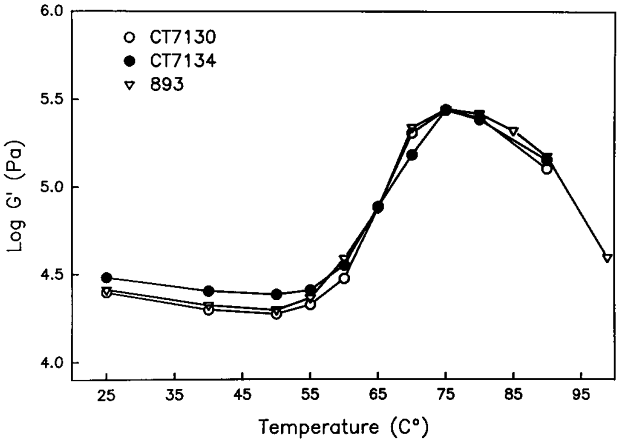

**Fig. 3.** Storage modulus *G*′ vs. temperature plots of wheat flour doughs that produce breads of different crumb grains.

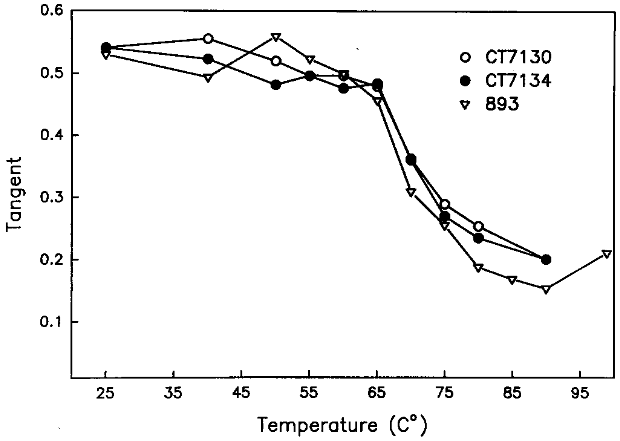

**Fig. 4.** Tangent (*G*″/*G*′) vs. temperature plots of wheat flour doughs that produce breads of different crumb grains.

facial tension and crumb grain. A second set of experiments with doughs mixed to optimum before testing with the alveograph (Fig. 2), also did not show any relationship between residual pressure ($\gamma$) of the doughs and their crumb grains.

These results suggest two possible conclusions. The first is that this method is inappropriate for testing surface tension in bread doughs. The second possibility, and the one we prefer, is that the procedure did measure the surface tension, but it was not related to crumb grain of breads.

### Rheological Properties

The $G'$ and tangent values of the different wheat flour doughs were calculated from dynamic rheometer measurements over the temperature range of 25–95°C (Figs. 3 and 4). The flour doughs showed no significant differences in their $G'$ and tangent values.

The strain level used in this test (1.0%) may not have been great enough to show differences in the rheological properties of the different wheat flour doughs. According to Van Vliet et al (1992), the biaxial rate of strain occurring during oven spring is $\approx 5 \times 10^{-4}$ sec$^{-1}$. This would correspond to a strain of 50–75% in the sample, much greater than the 1.0% used in this study. Strain levels of this magnitude are not possible in the dynamic oscillatory rheometer. However, biaxial extension tests, performed using lubricated uniaxial compression, are able to achieve the level of strain and biaxial strain rate for oven spring (Chatrei et al 1981, Bagley and Christianson 1986, Campanella et al 1987, Bagley et al 1988).

### Lubricated Uniaxial Compression

Lubricated uniaxial experiments with wheat flour doughs tested at different, initial, biaxial strain rates ($5.0 \times 10^{-3}$ sec$^{-1}$ and $5.0 \times 10^{-2}$ sec$^{-1}$) failed to show significant differences (data not shown).

Possibly no significant differences existed between the different wheat flour doughs in their resistance to biaxial extension. If so, strain hardening would not affect gas cell failure and coalescence, and this method would not be useful as a predictor of crumb grain. However, it also is possible that the lubricated uniaxial compression tests must be performed on doughs in the temperature range where gas cell coalescence occurs. No data are available on biaxial extension of wheat flour doughs, starch, and gluten at temperatures of 60–70°C.

### Effect of Inclusions on Gas Cell Wall Stability

One factor that might affect the stability of gas cells in bread dough and the subsequent crumb grain of the baked product is the number of large starch granules in the bread dough system. The starch granules can be considered as inclusions in the gluten protein matrix. During baking, if the gas cell wall thins to a film thickness smaller than the diameter of a starch granule (actually the thickness of the granule when its large dimension is parallel to the surface of the cell wall), the gas cell wall will fail and coalesce with adjacent gas cells. This suggests that if the starch fraction of a wheat flour contained predominately large, lenticular granules, gas cell wall failure would be more common because the minimum thickness for stability of the gas cell wall would be reached more frequently. It follows that, because of the larger size (100 μm), the addition of potato starch granules to a wheat flour dough should result in even greater cell wall failure and more open crumb grain. Excessive cell wall failure during oven spring will affect not only the crumb grain but also loaf volume because of decreased $CO_2$ retention.

The addition of wheat starch + gluten and potato starch + gluten to the 893 wheat flour affected the crumb grain of the baked products differently (Fig. 5). Breads baked from the 893 flour and wheat starch + gluten blend were of similar, intermediate crumb grain up to a level of 50% addition. These results suggest that although the amount of commercial wheat starch in the flour increased, the size distribution of the starch granules was not affected and, hence, crumb grain of the bread was not affected. Breads baked from the 893 flour and potato starch + gluten blend had crumb grains similar to breads made with the 893 flour alone up to a supplementation

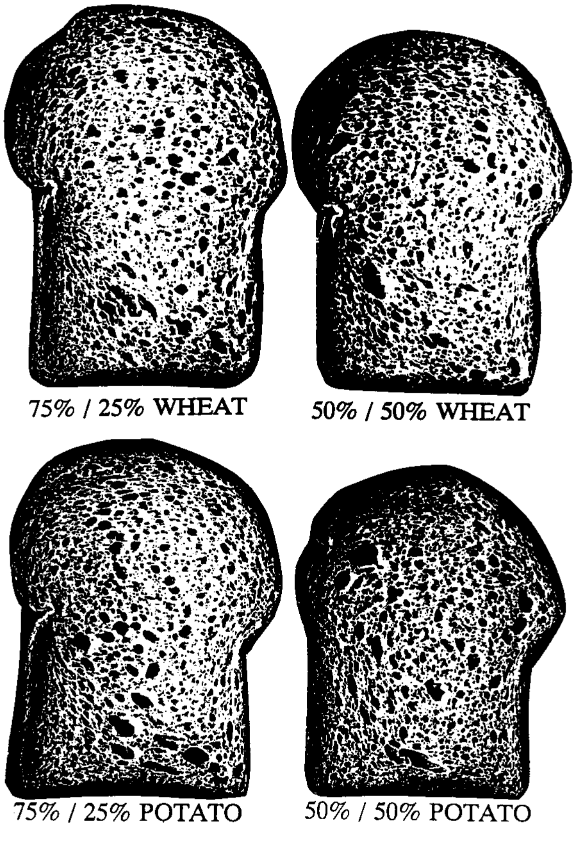

**Fig. 5.** Crumb grains of breads baked with 893 flour and wheat starch or potato starch + gluten blends of 75-25% and 50-50%.

**TABLE I**
**Contents of Protein, Moisture, and Ash Values (%) and Crumb Grains of Breads Made from Wheat Flour Samples**

| Flour | Protein | Moisture | Ash | Crumb Score |
|---|---|---|---|---|
| 892 | 11.5 | 11.9 | 0.49 | Open |
| 893 | 11.7 | 13.7 | 0.48 | Open |
| CT7130 | 13.8 | 12.9 | 0.48 | Fine |
| CT7134 | 14.7 | 12.4 | 0.45 | Intermediate |

**TABLE II**
**Loaf Volumes of Breads Baked With Different Levels of 893 Flour and Starch Plus Gluten Blends**

| Flour (%) | Starch Type | % Starch | Loaf Volume (cm$^3$) |
|---|---|---|---|
| 95 | Wheat | 5 | 890 ± 10 |
| 95 | Potato | 5 | 895 ± 7 |
| 90 | Wheat | 10 | 870 ± 8 |
| 90 | Potato | 10 | 855 ± 10 |
| 75 | Wheat | 25 | 850 ± 10 |
| 75 | Potato | 25 | 815 ± 3 |
| 50 | Wheat | 50 | 800 ± 7 |
| 50 | Potato | 50 | 710 ± 3 |

**TABLE III**
**Image Analysis of the Crumb Grains of Breads Produced from Reconstituted Flours Containing Large or Small Starch Granules[a]**

| Starch Granule Size | Number of Cells[b] | Cell Size[c] |
|---|---|---|
| Large | 5.72b | 5.96a |
| Small | 5.85a | 5.79b |

[a] Values followed by the same letter are not significantly different ($\alpha = 0.05$). $n = 18$.
[b] Least significant difference = 0.1143; log mean.
[c] Least significant difference = 0.1537; log mean; size based on pixel area = $5.33 \times 10^{-4}$ mm$^2$/pixel.

level of only 10%. Addition of the potato starch + gluten blend at 25% changed the crumb grain, resulting in an increase in intermediate-sized, round gas cells with thick cell walls (Fig. 5). Addition of the potato starch + gluten blend at 50% resulted in open crumb grain and decreased loaf volumes (Table II).

Although these results were encourging, they were far from definative. Potato starch granules are different from wheat starch granules. Thus, other factors besides size of the granules also may be important. Therefore, wheat starch was isolated and separated into small and large granule fractions. In the total starch fraction (tailings + prime starch), 62.8% of the particles were <10 μm in diameter, and the remaining 37.2% had diameters of 10–50 μm. In the isolated small granule fraction, 84.9% of the particles were <10 μm in diameter, and 14.7% of the granules had diameters of 10–40 μm. Only 0.4% of the particles in the small granule fraction were >50 μm in diameter. Analysis of the large granule fraction showed that 76.6% of the particles had diameters of 10–40 μm, 22.3% had diameters of 0–10 μm, and 1.1% had diameters >50 μm. Thus, the method used for particle size analysis of the isolated starch fractions provided a good separation of large and small granules. However, Stokes' sedimentation equation is based on spherical bodies. Because the large starch granules are lenticular, the particle size diameters might be slightly inaccurate.

In bake tests conducted using the starch granule fractions in a ratio of 80% starch granules and 20% gluten, visual differences were observed in the crumb grains of the breads baked with the large and small starch granule fractions. The large granule fraction gave a more open grain with larger cells and thicker cell walls, and the small granule fraction gave loaves exhibit a finer grain with smaller cells and thinner cell walls.

To confirm these subjective evaluations of crumb grain, a visual imaging system was used to evaluate the bread's crumb grain. The system used (Shen 1996) provides, among other attributes, the number of cells in a field and the average cell size. Analysis of the data did not show a difference in cell size between the large and small granules at $\alpha = 0.05$. However, data of this type often are skewed. Therefore, a log transformation was performed so the data would more closely approximate a normal distribution. These data (Table III) indicate that the crumb grains of breads made from reconstituted flours containing large and small granules were significantly different in the numbers of cells and also in the sizes of the cells. The crumb grain of the bread made from flour with large starch granules had fewer cells and larger cell size, whereas the crumb grain of bread made from flour with small granules had a greater number of cells and a smaller cell size. This indicates that in the dough made from reconstituted flours containing large starch granules, the cells coalesced and formed larger individual cells. This gives merit to the idea that a flour with a greater proportion of large starch granules results in a bread with an open crumb structure and thick cell walls.

## CONCLUSIONS

The negative results of surface tension measurements made by determining stress relaxation of a gas bubble in dough with the alveograph suggested two possible conclusions. Either the method was inappropriate for determining surface tension in bread doughs, or the method did measure surface tension, but it was not related to differences in crumb grains of breads. As measured by dynamic oscillatory rheometry and lubricated uniaxial compression, the rheological properties of doughs producing breads of different crumb grains were not different. However, the strain and temperature under which the tests were run may not have been optimum. A greater proportion of large starch granules caused cell coalescence and open crumb grain in the final baked product. This suggests that distribution of starch granule size may be one factor that affects the crumb grain of bread.

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