Measurement and Interpretation of Dough Densities

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ABSTRACT

Dough density is often used in determining the void fraction of gas in a dough. A new method is presented for the measurement of dough density that is more convenient than previous methods. A straightforward procedure for estimating the gas-free dough density, which permits accurate calculation of the void fraction of gas in a dough, is described. The void fraction of gas is proportional to the pressure at which the dough is mixed and depends on mixer design and blade speed. Oxygen deprivation of dough mixed below atmospheric pressures may affect the gas-free dough density. A technique of delayed pressure reduction minimizes oxygen deprivation and permits accurate determination of the gas-free dough density. Investigations of dough aeration can then decouple the effects of different mixing conditions on the gas-free dough density and on the void fraction of gas in the dough.

The void fraction of gas in a dough is not an easily measured quantity, yet it has an important influence on the development of the aerated structure of the dough during proving. Dough density has been used for over half a century as an indication of the void fraction of gas in a dough. Baker and Mize (1937) first measured dough density by measuring the volume of a known weight of dough against the displacement of mineral oil. More recently, Dus and Kokini (1990) measured dough density using the same technique. Baker and Mize (1946) determined dough density by dropping dough samples into a series of calcium chloride solutions of known density, taking the solution in which the sample was neutrally buoyant as the dough density. Junge et al (1981) and Chamberlain et al (1967, 1970) used the same technique. It was rapid and allowed measurement of the changes in dough density throughout mixing. Dough density was considered indicative of changes in the amount of gas entrained into the dough during mechanical development. Although the method is rapid, it is inconvenient for routine density measurement; a large number of calcium chloride solutions with different densities must be prepared and maintained at constant temperature. Furthermore, the samples must be analyzed immediately, before proving or drying of the dough occurs.

The void fraction, or volume fraction, of gas in a dough (α) can be calculated from the measured dough density (ρ):

$$\alpha = 1 - \rho/\rho_{gf} \qquad (1)$$

Clearly, to calculate the void fraction using this equation, the gas-free dough density (ρ_{gf}) must be known. Baker and Mize (1937) estimated ρ_{gf} by mixing dough under a very high vacuum. However, this deprives the dough of oxygen during mixing, altering the dough chemistry and possibly affecting the gas-free dough density. Such a technique requires a mixer capable of applying almost full vacuum during mixing, which is not available in most baking laboratories.

This article presents a new method for measuring dough density that is more convenient than the Baker and Mize (1946) method of using a series of $CaCl_2$ solutions. The new method determines the gas-free dough density without mixing dough under almost full vacuum. It has been used to investigate the effect of oxygen deprivation during mixing on the gas-free dough density. Some previous density results reported in the literature have been reinterpreted in the light of these findings.

MATERIALS AND METHODS

Measuring Dough Density

Doughs in these experiments were made from 4.5 kg of flour mixed in a Tweedy 10 laboratory mixer (Tweedy Co., Burnley,

U.K.) to a total work input of 10 Wh/kg of dough. The dough formulation is given in Table I. All doughs in these experiments used the same flour (a blend of strong British baking flours) and the same water content. Dough samples were taken after mixing, immediately frozen in liquid nitrogen at $-196°C$, and stored in liquid nitrogen until analysis. Storage at temperatures greater than $-70°C$ would have allowed ice crystal growth that affects the dough density. A high density solution (about 1.5 g/cm³) of calcium chloride and distilled water was prepared. Dough samples were removed from frozen storage and transferred to glass jars containing the high density solution. Three or more samples taken from each dough were analyzed. Distilled water was added and mixed with the $CaCl_2$ solution until the sample was just neutrally buoyant. This procedure took about 10 min, during which time the dough sample thawed completely. The density of the solution was measured using a calibrated 10 cm³ density bottle.

The primary advantage of this method is its convenience: one person can perform the measurements at any time using only one calcium chloride solution. The disadvantage is that the density of dough that has been frozen and then thawed differs slightly from the density of unfrozen dough. The reason for this is not clear, but it may be related to the release of bound water in the freeze-thaw cycle. However, an allowance can be made for this difference: for the same dough, the densities of unfrozen samples were about 3% smaller (at all mixing pressures) than those of samples that were frozen then thawed. Moreover, an absolute value of dough density is not required when the density measurement is simply a means of determining the void fraction of gas in a dough sample.

RESULTS AND DISCUSSION

Errors in Dough Density Measurements

The precision error in the new method was determined by measuring densities of replicate dough samples from the same batch of dough. The standard deviation for a given dough density measurement was 0.0021 g/cm³. Standard error is $0.0021/\sqrt{n}$ g/cm³, where n is the number of measurements. All errors are ± 1 standard deviation. No error bars are shown on Figures 1–6, as they were of a size similar to, or smaller than, the symbols used.

TABLE I
Formula for Bread Dough

Ingredient	Percent on Flour Weight
Flour	100.0
Salt	1.8
Yeast	2.5
Commercial improver (Green Dynarex)	1.0
Water	61.0[a]

[a] Determined by separate water absorption experiments.

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Density of Doughs Mixed at Different Pressures

Doughs were mixed at four pressures: 30 (atmospheric), 20, 10, and 5 in. Hg abs. Four density measurements were made for each dough. The standard error of a given density measurement is 0.00105 g/cm^3. Figure 1 shows that the density decreases linearly with increasing pressure; this suggests that the gas-free dough density may be found easily by extrapolation back to zero pressure. Regression lines were fitted to the data of Figure 1, giving the gas-free dough density as 1.2763 ± 0.0021 g/cm^3. Void fractions of gas in the dough were then calculated using Equation 1 (Fig. 2). Appendix I details how the errors in ρ_{gf} and α were calculated.

The void fraction of gas in the dough is proportional to the pressure at which it was mixed (the correlation coefficients for the linear regressions of Figs. 1 and 2 are $R^2 = 0.999$). Campbell (1991) showed that this linearity must be reflected in any mechanisms that are proposed to describe how gas is incorporated into dough during mixing. Campbell (1991) also confirmed this linear relationship between void fraction and mixing pressure for other mixer designs.

Reinterpreting Previous Results

Chamberlain et al (1967) described experiments in which doughs were mixed at three different blade speeds (150, 300, and 600 rpm) in a variable-speed Morton Duplex mixer. Four mixing pressures were used: 5, 15, 25, and 30 in. Hg abs. Dough densities were measured using a series of calcium chloride solutions of different densities. The gas-free dough density was estimated by considering the mass of each dough ingredient; the volume occupied by each ingredient was calculated from its individual density. The mean density was taken to be the total mass divided by the total volume. This is illustrated for the strong flour in Table II, using the original data from Chamberlain et al (1967).

Chamberlain et al (1970) reported void fractions of air in doughs made from three flours: a weak English flour, a strong Canadian flour, and a 50:50 blend of the weak and strong flours (classified according to water absorption). This procedure assumes ideal solution behavior and ignores volume changes during dissolution of the ingredients. Thus, the original estimates of the gas-free dough density obtained by Chamberlain et al (1970) are inaccurate; so much so that some of the calculated void fractions are negative. We have reinterpreted these measurements, using the new procedure for finding the gas-free dough density.

Chamberlain et al (1970) did not report water absorption figures for the weak English flour or the blend flour. Chamberlain et al (1967) reported water absorption figures for Canadian and English flours. The water absorption of the English flour was 87.65% of that of the Canadian flour. Assuming a similar ratio for the flours used in the 1970 study, the water absorption for the English flour was estimated to be 52.90%, from which the gas-free dough
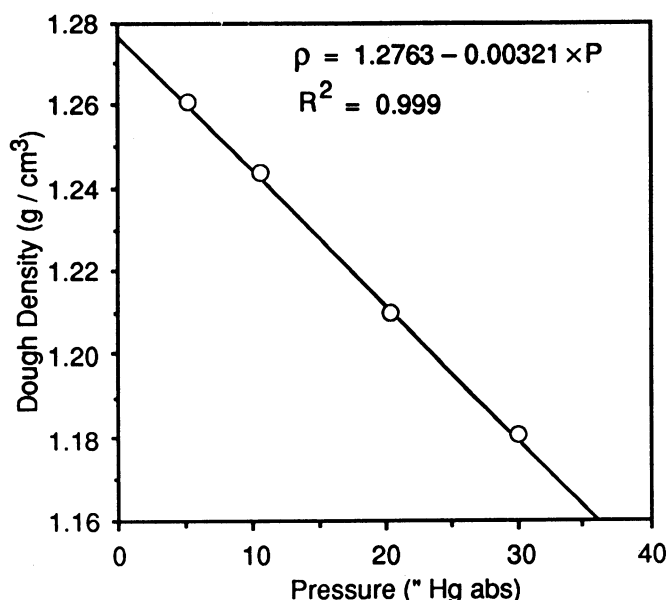

Fig. 1. Dough density measurements of doughs mixed under vacuum at four different pressures: 30 (atmospheric), 20, 10, and 5 in. Hg abs in a Tweedy 10 mixer. The linear regression line is used to extrapolate back to the gas-free dough density.

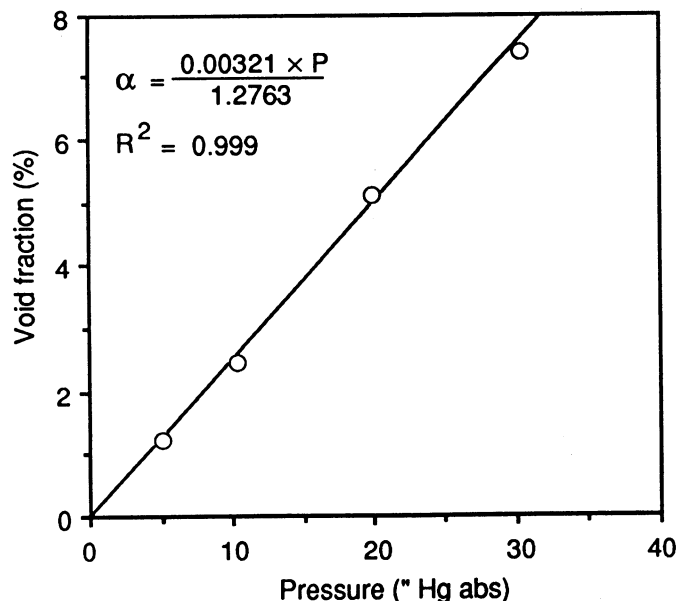$$\rho = 1.2763 - 0.00321 \times P$$
$$R^2 = 0.999$$

Fig. 2. Calculated void fractions of doughs mixed under vacuum at four different pressures: 30 (atmospheric), 20, 10, and 5 in. Hg abs in a Tweedy 10 mixer.

$$\alpha = \frac{0.00321 \times P}{1.2763}$$
$$R^2 = 0.999$$

TABLE II
Estimated Gas-Free Dough Density for a Strong Canadian Flour[a]

Ingredient	Mass (g)	Density (g/cm^3)	Volume (cm^3)
Flour	100.00	1.45	69.97[b]
Yeast	2.14	1.00	2.14
Salt	1.78	2.17	0.82
Fat	0.71	0.90	0.79
Water	60.35	1.00	60.35
Totals	164.98		134.07

[a] Based on data from method of Chamberlain et al (1970). Estimated ρ_{gf} for the strong Canadian flour = $164.98/134.07 = 1.2306$ g/cm^3.

[b] The flour volume of 69.97 cm^3 given by Chamberlain et al (1970) is, in fact, not correct because $100/1.45 = 68.97$. However, 69.97 has been used in these calculations, to allow consistent reinterpretation of the Chamberlain et al (1970) measurements.

TABLE III
Densities of Doughs Mixed from Three Flours
at Three Blade Speeds and Four Mixing Pressures[a]

Blade Speed (rpm)	Pressure (in. Hg abs)	Weak ρ (g/cm^3)	Blend ρ (g/cm^3)	Strong ρ (g/cm^3)
150	5	1.2615	1.2583	1.2454
	15	1.2279	(1.1989)[b]	1.2195
	25	1.1918	1.1989	1.1974
	30	1.1719	1.1866	1.1851
300	5	1.2565	1.2559	1.2404
	15	1.2118	1.2150	1.2109
	25	1.1732	1.1816	1.1789
	30	1.1570	1.1717	1.1752
600	5	1.2565	1.2533	1.2355
	15	1.2155	1.2200	1.2109
	25	1.1807	1.1890	1.1838
	30	1.1707	1.1779	1.1752

[a] Data used are from the results of Chamberlain et al (1970).
[b] This measurement appears to be incorrect, so has been ignored.

density was estimated as 1.2441 g/cm³. For the blend flour, the gas-free dough density estimate was the average of those for the weak and strong flours (1.2373 g/cm³). The original measured dough densities (Table III) were calculated from the void fractions presented by Chamberlain et al (1970). These estimates of the gas-free dough densities were used for the three flours.

Regression lines were fitted to these data to allow extrapolation back to zero absolute pressure. Estimates of the gas-free dough density for each flour at each blade speed are given in Table IV and Figure 3. The gas-free dough density appears to decrease with flour strength (due, in part, to the lower water absorption of weak flours), and it decreases with increasing blade speed. This suggests that water is a major contributor to dough density. However, the data of Table IV and Figure 3 suggest that the gas-free dough density is not directly proportional to moisture content. It is reasonable to suppose that the gas-free dough density would change with dough formulation and with mixer design. An important conclusion from this work is that the gas-free dough density is not constant and must be measured for each experimental condition. Thus, a rapid and precise method for measuring gas-free dough densities is required. Void fractions of gas in the dough can be calculated using the gas-free dough density estimate. Campbell (1991) discusses the effect of the void fraction of gas in dough on the baked loaf quality.

Void fractions of gas in the doughs were calculated using Equation 1 (Fig. 4). The void fraction of air in a dough increases linearly with increasing pressure, as we found previously in our experiments. Chamberlain et al (1970) also indicated that the void fraction decreases with increasing flour strength. In this study, it was greater at a mixing speed of 300 rpm than at either 150 or 600 rpm.

Effect of Delayed Pressure Reduction on the Gas-Free Dough Density

Mixing dough below atmospheric pressure reduces the availability of oxygen during mixing (Baker and Mize 1937). This changes the dough chemistry and may, therefore, affect the gas-free dough density. Baker and Mize (1937) also demonstrated experimentally that entrapment of gas in the interstices of flour particles does not contribute significantly to the gas content of the dough after mixing. The effect of mixing under vacuum was investigated by mixing doughs in the Tweedy 10 mixer at four pressures: 30, 20, 10, and 5 in. Hg abs (these pressures remained constant throughout mixing). Three additional doughs were mixed at 30 in. Hg abs (atmospheric pressure) initially, then the pressure was decreased to 20, 10, and 5 in. Hg abs, respectively, for the final 25 sec of mixing. This process reduced the void fraction of gas in the dough at the end of mixing to the same level as that resulting from pressure being reduced throughout the entire mix. However, it almost completely eliminated the difference in availability of oxygen during mixing. This procedure is called delayed pressure reduction.

Approximate calculations were made of the amount of water removed from the headspace of the mixer during evacuation. Assuming that the headspace gas was saturated with water vapor at the initial water temperature of 12–15°C, less than 0.05% of the water added to the dough was removed as the pressure was reduced to 5 in. Hg abs.

Figure 5 shows the density of doughs mixed at different pressures, with and without delayed pressure reduction. Doughs mixed
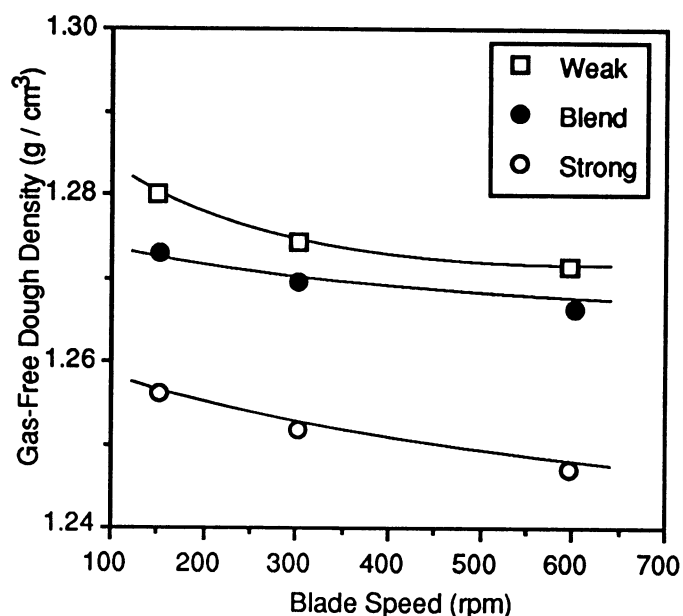
Fig. 3. Gas-free dough density measurements for three flours at three blade speeds (150, 300, and 600 rpm) calculated from the data of Chamberlain et al (1970) using linear regression.
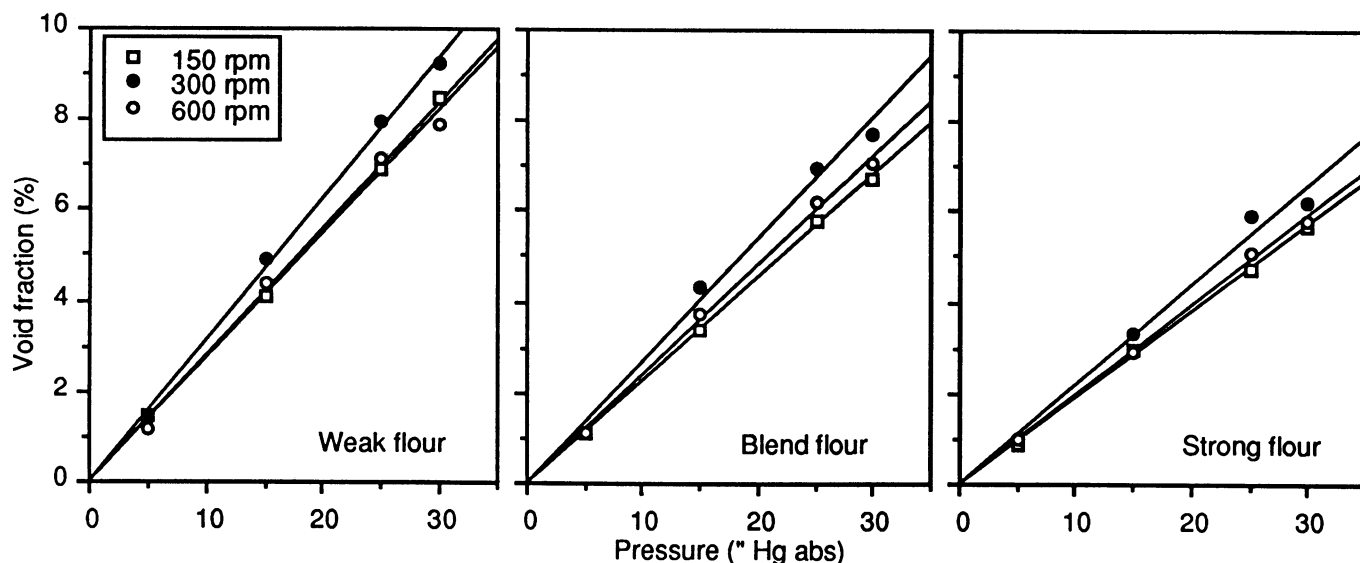
TABLE IV
Gas-Free Dough Densities for Three Flours at Three Blade Speeds

Blade Speed (rpm)	Weak ρ_{gf} (g/cm³)	Blend ρ_{gf} (g/cm³)	Strong ρ_{gf} (g/cm³)
150	1.2803	1.2725	1.2567
300	1.2745	1.2700	1.2526
600	1.2712	1.2673	1.2476

Fig. 4. Recalculated gas void fractions from the data of Chamberlain et al (1970) showing the effects of flour strength and mixer blade speed.

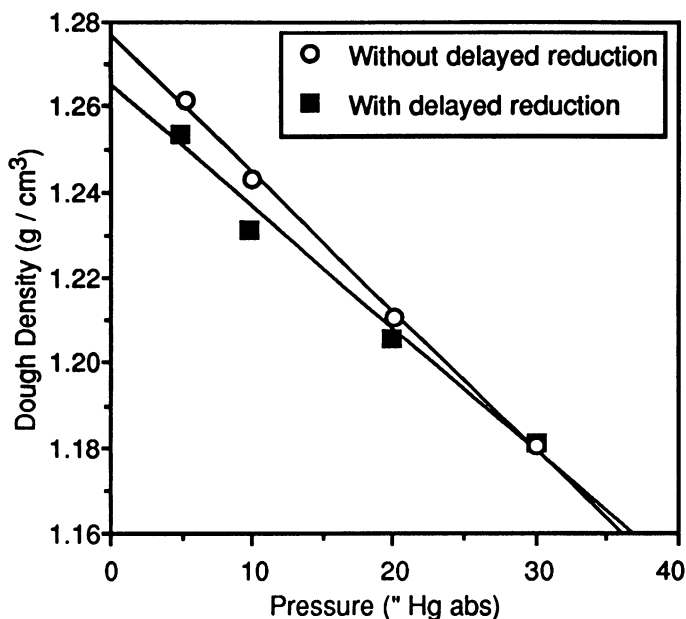**Fig. 5.** The effects of oxygen deprivation on the density of doughs mixed in the Tweedy 10 mixer.
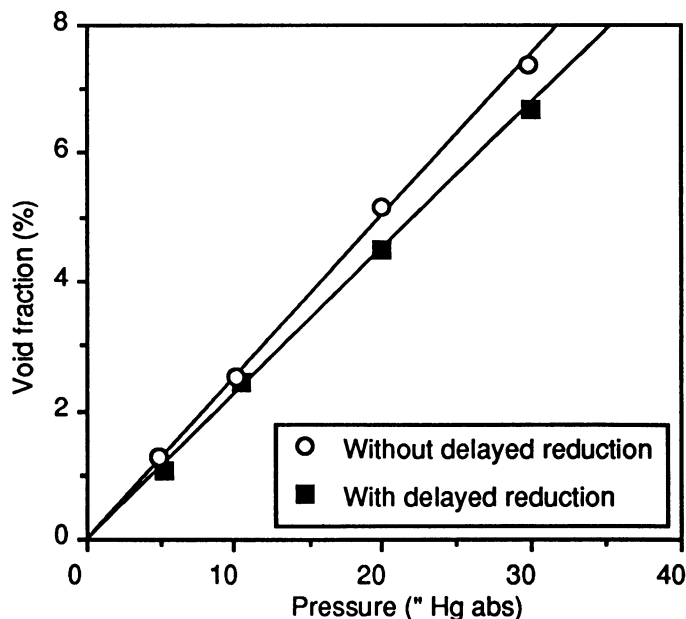

Fig. 6. Calculated void fractions with and without delayed pressure reduction in the Tweedy 10 mixer.

at constant pressures (<30 in. Hg abs) had a higher density than did those mixed with delayed pressure reduction. Least-squares regression lines were fitted to both sets of data. The gas-free dough density without delayed pressure reduction was 1.2763 g/cm³, with a standard deviation of 0.0021 g/cm³. The gas-free dough density with delayed pressure reduction was 1.2655 g/cm³, with a standard deviation of 0.0021 g/cm³. The difference is 0.0108 g/cm³, with a standard deviation of 0.0029 g/cm³ (obtained by adding the variances). This gives a t-statistic of 3.7, with 24 degrees of freedom, which is significant at the 95% level of confidence. Thus, oxygen deprivation of doughs mixed at reduced pressure significantly increases the gas-free density of the dough. Using delayed pressure reduction eliminates oxygen deprivation and gives a more precise determination of the gas-free dough density.

Figure 6 shows a comparison of the void fractions of gas calculated from doughs mixed with, and without, delayed pressure

reduction, using the two estimates of ρ_{gf}. The estimate obtained without delayed pressure reduction overestimated the calculated percentage void fractions of gas by as much as 0.8% (a relative error of over 10%).

CONCLUSIONS

A new method for measuring dough density has been presented that is more convenient than the previously popular method of using a series of solutions with differing densities. Calculation of the void fraction of gas in a dough requires knowledge of the gas-free dough density. This can be readily estimated by extrapolating the densities of doughs mixed at different pressures back to zero pressure. The gas-free density varies with oxygen availability during mixing, mixer design, mixing speed, and dough formulation. Extrapolation of the data from doughs mixed at different pressures can determine the effect of delayed pressure reduction on the gas-free dough density. This makes it possible to decouple the effects on the void fraction of gas incorporated during mixing from the effects on the gas-free dough density.

The void fraction of gas in a dough is proportional to the pressure at which it is mixed. A reinterpretation of previous results (from Chamberlain et al 1970) shows that strong flours entrain less air than weak flours. It also shows that the void fraction of air depends on the mixing speed. Dough density measurements constitute a powerful tool for investigating dough aeration. However, the interpretation of measurements must be approached carefully; a poor estimation of the gas-free dough density can lead to erroneous conclusions.

APPENDIX I

When the variance in a dough density measurement is $v(\rho) = \sigma^2/n$, then the variance in ρ_{gf} is:

$$v(\rho_{gf}) = \frac{\dfrac{v(\rho)}{N} \sum_{j=1}^{N} P_j^2}{\sum_{j=1}^{N} (P_j - \bar{P})^2} \qquad (2)$$

where: N = number of different pressure levels
P_j = pressure level j ($j = 1,N$)
$\bar{P}$ = average pressure

The covariance Cov (ρ,ρ_{gf}) of ρ and ρ_{gf} is:

$$\mathrm{Cov}(\rho,\rho_{gf}) = v(\rho) \left(\frac{1}{N} - \frac{(P_j - \bar{P})\bar{P}}{\sum_{j=1}^{N} (P_j - \bar{P})^2} \right) \qquad (3)$$

Then the standard deviation of α, s_α, calculated from ρ using equation 1 is

$$s_\alpha = \frac{1}{\rho_{gf}} \sqrt{v(\rho) + (1 - \alpha)^2\, v(\rho_{gf}) - 2(1 - \alpha)\mathrm{Cov}(\rho,\rho_{gf})} \qquad (4)$$

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Amylopectin and Intermediate Materials in Starches from Mutant Genotypes of the Oh43 Inbred Line[1]

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ABSTRACT

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Amylopectin (AP) and intermediate materials (IM) from five endosperm mutant genotypes in a common Oh43 inbred line were isolated and examined by gel-permeation chromatography, iodine affinity, blue value (BV), and viscosity. The chain-length distributions of AP and IM were determined using an enzymatic-chromatographic method. The degrees of branching in AP and IM decreased when the amylose-extender (ae) gene was present. The dull-1 (dul) gene produced AP and IM with the highest degrees of branching among the samples. The ae starch had a significantly ($P < 0.01$) longer peak average chain length (CL) of the long-B chains in the IM fraction (177 glucose units) than did the AP fraction (73 glucose units) or the other starches (37-56 glucose units). The higher iodine affinity in ae starch of the IM (6.1) compared with

that of the AP (2.8) supported the idea that the IM had a longer CL than did the AP. There were no significant differences in the peak CL of A or B chains in AP and IM fractions of brittle-1 (btl), dul, ae btl, and ae dul starches. The IM of ae and ae dul starches had higher BV than did the AP fractions; however, the IM of dul and ae btl had lower BV than did the AP fractions. The limiting viscosity number and gel-permeation chromatography results indicated that the AP and IM fractions of btl and dul starches possessed more branching and larger hydrodynamic volume properties than those of the ae, ae btl, and ae dul starches. The present study demonstrated that genetic background affects the CL of starch branches, degree of branching, and iodine binding properties of starches.

Starch is composed of two primary components: amylose (AM), an essentially linear molecule; and amylopectin (AP), a highly branched molecule. The existence of a third component in normal maize starch, an intermediate material (IM) with properties different from those of AM and AP, was first postulated by Lansky et al (1949). Banks and Greenwood (1975) suggested that type and amount of IM depended primarily on the AM percentage of the starch, although it varied considerably among starches.

The AM content in normal maize (Zea mays L.) starch ranges from 25 to 30%; however, the AM content can be altered with mutant genes. Amylomaize, which contains the recessive mutant gene amylose-extender (ae), has an apparent AM content of up to 80% (Banks and Greenwood 1975) and is associated with the presence of abnormal AP (Mercier 1973, Ikawa et al 1978, Boyer et al 1980, Ikawa et al 1981). Wolff et al (1955) demonstrated that the AP fraction in a 50% amylomaize starch had longer inner and outer chains than those of normal AP, where the inner and the outer chains were divided at the point of α-1,6-glucoside bonds. Montgomery et al (1964) supported the proposal of Wolff

et al (1955) that the AP in amylomaize starch was less highly branched than was normal AP. Some investigators (Banks and Greenwood 1968, Adkins and Greenwood 1969), however, proposed that the resulting abnormal AP came from contaminating short-chain AM. The discrepancy might result from the fact that investigators seldom used exactly the same techniques for the dispersion and fractionation of starch (Banks and Greenwood 1975). Although the fine structure of abnormal AP from amylomaize has not been completely clarified, there are many reports showing the presence of abnormal AP in amylomaize starch (Mercier 1973, Ikawa et al 1978, Boyer et al 1980, Ikawa et al 1981).

More recently, Baba and Arai (1984) examined the fine structures of AP and IM in a 50% amylomaize starch. They found that the IM and the AP of amylomaize possessed an average chain length (CL) that was 20 and 10 glucose units longer than that of the AP of waxy (wx) maize, respectively. The IM of amylomaize had an average degree of polymerization of 250-300 glucose units per molecule, with four or five branches having a CL of approximately 50 glucose units.

In addition to the ae gene, the combinations of a dull-1 (dul) or sugary-1 (sul) gene with other recessive mutant genes (except the wx gene) also produced starches with increased AM contents (Ikawa et al 1981; Yeh et al 1981; Inouchi et al 1983, 1987; Boyer and Liu 1985; Wang et al 1993). In a previous report (Wang et al 1993), several mutant genotypes (ae, dul, ae brittle-1 [btl], and ae dul) evidenced increased AM as well as increased IM content. This study was undertaken to examine the structures and the physicochemical properties of AP and IM from several mutant genotypes in an Oh43 inbred background to illustrate the influences of recessive mutant genes on the starches.