Rheological Changes of Fortified Wheat and Corn Flour Doughs with Mixing Time

LEO L. NAVICKIS[1]

ABSTRACT

Rheological properties of doughs blended from wheat and corn flours fortified with vital wheat gluten were measured on rested doughs for a series of mixing times (at increasing work energy inputs) all at the same water content. As mixing time increased, the volume of loaves baked from these doughs increased to a maximum, then decreased. The shear modulus obtained at small strains (0.2%) increased with mixing time, whereas the relaxation time generally decreased. The dynamic storage modulus G' increased with mixing time while the loss modulus G'' decreased. The ratio G''/G' was close to 1.0 at the mixing time that gave the greatest loaf volume. This ratio (1.0) shifted to a longer mixing time at 1% higher water content. The response of these doughs to large torsional deformations was also examined. The maximum torque attained at first showed a stiffening dough, followed by less resistance as mixing time increased. The strain corresponding to the maximum torque generally decreased until the doughs were mixed well past the point of minimum mobility. A similarity is noted between maximum torque values and maximum strains of these blended flours and extensigraph measurements reported for all-wheat flours as influenced by mixing times.

Converting flour into a baked product such as bread requires preparing a dough by applying mechanical work to a mixture of dry ingredients and water until they form a coherent mass possessing the physical properties to give an acceptable product (Hoseney and Finney 1974). Additional energy is imparted to the dough during its subsequent fermentation, punching, molding, and pan proofing. Each of these steps alters the rheological properties of the dough and of the baked product to varying extents. The importance of assessing rheological properties of doughs has been discussed by Bloksma (1970, 1972), Muller (1975), and Faubion and Faridi (1986). Dough is, rheologically, a nonlinear viscoelastic material; therefore, it possesses properties dependent on strain as well as time. This was demonstrated first by the classical work of Schofield and Scott-Blair (1932, 1933a,b) who separated and quantified several rheological properties by extensional deformation of wheat flour doughs.

The effect of the amount of work imposed on the dough and the importance of the rate of work input was demonstrated by Kilbourn and Tipples (1972a,b), Skeggs and Kingswood (1981), and Frazier et al (1975, 1985). Sample resting prior to measurement also affects dough properties. The physical changes in wheat doughs rested for varied periods of time have been investigated using the concept of "structural relaxation" by, for example, Dempster and co-workers (1952, 1958).

One approach to studying rheological properties of materials is by dynamic stressing at small strains, as in the work of Smith et al (1970) and Hibberd and Wallace (1966), who applied such methods to studies of wheat doughs. Bohlin and Carlson (1980) and Abdelrahman and Spies (1986) also applied dynamic testing to the measurement of rheological properties as they relate to mixing times of wheat flour doughs. The rheological response of doughs is dependent on several factors related to the method of preparation (type of mixing action, mechanical work input, resting time, etc.) and the type of measurement. Because of growing commercial interest in speciality breads and other baked goods, we have been investigating rheological and baking properties of doughs prepared from blends of wheat and corn flours (Navickis 1987). Rheological studies have been made on all-wheat flour doughs by many investigators, but little has been published on wheat flour-corn blends. The purpose of this paper is to describe changes in some rheological properties of rested doughs prepared from such blends, fortified with wheat gluten, as a function of length of time mixing, i.e., increasing work input.

In contrast to commonly used mixing or extensional types of testing instruments, where the strains imposed on the dough are large and ill-defined, small strains with well-defined geometries and known strain rates (time-scale) can be used to measure basic rheological properties more or less separately. Such small strains are used in the simple shear, dynamic, and relaxation measurements described in this paper. Larger strains are imposed in the torsional measurements. Further, whereas rapid deformation rates are normally used in dough mixers and extensigraphs, a relatively slow rate of deformation is used in this study for the large deformation torque measurements.

MATERIALS AND METHODS

Unbleached hard red spring wheat flour (Len cultivar) was obtained from a pilot-plant Miag Multomat mill at 70.7% extraction. Protein was determined by AACC method 46-13 as 15.1% (db). Ash was determined by AACC method 08-01 as 0.48% (db). The absorption was 63.5% (14% moisture basis). Corn flour was a commercial grade obtained from Illinois Cereal Mills, Paris, IL. Wheat gluten was a flash-dried commercial product (Midsol, obtained from Midwest Solvents Co., Pekin, IL) having 72.9% total protein (db). No further assessment was made of the materials because the same lot of each was used throughout the series of mixes.

Dough Preparation

Corn and wheat flour doughs were prepared by AACC method 10-10A, except that a different fermentation cabinet and oven were used. Wheat flour-corn flour blends were mixed to equal percentage levels of solids. Wheat gluten was added to these blends to maintain the same total wheat gluten level as in the wheat flour alone (0.124 g gluten/g solids). The total water content for baking and rheological measurements was adjusted to 45.5% based on flour solids. This level was chosen to avoid excessive stickiness on longer mixing and is not necessarily the optimum. In addition, a few doughs were prepared at 46.5% water level for rheological measurements. All doughs contained 15 ppm of ascorbic acid and 7 ppm of bromate. When doughs were baked into bread, 2% yeast was added along with sugar and nonfat dry milk.

Doughs were mixed in air with a 300-g Swanson pin-type mixer (National Mfg. Co., Lincoln, NE). Replicate mixes were made on different days. Dough samples (90 g) taken at different times during mixing, were kept in a fermentation cabinet for 50 min at $31 \pm 1°C$ (85–93% rh), then passed between 3-in. wide sheeter rolls (National Mfg.) with a 5/16-in. opening. After a second fermentation period of 25 min, the second punch was made at a 5/16-in. opening and followed immediately by a pass through a 3/16-in. opening. Doughs for rheological measurement were bagged after this punch (i.e., not molded or proofed). Molding for baking was done with six to eight revolutions on a three-

roll molder (National Mfg. Co.) with the height set for a gentle action. Proofing in pup pans was for 38 min (31 ± 1°C, 85–93% rh). Bread was baked in an electric oven for 24 min at 218 ± 4°C. Loaf volumes were measured by rape seed displacement.

Rheological Measurements

Rheological measurements were made on a Rheometrics (K-71) mechanical spectrometer linked to a mainframe computer (Mod-comp Classic). Disks cut from the sheeted doughs were rested in sealed bags at constant room temperature (22.2°C) for 1–5 hr before being placed in the instrument. All disks were bonded, using a cyanoacrylate adhesive (Navickis and Bagley 1983), to 2.5-cm circular platens. The adhesive is required because in its absence there was evidence of the dough becoming detached from the platen(s) after the large stresses applied for the torque measurements. It is applied as a very thin layer to minimize the effect of the composite layer of adhesive and dough. Sample edges were then trimmed to platen size, the trimmed edge being subsequently coated with a paraffin oil to prevent drying. Dough heights of 4.00-mm were used. A 10- to 30-min wait was needed to allow stresses introduced during the loading to reach a steady state. A modulus of deformability, G (Mohsenin 1986), and a relaxation time, t_{50}, were first determined in simple shear by a lateral displacement of the lower platen, the displacement giving a shear strain of 0.23–0.29%. A simple lever and "stop" arrangement attached to the micrometer permitted uniformly rapid rates of deformation as confirmed from examination of data. The maximum force attained at the end of this rapid (0.3 sec, shear rate = 0.008/sec) displacement and the subsequent relaxation of the force with time were recorded by the computer every 0.02 sec to obtain t_{50}. This value was conveniently read from the computer printout where $P_t / P_o = 0.50$, P_t being the force at time t, after the maximum displacement, and P_o the maximum force attained when the maximum displacement is reached ($t = 0$) (Navickis 1987). P_o was also used to compute G as: $G = (P_o \times 981.3 \times h)/(6.283 \times R^2 \times a)$, where $R =$ material radius (mm); $a =$ lateral displacement (mm); and $h =$ material thickness (mm). A correction was made for instrument compliance (Macosco and Davis 1974). With the same dough in the platens, dynamic moduli G' and G'' were next determined in the eccentric rotating disk mode as described elsewhere (Navickis et al 1982). The angular velocity was 10.00 ± 0.04 radians/sec, the strain (a/h) being 0.23–0.28%. The ratio G''/G' was calculated after correction for instrument compliance. Finally, the behavior of the same dough disk in torsion (large strains) was measured with the upper and lower platens coincident. The upper platen angular velocity was maintained at 0.100 ± 0.006 radians/sec through a monitored angle of twist until the torque passed through a maximum value (T_{max}). The corresponding strain, (E_{max}), is defined here as: $E_{max} = (\theta \times R)/h$, where $\theta =$ radians of twist; $R =$ material radius (mm); and $h =$ material height (mm). T_{max} and E_{max} were plotted against mixing time. The adhesive bond between sample and platens was examined after the experiment; when any failure of the bond between sample and platen was noted, the results—torsion, simple shear, and dynamic—for that experiment were discarded.

RESULTS AND DISCUSSION

Frazier et al (1975), Dempster et al (1952), and Dempster and Hylinka (1958) showed that "structural relaxation" (i.e., changes in rheological properties) in their wheat flour dough samples was essentially complete after 45–60 min of resting before measurement. The rheological measurements on the wheat flour-corn flour dough samples were therefore made after rest periods of 1–5 hr. Samples were measured in order of increasing sampling (mixing) times, but in several series of samplings the measurements were made in reverse order so that the least mixed doughs were rested for about 5 hr instead of 1 hr. Replicate results were the same for 1 and 5 hr of resting.

For doughs with 45.5% water, line "a" in Figure 1 shows a general decrease of the relaxation time (t_{50}) with mixing time. The error bars represent one standard deviation from the mean. Because relaxation times are related to the viscosity (ϵ) and a modulus (G) by $T_{relax} = \epsilon/G$; because G, measured here in simple shear, increases linearly (line b, Fig. 1), only a rapid decrease in the viscous component of the material can explain the dip in t_{50} between 1.5 and 4 min. The rapid decrease of the viscosity in this region is also shown by dynamic measurement of the shear loss modulus G''. Such a decrease is illustrated in Figure 2, where G' and G'' are given at two water levels, 45.5 and 46.5%. Thus, t_{50} from a static measurement can be interpreted as a change in the viscosity-related loss modulus obtained from dynamic measurement.

Another measure of deformability related to G, the dynamic shear storage (elastic) modulus G', also increased with further mixing (45.5% water, Fig. 2). Bohlin and Carlson (1980) and Abdelrahman and Spies (1986) found a similar behavior for G' with wheat flour doughs. With 46.5% water, G' behaved differently, decreasing until about 8 min, then increasing. A major increase in G' at both water levels occurred where G' and G'' were nearly equal.

Abdelrahman and Spies (1986) reported that loaf volumes of baked goods increase as G' increases. In contrast, with the wheat flour-corn flour doughs plus added gluten, the loaf volume decreased at mix times beyond the 4.5-min optimum (Fig. 3), whereas there was a significant increase in G'. LeGreys et al (1981), studying the rheological behavior of commercial glutens, also found that the loaf volumes of breads prepared from reconstituted flours of gluten-starch solubles decreased with increasing G', in agreement with our results.

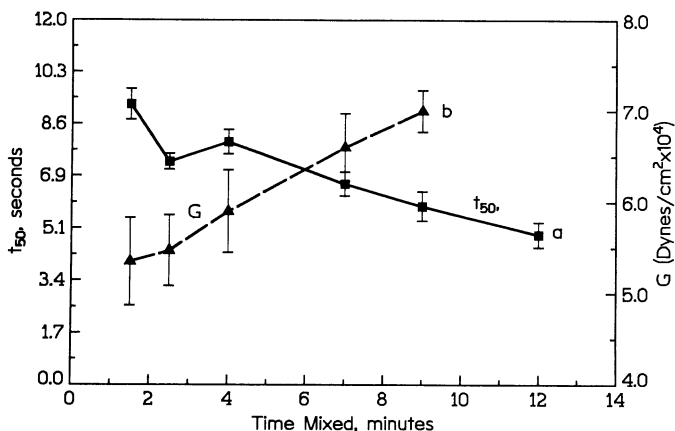Wheat flour-corn doughs further showed a distinctly different

Fig. 1. Water content = 45.5%. Plots of deformation (simple shear) modulus G (–▲–) and t_{50} (–■–) versus time of dough mixing.
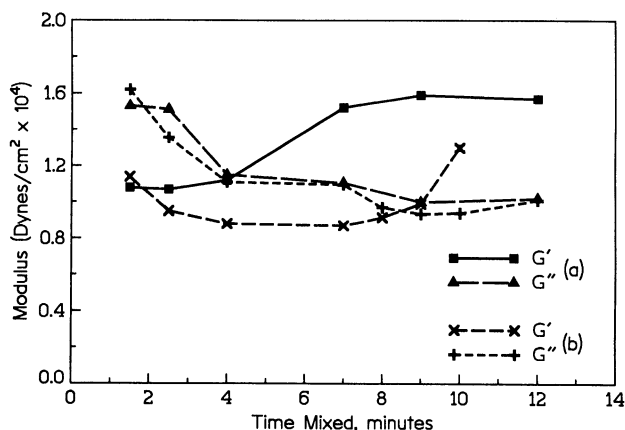

Fig. 2. Variation of dynamic moduli G' and G'' with minutes of mixing: 45.5% water doughs (–▲– and –■–); 46.5% water doughs (x- -x and +- -+). Angular velocity ≈ 10.0 radians/sec. The coefficient of variation of means (SEM/mean × 100) ranges from 0.9 to 7.2% with one exception at 8.8%. Each data point represents three to six mixes.
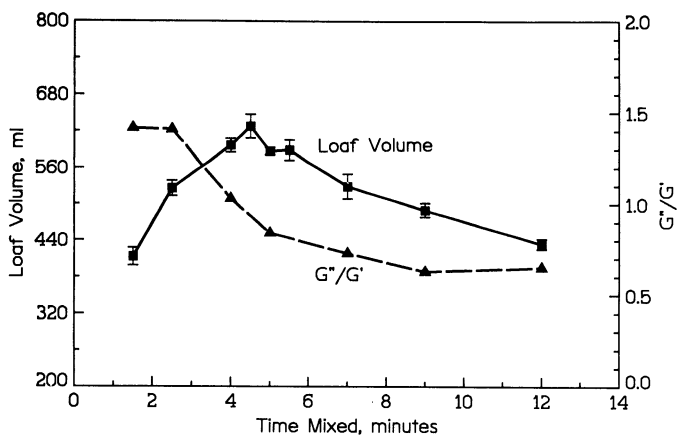
Fig. 3. Water content = 45.5%. Change in loaf volume (–■–) and G''/G' (- ▲ -) with minutes of mixing.
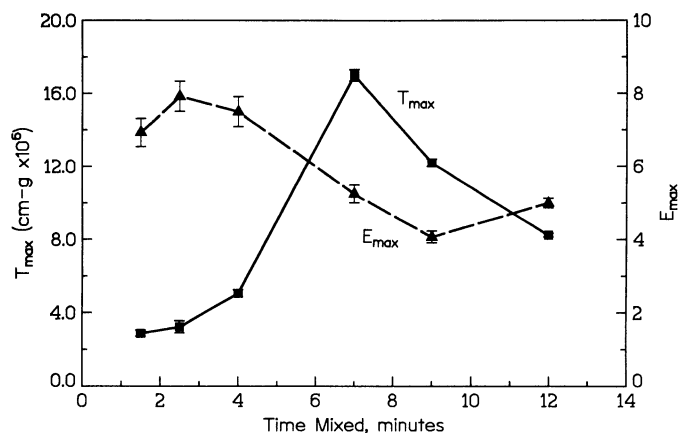

Fig. 4. Change in maximum torque attained (–■–) and strain at maximum torque (- ▲ -) with minutes of mixing of 45.5% water doughs. Angular velocity of top platen = 0.10 radians/sec.

(by rolling out from the gap), the only data considered here are the maximum torque attained while twisting the cylinder, T_{max}, and the corresponding strain, E_{max}. T_{max} may be considered as an "apparent yield point" since the strain increased with no further increase in the applied stress.

Results are shown in Figure 4, which shows that these rested doughs have a permanent structure that will support more stressing before it yields as more work is imparted during the initial mixing. The pronounced increase in T_{max} between about 3 and 7 min is in contrast to the more uniform and gradual increase in the small deformation shear modulus G (Fig. 1). The increase in T_{max} followed by a gradual decrease with extended mixing is, interestingly, very similar to the values of "maximum resistance" reported by Smith and Andrews (1952), who streched rested wheat flour doughs in the extensigraph after intensive pin-type mixing for 1–10 min. The initial rise in E_{max} followed by a decrease is also similar to extensigraph "extensibility" results of wheat flour doughs. Both first increase, then decrease with longer mixing times (Fisher et al 1949). This similarity between the results from two different methods of deformation, stretching and torsional shear, is of interest and could be the basis for more detailed studies.

SUMMARY

Several rheological properties of unleavened, rested wheat flour-corn flour doughs fortified with a commercial gluten at a constant water level were determined as functions of increasing mixing times. Measured at small strains, a modulus (G) increased while the relaxation time decreased with mixing time. The dynamic shear loss modulus G'' decreased with increasing mix times, whereas the storage modulus G' increased. The ratio of G''/G' is nearly 1.0 for the doughs mixed for the "optimum" time determined from bake tests. The ratio (1.0) shifted to longer mixing times as the percentage of water was raised. The maximum torque the rested dough structure supported in torsional straining to large deformations first increased, then decreased with over-mixing.

LITERATURE CITED

AMERICAN ASSOCIATION OF CEREAL CHEMISTS. 1983. Approved Methods of the AACC. Method 08-01, revised October 1981; Method 10-10A, approved January 1983; and Method 46-13, revised October 1986. The Association: St. Paul, MN.

ABDELRAHMAN, A., and SPIES, R. 1986. Dynamic rheological studies of dough systems. Pages 87-103 in: Fundamentals of Dough Rheology. H. Faridi and J. M. Faubion, eds. Am. Assoc. Cereal Chem.: St. Paul, MN.

BLOKSMA, A. H. 1970. Rheology in elucidating functionality in breadmaking. Symp. Composition and Functionality in Breadmaking. Am. Assoc. Cereal Chem.: St. Paul, MN.

BLOKSMA, A. H. 1972. Rheology of wheat flour doughs. J. Texture Stud. 3:3-17.

BOHLIN, L., and CARLSON, T. L. G. 1980. Dynamic viscoelastic properties of wheat flour doughs: Dependence on mixing time. Cereal Chem. 57(3):174.

DEMPSTER, C. J., and HYLINKA, I. 1958. Some effects of the mixing process on the physical properties of dough. Cereal Chem. 35:483.

DEMPSTER, C. J., HYLINKA, I., and WINKLER, C. A. 1952. Quantitative extensograph studies of internal stress in non-fermenting bromated and unbromated doughs. Cereal Chem. 29:39.

FAUBION, J. M., and FARIDI, H. A. 1986. Dough rheology: Its benefits to cereal chemists. Pages 1-9 in: Fundamentals of Dough Rheology. H. Faridi and J. M. Faubion, eds. Am. Assoc. Cereal Chem.: St. Paul, MN.

FISHER, M. H., AITKEN, T. R., and ANDERSON, J. A. 1949. Effects of mixing on extensograms. Cereal Chem. 26:81.

FRAZIER, P. J., DANIELS, N. W. R., and RUSSELL EGGITT, P. W.

rheological behavior from that reported for wheat doughs by Abdelrahman and Spies (1986) and by Bohlin and Carlson (1980) in that the loss modulus, G'', in our systems decreased with mixing time. It is of particular interest that the "crossover" of G' and G'' for curves "a" (45.5% water) of Figure 2 at 4.2 min is near the mix time of 4.5 min at which the loaf volume is greatest (Fig. 3). A plot of G''/G' (loss tangent) shows this ratio to be nearly 1.0, where the loaf volume is maximized with 45.5% water doughs (Fig. 3). Correlation of basic properties of an unyeasted dough to the same dough containing yeast cells and baking ingredients is tenuous. The correspondence of the ratio G''/G' being unity with maximum loaf volume is difficult to explain. Nevertheless it is reported here for these flour blends as an experimental fact. For explanation, one could postulate that the flow behavior of the continuous "gluten matrix", with and without gas cells, etc., and at different shear rates, are related. Increasing the water content of wheat flour doughs requires a longer mixing time for maximum development (to peak time in the farinograph or mixograph, for example) by common experience. Apparently this is also the case for these wheat flour-corn flour doughs, because the equivalence point shifted to 8.5 min when the water content was raised to 46.5% (Fig. 2).

With the same dough cylinder between the platens of the instrument, it was convenient to observe responses to large deformations in torsion as a function of increasing mixing times. Large deformations are experienced by dough during mixing and rising, and during various other mechanical process steps (dividing, sheeting). An angular velocity of the top (driven) platen of 0.10 radians/sec (shear rate = 0.312/sec) was chosen for ease of data reduction. Due to the viscoelastic nature of the material, a faster or slower rate would give different absolute values. Because of the irregular manner in which the material behaved at "failure"

1975. Rheology and the continuous breadmaking process. Cereal Chem. 52:106.

FRAZIER, P. J., DANIELS, N. W. R., and RUSSELL EGGITT, P. W. 1985. Laboratory measure of dough development. Pages 151-175 in: Rheology of Wheat Products. H. Faridi, ed. Am. Assoc. Cereal Chem.: St. Paul, MN.

HIBBERT, G. E., and WALLACE, W. J. 1966. Dynamic viscoelastic behavior of wheat flour doughs. Rheol. Acta. 5(3):193.

HOSENEY, R.C., and FINNEY, P.L. 1974. Mixing—A contrary view. Baker's Dig. 48(1):22.

KILBOURN, R.H., and TIPPLES, K.H. 1972b. Factors affecting mechanical dough development II. Implications of mixing at a constant rate of energy input. Cereal Chem. 49:48.

LeGRYS, G. A., BOOTH, M. R., and AL-BAGHDADI, S. M. 1981. The physical properties of wheat proteins. Pages 243-264 in: Cereals: A Renewable Resource, Theory and Practice. Y. Pomeranz and L. Munck eds. Am. Assoc. Cereal Chem.: St. Paul, MN.

MACOSCO, C. W., and DAVIS, W. M. 1974. Dynamic mechanical measurements with eccentric rotating disks flow. Rheol. Acta 13:814.

MOHSENIN, N. N. 1986. Physical properties of plant and animal materials. Gordon and Breach: New York.

MULLER, H. G. 1975. Rheology and the conventional bread and biscuit-making process. Cereal Chem. 52:89.

NAVICKIS, L. L. 1987. Corn flour addition to wheat flour doughs—Effect on rheological properties. Cereal Chem. 64:307.

NAVICKIS, L. L., and BAGLEY, E. B. 1983. Yield stresses in concentrated dispersions of closely packed, deformable gel particles. J. Rheol. N.Y. 27:519.

NAVICKIS, L. L., ANDERSON, R. A., BAGLEY, E. B., and JASBERG, B. K. 1982. Viscoelastic properties of wheat flour doughs; variation of dynamic moduli with water and protein content. J. Texture Stud. 13:249.

SCHOFIELD, R. K., and SCOTT-BLAIR, G. W. 1932. The relationship between viscosity, elasticity and plastic strength of soft materials as illustrated by some mechanical properties of flour doughs I. Proc. R. Soc. London, A 138:707.

SCHOFIELD, R. K., and SCOTT-BLAIR, G. W. 1933a. The relationship between viscosity, elasticity and plastic strength of soft materials as illustrated by some mechanical properties of flour doughs II. Proc. R. Soc. London, A 138:557.

SCHOFIELD, R. K., and SCOTT-BLAIR, G. W. 1933b. The relationship between viscosity, elasticity and plastic strength of soft materials as illustrated by some mechanical properties of flour doughs III. Proc. R. Soc. London, A 139:557.

SKEGGS, P. K., and KINGSWOOD, K. 1981. Mechanical dough development—Pilot plant studies. Cereal Chem. 58:256.

SMITH, D. F., and ANDREWS, J. S. 1952. Effect of oxidizing agents upon dough extensograms. Cereal Chem. 29:1.

SMITH, J. R., SMITH, T. L., and TSCHOEL, G. L. 1970. Rheological properties of wheat flour doughs. Rheol. Acta 9(2):239.