Dynamic Viscoelastic Properties of Wheat Flour Dough: Dependence on Mixing Time

L. BOHLIN and T. L.-G. CARLSON, University of Lund, Department of Food Technology, Box 740, S-220 07 Lund 7 Sweden

ABSTRACT

Cereal Chem. 57(3):174–177

The dynamic rheological properties of wheat flour dough as a function of mixing time are reported for two wheat varieties, Amy and Starke, with strong and medium baking strengths, respectively. The rheological measurements were done with a balance rheometer (Contraves, Zürich) at a shear strain amplitude of 0.37 in the frequency range 0.08–20.9 rad s^{-1}. The result was evaluated according to a recently developed cooperative flow theory. Differences between a strong (Amy) and a medium (Starke) baking flour were observed. No simple relation was found, however, between the dynamic data's dependence on mixing time and the farinogram.

Flour baking performance has commonly been judged from rheological measurements (Bushuk 1975). The rheological methods are usually empirical, ie, they do not involve the measurement of a well-defined physical quantity. If such an approach is to be successful, many types of empirical tests must be performed and correlated with a technical test (eg, baking). Fundamental rheological tests, on the other hand, are seldom used when judging flour baking performance. No fundamental study has, to our knowledge, been published on dough rheology in which an empirical rheological test or baking test is compared with a fundamental rheological test. The first fundamental rheological measurements of wheat flour doughs in shear were reported by Bloksma (1962). The most extensive works on fundamental rheological properties of wheat flour systems have used dynamic

viscoelastic methods. They have investigated linear behavior (Hibberd and Wallace 1966), influence of water content (Hibberd 1970a) and protein starch content (Hibberd 1970b), and nonlinear behavior (Hibberd and Parker 1975b) of dough systems. Fundamental dough rheology has recently been reviewed by Hibberd and Parker (1975a).

In this work we report the first dynamic measurements of the dependence on mixing time of the rheological properties of wheat flour dough. One would expect that at the relatively high frequencies involved in a dynamic experiment, the rheological properties of the dough would be less significant for judging baking quality than at the very low shear rates involved in the fermentation process (Bloksma 1962). We conclude from this work, however, that the dependence of the dynamic modulus on mixing time is distinctly different for a standard bread flour (a winter wheat) and a strong bread flour (a spring wheat). No apparent correlation with the farinograms was found, however. The observed behavior is discussed in relation to the colloidal structure of wheat flour dough.

MATERIALS AND METHODS

Materials

Untreated samples of a spring wheat (Amy, 1975 crop) and a winter wheat (Starke II, 1975 crop) were experimentally milled in a Brabender Quadrumat Senior with extractions of 65 and 68% (w/w), respectively. Chemical analysis of the spring and the winter wheats gave the following contents, calculated on a dry basis (w/w): protein 13.5 and 10.0% (N × 5.7), respectively; ash less than 0.5%. AACC methods (1976) were used for all chemical analyses.

Preparation of Dough

All doughs were mixed at a speed of 62 rpm in a 10-g farinograph mixing bowl at 25° C. The procedure of Voisey et al (1971) was used with variation of mixing time. The water was added by pipettes accurate to 5 μl. Doughs were mixed with a water content corresponding to water absorption by the constant flour weight method (Bloksma 1962). Water absorptions were 58.6% for Amy and 54.9% for Starke II.

Balance Rheometer Measurements

The balance rheometer (Contraves, Zürich) consists of two concentric spheres rotating with the same angular velocity, ω, about two axes that pass through the center of the spheres. The angle between the rotating axes is small (<6°), and the maximum angular velocity is ~20 Hz. The sample is contained in the gap between the spheres, and the dynamic modulus is determined by measuring the couple on the inner sphere about two mutually perpendicular axes (Jones and Walter 1969). The rheometer was zeroed without sample at zero angle. About 5 g of freshly made dough was centered on the top sphere. The sample was spread evenly with a spatula, and the top sphere was inserted in its measuring position. The dough was worked for 5 min at an angle of 1° (shear amplitude 0.37) at a frequency of 3.14 rad s^{-1} before the start of the measurement. The deviation from zero torque at zero angle at 3.14 rad s^{-1} was noted. All measurements were done at an angle of 1° and a temperature of 25 ± 2° C. The loss torque was first measured from low to high frequency, and the same procedure was then repeated for the storage torque. After running the highest frequency, a low frequency was measured in order to check any
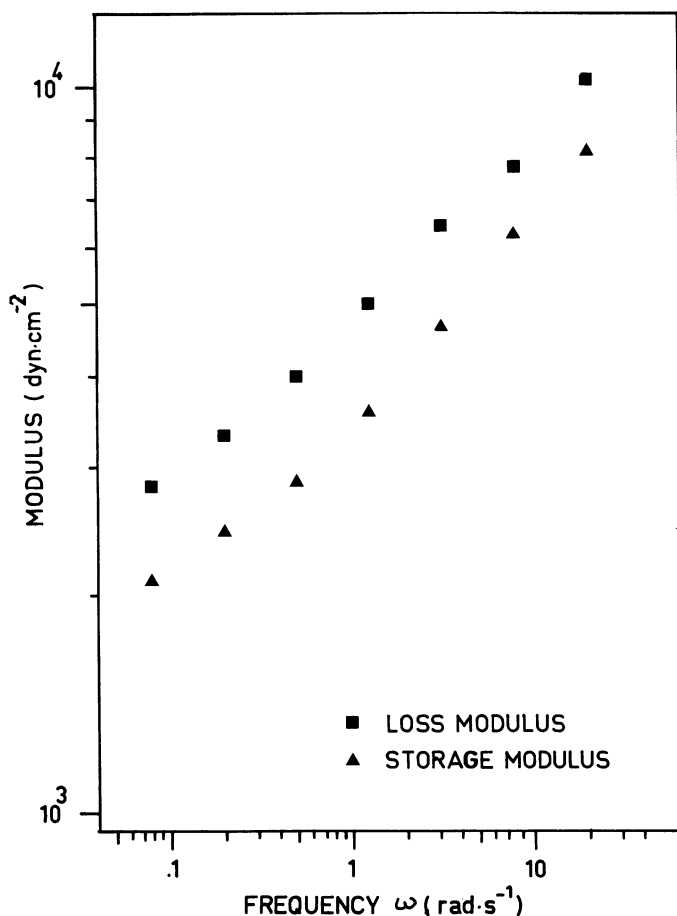

Fig. 1. Frequency dependence of the dynamic modulus for wheat flour dough (Starke), mixed for 8 min at 25° C. The shear amplitude is 0.37.
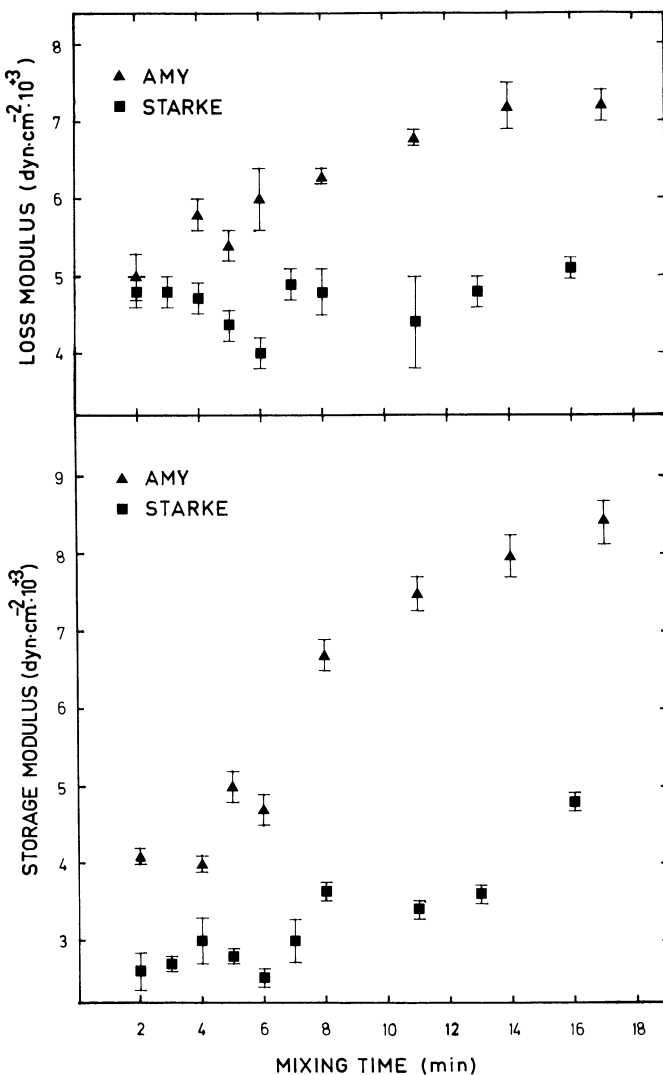

Fig. 2. Loss and storage modula at $\omega = 1$ rad s^{-1} as a function of the mixing time for flour varieties Amy and Starke. Error bars show standard deviation from mean value of at least three measurements.

hysteresis effect. We have noticed, when doing shear stress relaxation experiments on dough, that putting a dough piece in a measuring cell without imposing stress on the dough is very difficult. Typically a stress will relax to 10% of its initial value in about 1 hr. We have therefore done all measurements at a shear strain amplitude of 0.37, at which the stress from the insertion of the sample is negligible. Because dough is not a rheological linear material at such strains (Hibberd and Parker 1975), the response in stress to a sinusoidal deformation is not strictly sinusoidal but contains higher harmonics. Our analysis of the response in terms of in-phase (storage modulus) and 90° out-of-phase (loss modulus) contributions is approximate, and the results represent averages, including the effect of the nonlinearity.

Reproducibility of Experiments

Great care must be taken in fundamental experiments on biological samples, particularly if small-scale preparations of heterogeneous materials are used. In dough from 10 g of flour, the amounts of water and flour must be known very accurately (Voisey et al 1971) in order to keep the farinograph consistency constant. The procedure is important, as is the insertion of the dough into the measuring cell. Two aspects are critical in this respect: the amount and symmetry of dough in the measuring cell and the dough's stress history. The former problem is a special one of the balance rheometer because surplus dough cannot be controlled accurately. The latter problem is solved by allowing the dough to relax from induced stresses in the measuring cell before the start of the measurements.

RESULTS AND DISCUSSION

The measurements were done in the frequency range 0.08–20.9 rad s^{-1}. Figure 1 shows the frequency dependence of the modulus
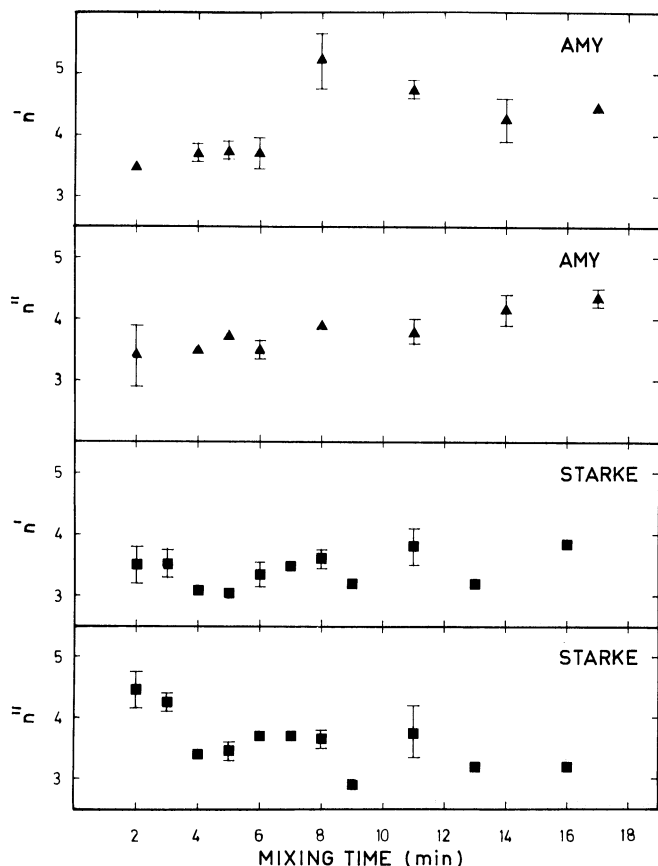
Fig. 3. Dependence on mixing time of the coordination number, n, of a cooperative flow unit for flour varieties Amy and Starke. ' = storage modulus, " = loss modulus. Error bars show standard deviation from mean value of at least three measurements.

for Starke dough mixed for 8 min. The behavior is typical for both flours and for all mixing times. The results at lower frequencies are less accurate because the measured torque may be the same magnitude as the torque at zero angle. We have therefore concentrated our evaluation on the high frequency region, where the double logarithmic plot is approximately linear. Runs in which a hysteresis effect larger than 5% was found were discarded. We have analyzed our data according to a theory of flow (Bohlin 1980) in which the main parameter is the coordination number (n) of cooperative flow units. From this theory, the frequency dependence of the dynamic modulus is qualitatively given by the equation:

$$G\,(\omega) = A \cdot \omega^{1/n}$$

The measured data are represented in this form with:

ω = frequency (rad s^{-1})
G = modulus (dyn/cm^2)
1/n = slope of linear portion of log G vs log ω
A = flow coefficient

In the following text, the storage and loss modula are designated by ' and ", respectively. The coordination number is used to discuss the structure that gives the rheological behavior. Bohlin (1979) has experimentally shown that, for simple well-defined amphiphile-water systems, n is in agreement with the coordination of structural units in the system. For the lamellar liquid crystalline system, n was two and for the hexagonal liquid crystalline system, six.

The relationship between G and the mixing time is given in Fig. 2. Generally the modulus increases with mixing time, with the exception of the loss modulus for Starke. This increase is pronounced for Amy and weak for Starke. The same trends are observed in the n parameter given in Fig. 3. Both n' and n" increase significantly for Amy whereas no significant mixing dependence is observed for Starke dough. Note that n' $\simeq$ n". The magnitude of the modulus at high frequencies is consistent with values reported by Bloksma (1962) from creep tests and with Hibberd and Parker's dynamic data at large amplitudes (1975).

The dynamic data on wheat flour dough (Fig. 3) indicate a structure having approximately a fourfold coordination of flow units in the frequency range studied. As a first step, the flow behavior of dough must be understood on the colloidal level. From a colloidal point of view, dough consists of a continuous aqueous protein-lipid gel with dispersed phases of starch granules and air cells. The continuous aqueous protein-lipid matrix with dispersed gas cells is called gluten. Analysis of stress relaxation experiments
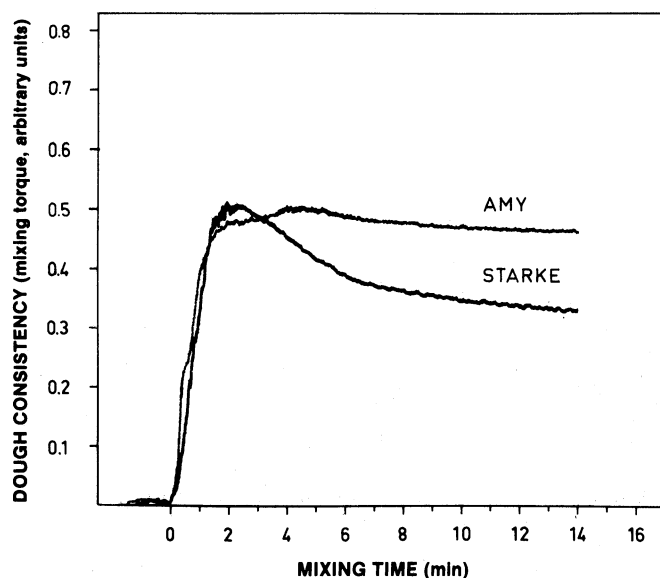
Fig. 4. Farinogram (10-g bowl) for wheat varieties Amy and Starke. Mixing was done with a water content corresponding to the water absorption (Bloksma 1962).

on dough (Bohlin and Carlson 1980) shows two flow mechanisms, one at short times (~ 1 sec) with a fourfold coordination and one at longer times (~ 100 sec) with a twofold coordination.

We have analyzed the recent creep data on wheat flour dough by Hibberd and Parker (1979) according to the flow theory (Bohlin 1980). From those creep data a fourfold coordination flow process can be identified at times corresponding to 3–20 sec. This fourfold cooperative flow process in dough, which occurs at the time scale of seconds, must be regarded as well established; it is found in three different fundamental rheological experiments. The relation between this cooperative coordination number of flow and the colloidal status of the dough has not been investigated. Dynamic data on reconstituted doughs (Hibberd 1970b) imply, however, that the cooperative coordination number increases with increasing starch content. Further experiments are required for an understanding of the relative importance of the dispersed phases in this respect.

We believe the observed differences in modulus as a function of mixing time must be related to the colloidal status of the doughs. In a recent work (Carlson and Bohlin 1978), we proposed that a major part of the elastic energy involved in the immediate deformation of dough appears as surface energy at the gas-gluten interface. This implies that the storage modulus at high frequencies should increase with increasing surface area, assuming constant surface tension. The observed increase of the storage modulus with mixing time for both Amy and Starke may be partly accounted for by an increase in surface area. We have not found any simple relation between the dynamic flow and farinogram consistency (Fig. 4) as a function of mixing time.

ACKNOWLEDGMENTS

LITERATURE CITED

AMERICAN ASSOCIATION OF CEREAL CHEMISTS. 1976. Approved Methods of the AACC. The Association: St. Paul, MN.

BLOKSMA, A. H. 1962. Slow creep of wheat flour doughs. Rheol. Acta 2:217.

BOHLIN, L. 1979. Coordination of structural units from flow measurements. J. Colloid Interface Sci. 69:194.

BOHLIN, L. 1980. A theory of flow as a cooperative phenomenon. J. Colloid Interface Sci. In press.

BOHLIN, L., and CARLSON, T. L-G. 1980. Sheer strain relaxation of wheat flour dough and gluten. Colloids Surfaces. In press.

BUSHUK, W. (Chairman). 1975. Rheology of wheat products: A symposium. Cereal Chem. 52:1r–183r.

CARLSON, T. L-G., and BOHLIN, L. 1978. On the importance of free surface energy in the elasticity of wheat flour dough. Cereal Chem. 55:539.

HIBBERD, G. E. 1970a. Dynamic viscoelastic behavior of wheat flour doughs. II. Effects of water content in the linear region. Rheol. Acta 9:497.

HIBBERD, G. E. 1970b. Dynamic viscoelastic behavior of wheat flour doughs. III. The influence of starch granules. Rheol. Acta 9:501.

HIBBERD, G. E., and PARKER, N. S. 1975a. Measurements of the fundamental rheological properties of wheat flour doughs. Cereal Chem. 52:1r.

HIBBERD, G. E., and PARKER, N. S. 1975b. Dynamic viscoelastic behavior of wheat flour doughs. IV. Non-linear behavior. Rheol. Acta 14:151.

HIBBERD, G. E., and PARKER, N. S. 1979. Nonlinear creep and creep recovery of wheat-flour doughs. Cereal Chem. 56:232.

HIBBERD, G. E., and WALLACE, W. J. 1966. Dynamic viscoelastic behavior of wheat flour doughs. I. Linear aspects. Rheol. Acta 5:193.

JONES, T. E. R., and WALTER, K. 1969. A theory for the balance rheometer. Br. J. Appl. Phys. 2:815.

VOISEY, P. M., MILLER, H., and BYRNE, P. L. 1971. The Ottawa electronic recording 10-g farinograph. Cereal Sci. Today 16:124.