Rheological Studies of Wheat Flour Dough

Part I. Measurement of Dynamic Visco-elasticity

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Dynamic rigidity G' , dynamic viscosity η' and the relaxation spectrum $L(t)$ of dough under periodic shear stress have been obtained. At first, G' and η' decreased rapidly with rest time, but maintained a constant value after 60 minutes. Values of both G' and η' decreased, and $L(t)$ became flat with the decrease in water absorption and with the temperature. G' increased slightly with the increase in salt content, but η' decreased in a low frequency range.

INTRODUCTION

The rheological behavior of wheat flour dough has been considered to be a more important field of research in cereal chemistry. Schofield and Scott Blair¹⁾ have adopted dough as a typical example of soft materials and have pointed out its intricate mechanical behaviors. And, many investigators have obtained numerous data using practical instruments, for example, such instruments as the Farinograph, Extensograph and Alveograph. Details of these have been reviewed by Bailey²⁾ and more recently by Greup, Hintzer³⁾ and Aitken⁴⁾.

Recently, Cunningham, Hlynka and Anderson^{5,6,7)} have devised a relaxometer, and measured the stress relaxation of dough by application of this instrument. The measurement of visco-elasticity may be divided in static and dynamic methods. Stress relaxation is a

typical example of the static method. On the other hand, Slater⁸⁾ has illustrated a method by which the dynamic property of concentrated flour-water suspension has been measured. In order to observe dynamic visco-elasticity of dough under periodic shear stress, the authors have modified the method described by Nakagawa and Senō⁹⁾. This method is adapted to a low frequency range: for the purpose of obtaining an over-all relaxation spectrum, it is necessary to use it in combination with other methods. But when the bread making process is taken into consideration, rheological behavior in the low frequency range would be especially useful.

EXPERIMENTAL

1. Apparatus. A sketch of the apparatus is given in Figure 1. Dough ⑩ is set in a cylindrical cup ⑤ (radius $r_1=2.84$ cm) which is supported by a stand ⑦ and put in a thermoregulated water-bath ⑥. A cylindrical bob ④ (radius $r_2=2.00$ cm), whose end is cone-shaped, is inserted into the center of the dough. The bob is suspended by a piano wire ③ and a driving device ① gives an oscillation $\theta=\theta_0 \sin \omega t$ to the top of the wire ②. The bob, which is inserted in the visco-elastic body, shows a different oscillation $\theta=A \sin(\omega t-\phi)$. To measure the amplitude ratio $p=$

1) R. K. Schofield and G. W. Scott Blair, *Proc. Roy. Soc. A*, **138**, 707 (1932); **A. 139**, 557 (1933); **A. 141**, 72 (1933); **A. 160**, 87 (1937).

2) C. H. Bailey, *Wheat Studies of the Food Research Institute*, **16**, 242 (1940).

3) D. H. Greup and H. M. R. Hintzer, "Foodstuffs" ed. by Scott Blair, North Holland Pub. (1953).

4) T. R. Aitken, *A. A. C. C. Trans.*, **12**, 157 (1954).

5) J. R. Cunningham and I. Hlynka, and J. A. Anderson, *Can. J. Technol.*, **31**, 98 (1953).

6) J. R. Cunningham and I. Hlynka, *J. Appl. Phys.*, **25**, 1075 (1954).

7) I. Hlynka and J. A. Anderson, *Agr. & Food Chem.*, **5**, 56 (1957).

8) L. E. Slater, *Food Eng.*, **26**, May 74 (1954).

9) T. Nakagawa & M. Senō, *Bull. Chem. Soc. Japan*, **29**, 471 (1956).

A/θ_0 and the phase difference ϕ , the optical Lissajous' method was adopted.

Small galvanometer mirrors M_1 and M_2 are fixed to the top of the piano wire, and to the bob. A convex lens L is placed in front of M_1 and M_2 . Light emitted from the source at ⑧ is made parallel by L , is reflected by M_1 and M_2 , and is then converged by L . A strip mirror M_3 is placed at an angle of 45° to the beam of light in the camera ⑨. M_3 is connected to the oscillation mechanism and a photographic paper ⑩ is

placed at the focus of L . Two Lissajous' figures, the one a linear line ① and the other an elliptic curve ② from two oscillations whose directions are at right angles to each other, are obtained. A typical Lissajous' figure is shown in Figure 2.

2. Calculations. Equation of motion of the bob is expressed as follows:

$$I\ddot{\theta} = -k_0\theta - R\dot{\theta} - K\theta \quad (1)$$

where, I Moment of inertia of the bob.
 k_0 Torison constant of the piano wire.

FIG. 1. Schematic diagram of the instrument.

FIG. 2. Typical Lissajous' figures.

R Resistance of dough.
 K Elastance of dough.

Nakagawa and Senō⁹⁾ have indicated a relationship between the data obtained from the Lissajous' figure and the solution of Equation (1), which is as follows:

$$\left. \begin{aligned} \sin \phi &= \frac{4}{\pi} \left[\frac{S}{S} \right] \\ p &= \frac{b'}{a'} \tan \phi \end{aligned} \right\} \quad (2)$$

$$\left. \begin{aligned} K &= k_0 \left(\frac{\cos \phi}{p} - 1 \right) + \frac{4\pi^2 I}{T_f^2} \\ R &= \frac{k_0 \cdot T_f \cdot \sin \phi}{2\pi p} \end{aligned} \right\} \quad (3)$$

$$\left. \begin{aligned} G' &= \frac{K}{4\pi l} \left(\frac{1}{r_1^2} - \frac{1}{r_2^2} \right) \\ \eta' &= \frac{R}{4\pi l} \left(\frac{1}{r_1^2} - \frac{1}{r_2^2} \right) \end{aligned} \right\} \quad (4)$$

where, G' Dynamic rigidity of dough.
 η' Dynamic viscosity of dough.
 $T_f (= 2\pi/\omega)$ Period of oscillation.
 (S) Area of elliptic curve.
 $[S] (= a'b')$ Area of the rectangle whose one side runs

parallel with the horizontal line and each side is tangent to the curve (See Fig. 2).
 ψ Angle between L and the horizontal line.
 l Depth of dough.

The real and imaginary part G' , G'' of complex dynamic modulus G^* can be expressed by the relaxation spectrum $L(t)$ as follows:

$$\left. \begin{aligned} G' &= \int_{-\infty}^{+\infty} \frac{\omega^2 \tau^2}{1 + \omega^2 \tau^2} L(t) d \log \tau \\ \eta' &= \int_{-\infty}^{+\infty} \frac{\omega \tau}{1 + \omega^2 \tau^2} L(t) d \log \tau \end{aligned} \right\} \quad (5)$$

Schwarzl¹⁰⁾ has indicated a method by which $L(t)$ is obtained approximately as follows:

$$\left. \begin{aligned} L(t) &= \frac{2}{\pi} [G''(\omega)]_{\omega=\tau^{-1}} \\ G''(\omega) &= \omega \eta'(\omega) \end{aligned} \right\} \quad (6)$$

The following data were obtained with the aid of of Equations (2), (3), (4), (6).

3. Material and Experimental Procedure. A long patent flour obtained from Canadian Manitoba Northern #3 wheat was used in this study. The flour contained 0.41 % ash and 11.3 % crude protein on a 14 % moisture basis. Dough was prepared by mixing the flour in Kenwood mixer for 1.5 min.. A hundred grams of dough was rounded by a Brabender Extensograph rounder 20 times and set in the cup. After a constant rest period, a forced oscillation (Amplitude, 0.062 radian) was given to the top of the piano wire. The diameter of the wire was 2.4 mm and the torsion constant was 3.65×10^6 dyne.cm.

RESULTS AND DISCUSSION

1. Changes of G' , η' with Rest Time. Results are shown in Figure 3. The experimental conditions were;

Temperature 28°C, Water absorption 63 %, 66 %, Period 2.7 sec..

At first, both G' and η' of dough decreased rapidly, but maintained a constant value after about 60 minutes. It is thought that these results are related to the structural relaxation of dough which has been reviewed by Hlynka and Anderson⁷⁾. From these results, a rest time of 60 minutes was selected for the following experiments.

2. Changes of Rheological Properties at different Water Absorptions. G' , η' and $L(t)$ of 63 % and 66 % water absorption are shown in Figure 4. Data represent the function of period. The

FIG. 3. Changes of G' and η' with rest time.

experimental conditions were;

Temperature 28°C, Rest time 60 min.,

Period 1.7, 2.7, 10.1, 23.5 sec..

G' and η' decreased and $L(t)$ became flat with the increase in water absorption. These results correspond to those of Halton and Scott

FIG. 4. Changes of G' , η' and $L(t)$ at different water absorptions.

10) F. Schwarzl, *Inter. Cong. Rheology*, 1953, 197.

FIG. 5. Changes of G' , η' and $L(t)$ at different temperatures.

FIG. 7. Changes of G' , η' and $L(t)$ at different salt contents.

FIG. 6. Shift of Figure 5.

Blair¹¹⁾ and Cunningham and Hlynka⁶⁾ obtained in static experiments.

3. Changes of Rheological Properties at Different Temperatures. G' , η' and $L(t)$ at 13°C, 23°C and 28°C are shown in Figure 5. Water absorption was 66% and other experimental conditions were the same as in the former experiment.

G' and η' decreased and $L(t)$ became flat with the increase in temperature. When the G' -log T_F relationship at 13°C was shifted

to the left along the time axis and the relationship at 28°C to the right, they formed part of a master curve as that in Figure 6. From this fact, it is suggested that flour dough is approximately thermorheologically simple as many high polymers and therefore the data in the low temperature range can be used instead of that in the high frequency range.

4. Changes of Rheological Properties at Different Salt Content. G' , η' and $L(t)$ at zero, 2 and 4% salt content to flour are shown in Figure 7. Water absorption was 63% and other experimental conditions were the same as these

11) P. Halton and G. W. Scott Blair, *Cereal Chem.*, **14**, 201 (1937).

in the former experiment.

G' increased slightly with the increase in salt content, but η' decreased in the low frequency range. As it is anticipated that inorganic ions have a strong influence on the rheological properties of dough, this problem will be the subject of future investigation.

These results lead to the following comments.

1) If a four parameter mechanical model can be assumed for dough, the relation between static and dynamic rigidity may readily be expressed as:

$$G' = G_1 + G_2 \frac{\omega^2 \tau_2^2}{1 + \omega^2 \tau_2^2} \quad (\tau_2 = \eta_2 / G_2) \quad (7)$$

As elasticity, which has been obtained by Halton and Scott Blair¹⁰⁾, is a mixture of instantaneous rigidity G_1 and retarded rigidity G_2 , the order of magnitude G' of the present experiments is the same as that of the former data.

2) Accuracy of the approximation by which relaxation spectrum is obtained, is in the same order magnitude as that of Cunningham and Hlynka⁶⁾. Moreover, this approximation method is very simple.

3) In contrast to data obtained from dough testing machines, the authors can obtain the data in c.g.s. units by this method. It is probable that these data are comparable with those of other materials other than wheat flour dough.

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