Effect of Added Fat on the Rheological Properties of Wheat Flour Doughs

J. FU,[1,2] S. J. MULVANEY,[1,3] and C. COHEN[4]

ABSTRACT

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The effect of added fat content on the rheological properties of wheat flour doughs was determined for three different added fat contents (2.5, 5.0, and 7.5%) at 25°C using dynamic mechanical analysis (DMA) and stress relaxation (SR) tests. Frequency sweeps indicated that added fat had a plasticizing effect on G' and G'' in the rubbery region. SR results were parameterized using a Maxwell model and a Williams-Watts (WW) model. The WW model indicated that each dough could be characterized by just two major relaxation modes, while four elements were needed for the Maxwell model. The average relaxation time for the shorter process was <1 sec and was not affected by added fat. However, the average relaxation time for the longer WW process actually increased from 107 to 261 sec with added fat up to 5%, and then decreased again. Taken together, these results suggest that added fat actually delayed the onset of viscous flow, while simultaneously attenuating the short-time elastic properties of the gluten fraction of the dough. Furthermore, rheological testing over a wide time (frequency) scale was needed to observe the effect of added fat on both the short-time elastic and longer-time viscous behavior of these doughs.

The flow and deformation behavior of doughs are recognized to be central to the successful manufacturing of bakery products (Menjivar 1990). Given that doughs are viscoelastic, oscillatory dynamic testing has been extensively used over the last thirty or so years to characterize the rheological properties of doughs (Faubion and Hoeseney 1990). However, the complex composite nature of doughs, which varies with the level of resolution used to view it (Bloksma 1990), makes it difficult to directly interpret rheological results in terms of molecular structure. At a resolution of >1 mm, a dough consists of a continuous liquid dough phase and a disperse gas phase, where the liquid dough phase can be divided into a continuous protein phase containing various dispersed solids, including starch granules, at the microscopic level (>0.1 µm), and finally the protein phase can be resolved into a continuous water phase with dissolved solutes and insoluble proteins with adsorbed lipids at the molecular level (>0.1 nm) (Bloksma 1990). In particular, Amemiya and Menjivar (1992) have discussed the limitations of using small deformation testing alone in resolving the relative contributions of starch and protein components and their interactions on viscoelastic properties. Smith et al (1970) have shown that the nonlinear strain-amplitude behavior common to doughs essentially vanishes for wet gluten, and attributed the thixotropic behavior of doughs to the disruption of the starch structure. However, the protein content of doughs is substantially less than that of gluten, and doughs are also characterized by many noncovalent molecular interactions, which could also contribute to the small linear viscoelastic region common to doughs.

In this article, we are concerned with the effect that added fat has on the rheological properties of mixed doughs, and we will try to resolve that effect into shorter-time effects and longer-time behavior related to the dynamics of larger molecular-weight entities. Much of the published work on dough rheology has focused on the effect of the major flour components (gluten, starch, water) on the rheological properties of developed doughs, as described in several recent review articles (Bloksma and Bushuk 1988, Eliasson 1990, Faubion and Hoeseney 1990, Castell-Perez and Steffe 1992). The effect of added fat on rheological properties has received relatively little attention, even though it is commonly added in amounts of 1–5% in breadmaking where it improves loaf quality considerably (Bloksma and Bushuk 1988). These authors also commented on the fact that addition of fat is hardly detected by farinograph or extensigraph measurements made at 30°C. Junge and Hoseney (1981), using a resistance baking oven, showed that bread doughs with 3% added fat (Crisco brand) expanded for a longer time (and to a higher temperature) than did doughs without added shortening. They also determined that the effect was not due to loss of CO_2 in the early stages of baking, but could not confirm through differential scanning calorimetry (DSC) that it was due to a delay in the gelatinization of starch. They did not discuss the possibility that changes in dough rheology due to the added shortening were responsible for the extended expansion during baking. In addition to bread doughs, shortening is also added to flour tortilla dough at a ~5% level. This may be important in developing appropriate rheological properties for the heat-pressing or sheeting of dough balls into flat tortillas before baking.

Slade et al (1989) have postulated that the increased baked-loaf volume with added shortening is due to lipid plasticization of gluten, which extends gluten's period of thermoplasticity early in the baking process, prior to thermosetting of the water-plasticized gluten network at the end of baking, in addition to the better known role of lipid to retard starch pasting (cited in Slade and Levine 1995). Bekes et al (1991) have hypothesized that the effect of lipids on baking quality is probably related to both the amount of free lipids in the flour and the ability of the protein in the flour to bind these lipids during mixing.

Menjivar and Faridi (1994) have also discussed the role of fats in cookie doughs made from soft wheat flours, where the overall fat content is higher than in bread doughs. They mention that fat and the aqueous phase compete for the surface of the flour particles during dough mixing, which can inhibit the formation of a gluten network if the fat coats the flour before it can be hydrated. Also, they cite the data of Manley (1983), which show that the desired consistency of the dough can be achieved by increasing the fat content while decreasing the amount of water. This is consistent with the idea that wheat flour doughs can be plasticized by either fats or water. Given (1994) pointed out that the interaction between flour proteins and endogenous polar galacto-lipids has been demonstrated (MacRitchie 1983, Bushuk 1986). Thus, these authors concluded that it is not surprising that added shortening affects dough quality and final product quality, since shortening can be expected to modify or compete with the interactions of endogenous components.

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[1] Institute of Food Science, Cornell University, Ithaca, NY 14853.
[2] Present address: Institute of Food Science, Department of Food Science and Technology, Food Research Laboratory, Geneva, NY 14456.
[3] Corresponding author. E-mail: sjm7@cornell.edu
[4] School of Chemical Engineering, Cornell University, Ithaca, NY 14853.

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Based on the above discussion, it is clear that the presence of added fat during mixing of a wheat flour dough will alter the dough's development and rheological properties. One can expect some differences in protein-lipid interactions to occur, which, in turn, could affect the development of the dough. According to Bloksma (1990), this is explained by alignmnent of glutenin molecules. It was assumed for this work that the beneficial effects of adding shortening in limited amounts are at least partially due to its effect on the rheological properties of the dough. It was further hypothesized that the added fat must be somehow molecularly incorporated, i.e. emulsified, into the dough during mixing, to exert a plasticizing effect on the viscoelastic properties of the dough. Although plasticization is often thought of as the softening of a polymer due to a lowering of its glass transition temperature in the presence of a smaller compatible molecule, a plasticizer can also function by reducing the concentration of entanglements (or physical crosslinks) giving rise to a_temporary network structure (Hatfield and Rathman 1954). This plasticizing effect on the viscoelastic properties would be expected to be much greater than the simple dilution effect due to the decrease in polymer concentration per unit volume due to the addition of plasticizer. In fact, results of strain sweeps (Fig. 1) indicate that the magnitude of the reduction in *G′* with added fat, at least up to 5% added, is much more than can be explained by simply correcting for the change in protein concentration as fat is added.

The overall objective of this study was to determine the effect that added plastic shortening had on the viscoelastic properties of a wheat flour dough, using dynamic mechanical analysis (DMA) and stress relaxation (SR) experiments. We have not seen such results reported before. These two testing modes were chosen so that both the short-time elastic and longer-time viscous flow phenomena could be determined. Due to the importance of noncovalent (electrostatic, hydrogen, and hydrophobic) bonds and the solid-to-liquid ratio of the added shortening on the rheological properties of dough systems, SR experiments were used rather than time-temperature superposition to extend the time range of the DMA experiments without altering the nature of these molecular interactions. In addition, a two-element Williams-Watts (WW) relaxation model, which we have also not seen used with dough systems, was compared to a four-element Maxwell model for the stress relaxation tests. The WW model uses an exponent between 0 and 1 to account for varying degrees of dispersion in relaxation times around a single Maxwell relaxation element. Thus, this exponent may provide additional insight into the relationship between polydispersity and relaxation phenomena in doughs.

MATERIALS AND METHODS

Materials and Dough Preparation

Bleached, enriched, all-purpose wheat flour (Gold Medal, General Mills, Minneapolis, MN) was used in the dough formulation. The moisture content of the flour was 11.6 % (wb), as determined using AACC Method 44-15A. Shortening (All-vegetable, Crisco, Procter & Gamble, Cincinnati, OH) and water were added to the flour to obtain levels of added shortening of 2.5, 5.0, and 7.5 %, while a dough was also prepared with no added shortening. According to the manufacturer, the solid fat content of this shortening is 15% at 21.1°C and drops to 7% solids at 40°C. The total water content of all of the doughs was kept constant at 40% (wb). Thus, the added shortening replaced flour solids in the formulation to determine its effectiveness as a plasticizer of dough. Based on the flour package labeling and the experimentally determined moisture content, the carbohydrate and protein contents (%wb) of the doughs were calculated to be 49.8 and 6.8, 47.7 and 6.5, 45.6 and 6.2, and 43.6 and 5.9 for the control, 2.5% fat, 5% fat, and 7.5% fat doughs, respectively. These dough formulations were chosen to bracket the fat content of a commercial flour tortilla formulation, although the results should also be relevant to other doughs as well. The dough-mixing procedures were also suggested by industry sources as representative of a commercial tortilla operation.

The flour and shortening were first mixed in a Hobart mixer at the 2 setting for 8 min. The ingredients were added at room temperature, and the temperature was not controlled during mixing. Distilled water at 52°C was then added to achieve a total moisture content of 40% (wb), and the dough was further mixed at the same setting for 6 min. Hot water seems to be generally used for preparing doughs for sheeting as it tends to increase the rate of hydration of the dry ingredients and aids in the mixing and uniform dispersion of the shortening into the dough. The dough was rested for 30 min, sheeted using a hand-roller to a thickness of ~2.5 mm to help remove air, relaxed again, and then analyzed using a rheometer.

Rheological Measurements

Rheological measurements were obtained with a Bohlin VOR rheometer (Bohlin Instruments, Cranbury, NJ), using a parallel-plate geometry (25 mm plate diameter and 2.5 mm plate gap) in shear mode. Glue (Slow Jet, Carl Goldberg Models, Chicago, IL) was used to adhere the disc-shaped sample to the lower plate to minimize slippage. The upper serrated 25-mm plate was lowered until it just contacted the sample. Sample thickness was 2.5 mm. The sample was trimmed after loading to obtain reproducible sample dimensions, and the exposed edge of the sample was covered with a thin layer of vacuum grease to minimize moisture loss during measurements. Strain sweeps at a frequency of 6.28 rad/sec were used to examine the effect of strain amplitude on the viscoelastic functions. Frequency sweeps from 0.0628 to 125.66 rad/sec at 25°C and using a fixed strain of 0.1%, were used to characterize the doughs. The storage modulus (*G′*), shear loss modulus (*G″*), and tan δ (*G″*/*G′*) were obtained. The shear modulus (*G*) was obtained from stress relaxation experiments at 25°C for 1,000 sec at a fixed strain of 0.1%. The rise time for the applied strain was 0.5 sec.

Results are reported as the average of measurements made on three samples, where each sample was obtained from a separately prepared batch of dough for each treatment level. In some cases, the three replicates for a treatment were subjected to regression analysis to obtain an average curve, which was then analyzed. These results are presented without error bars or standard deviations. This approach was justified on the basis of the excellent reproducibility within a treatment, as can be seen in the strain sweeps of Fig. 1, for example.

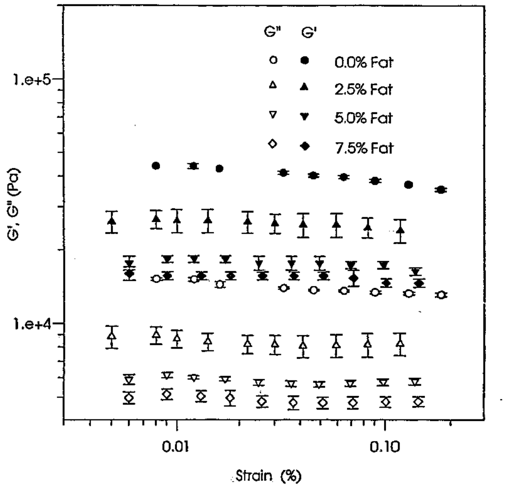

Fig. 1. Effect of strain (%) on *G′* and *G″* for wheat flour doughs with different fat content. All doughs had 40% mc and were tested at 25°C.

RESULTS

Strain sweeps were used to determine the effect of added fat on the linear viscoelastic range. The results shown in Fig. 1 indicate that added fat extended the strain amplitude at which the dough structure began to break down. In any case, the generally small viscoelastic region indicates the lack of a true three-dimensional elastomeric network. It is well documented that the moduli of a dough can be affected by a multitude of compositional or processing factors. However, the decrease in the moduli in the small-strain region with increasing fat is nonlinear. It was greatest for the first 2.5% added fat and decreased thereafter, which indicates that the effect of added fat is not a simple dilution effect. Possible explanations for these observations will be discussed together with the SR and DMA results presented below.

Stress Relaxation

Stress relaxation experiments were used to extend the accessible experimental time without changing the temperature of the dough. A parameter, t_{50}, was used to normalize the raw modulus-time data according to Sharif et al (1993). This parameter is the time required for the modulus to decay to one-half of its initial value. Two dimensionless parameters were introduced for normalizing the modulus-time data:

$$\overline{G} = G(\mathrm{t})/G_o \tag{1}$$

$$\tau = t/t_{50} \tag{2}$$

where $G(\mathrm{t})$ = modulus of sample at any time; G_o = initial modulus of sample; t = time; and t_{50} = time required for the modulus to decay to one-half of its original value.

The purpose of this normalization was to evaluate the time course of the molecular relaxation phenomena independent of the initial modulus, which was found to decrease with added fat. Although the choice of the one-half relaxation time was arbitrary, it does serve as an easily obtained indicator of the relative rate of relaxation, and is sometimes used also as a shift factor for time-temperature superpositioning of stress relaxation data.

The effect of fat content on the stress relaxation response is shown in Fig. 2, while Table I shows the mean values of G_o and t_{50} based on three replicates for each dough. The normalized curves show very similar relaxation behavior for the four doughs at short times, with the effect of fat becoming more noticeable for values of $\overline{G} < 0.1$. The value of G_o decreased with increasing fat content, which could be due to a combination of increased relaxation during the 0.5-sec rise time or a decrease in the number of elastic energy storage elements in the dough. It also appears that a limiting value of G_o would be reached for even higher fat contents, which is consistent with the strain-sweep results shown in Fig. 1. However, the values for t_{50} increased from ~4 to 6 sec as the level of added fat was increased to 7.5%, which reflects an overall decrease in the rate of relaxation at longer times, as fat is added to the dough. This effect can be clearly seen for normalized times >10 in Fig. 2.

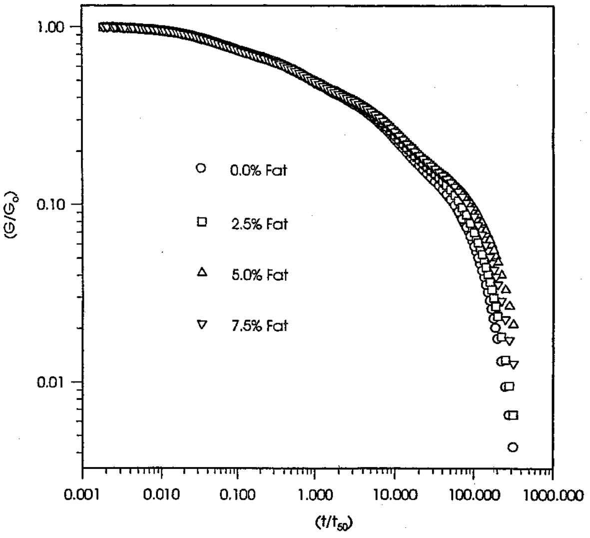

Fig. 2. Normalized stress-relaxation curves for wheat flour doughs with different fat content. G_o and t_{50} represent the initial modulus and time to relax to 50% of initial modulus, respectively.

Maxwell Model

A four-element, generalized Maxwell model (Eq. 3) was used to quantify the effect of fat content on stress relaxation. This choice was based on a nonlinear statistical *F*-test (Neter et al 1990), which indicated that the four-element model was significantly better than a three-element model. The coefficient of determination (r^2) was ≥0.9964 for all doughs using a four-element model. The Maxwell model was used primarily for comparison with the two-element WW model to be discussed later.

$$G(\tau) = G_o(\phi_1 \exp(-\tau/\tau_1) + \phi_2 \exp(-\tau/\tau_2) + \phi_3 \exp(-\tau/\tau_3) + \phi_4 \exp(-\tau/\tau_4)) \tag{3}$$

Here, τ is the same dimensionless time as in Eq. 2. Eq. 3 represents a discrete spectrum of relaxation modes with dimensionless relaxation times (τ_i, relaxation time normalized by dividing by t_{50}), which are associated with weighting factors, ϕ_i. These weighting factors determine the relative contribution of each relaxation mode to the initial modulus, as indicated by Eq. 3. Values for ϕ_i and τ_i are shown in Table II as a function of added fat content. It is clear that ϕ_i for the discrete modes showed little sensitivity to the level of added fat, indicating that the weighting of a particular mode of the Maxwell model was not affected by the level of added fat, only G_o. However, for a particular fat content (fixed G_o), the longest relaxing process was weighted the least. This is contrary to the physical nature of viscoelastic materials with broad molecular-weight distributions, where those modes with the longest relaxation times would contribute the most to the initial modulus in a stress-relaxation test. This demonstrates the well-known arbitrary nature of viscoelastic models based on mechanical elements.

TABLE I

Mean Values of Initial Modulus (G_o, kPa) and t_{50}[a] for Wheat Flour Dough[b] with Different Added Fat Content

Added Fat (%)	G_o	t_{50}
0.0	33.7 ± 0.6	4.15 ± 1.09
2.5	23.3 ± 2.1	4.48 ± 0.26
5.0	16.3 ± 0.6	4.83 ± 0.31
7.5	13.3 ± 1.2	6.32 ± 0.36

[a] Time (sec) required for modulus to decay to one-half of its original value.
[b] Values ± standard deviation. Average of three replicates.

TABLE II

Dimensionless Parameters of a Four-Element Maxwell Model for Stress Relaxation at 25°C for Wheat Flour Doughs with Different Added Fat Content (%)

Parameter	0.0	2.5	5.0	7.5
ϕ_1	0.195	0.20	0.19	0.20
τ_1	83.06	91.282	143.31	113.71
ϕ_2	0.29	0.29	0.28	0.28
τ_2	6.422	6.297	8.242	7.221
ϕ_3	0.29	0.28	0.28	0.28
τ_3	0.527	0.493	0.633	0.569
ϕ_4	0.23	0.23	0.25	0.24
τ_4	0.0448	0.0404	0.0490	0.0459

However, it is still interesting to note that the actual relaxation times ($t_{50} \times \tau_1$) of the longest relaxing mode (344, 409, 692, and 719 sec for 0, 2.5, 5, and 7.5% fat doughs, respectively) actually increased with added fat content. Thus, added fat actually decreased the rate of relaxation at longer times. This could be due to an increased number of noncovalent crosslinks between more or less linear glutenin molecules, which would tend to increase the resistance to viscous flow. Bloksma (1990) has proposed that viscous deformation could be explained by glutenin molecules sliding one along another by breaking noncovalent crosslinks. However, the extensive stress relaxation indicates that the short-time crosslinked network is also due to either transient covalent bonds that are constantly forming and breaking or other noncovalent physical crosslinks such as entanglements.

To look further at the relaxation phenomena, we plotted the "rate" of stress relaxation data as the tangents versus time on a logarithmic scale, as shown in Fig. 3. The time at which the tangent reaches a value of –1 (as indicated on the figure) gives an estimate of the terminal relaxation time, which has many practical implications for processing. As stated by Ferry (1980a): "… it is a measure of the time to relax internal stresses during an annealing process, to achieve steady-state flow under constant stress or for elastic recoil to be accomplished after removal of stress (always assuming linear viscoelastic behavior). It also represents, in order of magnitude, the ratio of energy stored to energy dissipated per second during steady-state flow." Clearly, added shortening will shift this value to longer times at 25°C, but it is not known whether this shift will be maintained at higher temperatures. In any event, it was not obvious that added shortening would actually decrease the rate of relaxation at longer times, and this finding may shed new light on some baking enigmas, such as the mechanism by which added shortening tends to improve loaf volume.

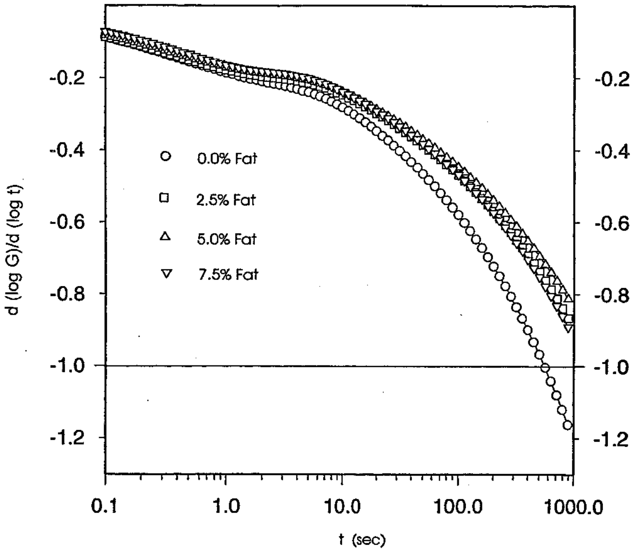

Fig. 3. Rate of stress relaxation for wheat flour doughs with different fat content. All doughs had 40% mc and were tested at 25°C. Line at –1 represents an empirical determination of the terminal relaxation time.

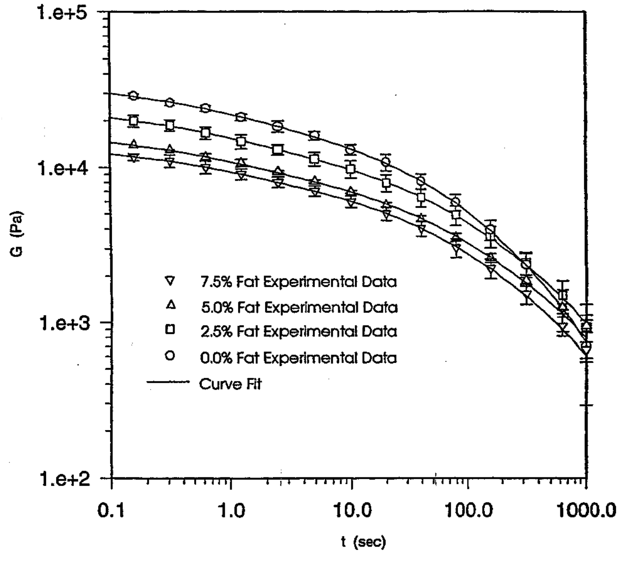

Fig. 4. Experimental stress-relaxation curves and curve fit of two-element Williams-Watt model (Eq. 4) for wheat flour doughs with different fat content.

WW Model

The WW model, which is parameterized by both a characteristic relaxation time and also an exponent related to the dispersion of relaxation times for each element, may provide a more useful approach for describing stress-relaxation data than does the Maxwell model. Stress-relaxation data were fitted to the two-element WW model (Williams and Watts 1970, Patterson 1983):

$$G(t) = G_{1o} \exp(-t/\tau_1)^{\beta_1} + G_{2o} \exp(-t/\tau_2)^{\beta_2} \qquad (4)$$

where: $G(t)$ = the shear modulus at any time; G_{io} = the initial modulus for each mode; t = time (sec); τ_i = the characteristic relaxation time of each mode (sec); β_i = a measure of the width of the distribution of relaxation times within a mode ($0 < \beta_i < 1$; where $\beta = 1$ corresponds to a single Maxwell element)

The average relaxation time of each mode is:

$$< \tau > = \int_0^\infty G(t)dt = \frac{\tau}{\beta}\Gamma(1/\beta) \qquad (5)$$

where: $\Gamma(x)$ = the gamma function.

Figure 4 shows that the two-element WW model fits the SR experimental data very well for each dough. Although both the Maxwell and WW models provide excellent fits to the experimental data, the WW model appears to better represent the physical situation. Table III shows the values of the weighting modulus for each mode and their ratio, as well as the experimental initial modulus, as a function of added fat. The WW model attributes the initial modulus almost entirely to the longer relaxing mode (see Table IV), G_{1o} , for each fat content, which is consistent with viscoelastic behavior but also tends to underestimate the experimental initial modulus. We have tried to obtain better fits of the initial modulus, but these trials led to poor agreement at long times, no matter the choice of τ_i and β_i. In addition, the ratio of the weighting moduli in the WW model (G_{2o}/G_{1o}) decreased with added fat content, which could reflect an increase in the relaxation of stress during the rise time of the test for the fast-relaxing mode.

The relaxation time and dispersion parameters of the WW model for each dough are shown in Table IV. The values of τ's tended to increase with added fat content, while $<\tau_2>$ remained

TABLE III

G_{io} and G_o (kPa) of the Williams-Watts Model for Wheat Flour Doughs with Different Fat Content

Added Fat (%)	G_{1o}	G_{2o}	G_o[a]	G_{2o}/G_{1o}
0.0	31.1	6.3	33.7	0.2
2.5	22.9	3.8	23.3	0.17
5.0	16.3	2.2	16.3	0.13
7.5	13.4	1.6	13.3	0.12

[a] Experimental. Average of three replicates.

constant. The values for β_1 are fairly constant relative to the values for β_2, which tended to increase with added fat. Qualitatively, these results indicate that the average relaxation time for the longer process increased with added fat, while the width of the distribution of relaxation times remained about the same. For the shorter process, the average relaxation time remained constant as fat was added, while the width of the distribution of relaxation times narrowed and approached Maxwell element (monodisperse) behavior. The much larger distribution of relaxation times of the longer process is consistent with the reported broader molecular weight distribution of the glutenins (Kokini et al 1994), while the much narrower distribution of relaxation times of the faster relaxing mode is consistent with the description of gliadin. However, the hypothesis that the two elements of the WW model may correspond (at least roughly) to the glutenin and gliadin fractions of gluten was not tested experimentally in this work. Therefore, it must be considered as speculation at this point.

Based on the WW model parameters, added fat preferentially increases $<\tau_1>$, while the relaxation behavior of the faster relaxing element remains largely unchanged (constant $<\tau_2>$). This scenario is also consistent with the relaxation data as plotted in Figs. 2 and 3, where the relaxation data has been either normalized or plotted as a rate of relaxation. In both cases, the short time relaxation phenomena was not affected by the level of added fat. The effect of added fat content is only evident at longer times, where disentanglement and flow of the higher molecular weight components of gluten dominate the relaxation behavior.

These results for the WW model are also consistent with the four-element Maxwell model, in the sense that both a fast and slow mode of relaxation were identified. Also, τ_1 (the slowest mode) of the Maxwell model increased with added lipid up to 5% and then decreased, which is similar to the behavior observed for τ_1 with the WW model. This may indicate that added lipid above a critical fat content does again increase the rate of relaxation at long times. However, no meaningful physical significance can be attributed to the parameters of the Maxwell model.

Dynamic Mechanical Analysis

DMA was used to corroborate the results from stress relaxation and to obtain additional data on other relevant viscoelastic properties. Assuming that $G(t)$ in stress relaxation is comparable to $G'(\omega)$ in DMA with $\omega = 1/t$, we note that DMA using the Bohlin rheometer extends to only about 16 sec in stress relaxation (maximum frequency of 125.66 rad/sec). Frequency sweep results for G' and G'' are shown in Figs. 5 and 6 and indicate that both moduli had lower values over the entire frequency range, as the amount of added shortening was increased. There was a more significant decrease from 0% fat to 2.5% fat and from 2.5% fat to 5.0% fat, with a smaller difference between 5% fat and 7.5% fat for all frequencies. In particular, the magnitude and frequency dependence of G' (Fig. 5) present a mirror image of the first 20 or so seconds of the stress relaxation response (Fig. 4). Based on the analysis presented above, it then follows that DMA in this frequency range represents a pseudoequilibrium elastic modulus that depends, perhaps, more on the development of the dough rather than on its composition per se. In other words, the shift in the moduli to higher frequencies apparently reflects a decrease in crosslinks as fat is mixed into the dough. This may help explain why no definite relationship between G' and dough composition (starch, protein, and water content) has been previously reported in the literature.

Power law parameters relating $G'$and G'' to ω were developed in the typical fashion, using the following equations:

$$G' = G_o'\omega^{n'} \tag{6}$$

$$G'' = G_o''\omega^{n''} \tag{7}$$

Slopes (n', n'') and intercepts (G_o', G_o'') of the power law model for frequency sweeps for the four wheat flour doughs at 25°C are shown in Table V. Power law fits for for G' and G'' for the four wheat flour doughs had r^2 values of 0.9863 ± 0.0094 and 0.9321 ± 0.0129, respectively. The values of n' and n'' for all of the doughs were approximately equal, with values ~0.20, while the intercept values for G' and G'' at a frequency of 1 rad/sec decreased in a nonlinear fashion from 26 kPa to 11 kPa, as the level of added fat was increased. This trend was similar to that found previously for G_o in stress relaxation, which was attributed primarily to a decrease in physical crosslinks or other short-time molecular interactions. According to Kokini et al (1994), the nonzero power law slope for doughs is due to the presence of both crosslinked and uncrosslinked material. The fact that n' remains constant with added fat may indicate that it is somehow analogous to $<\tau_2>$ of the WW stress relaxation model in that neither was affected by added fat.

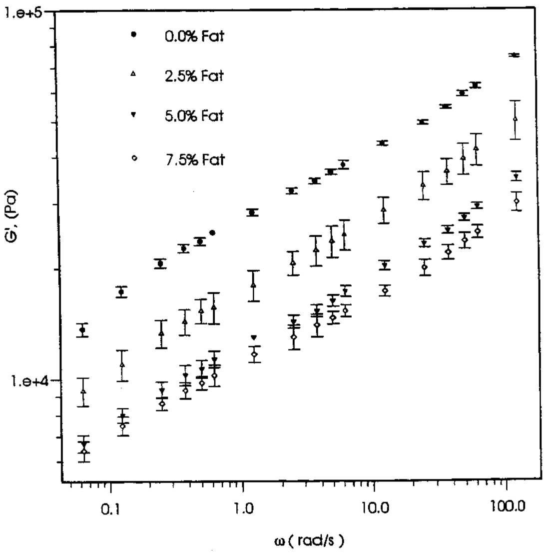

Fig. 5. Effect of frequency on G' for wheat flour doughs with different fat content. All doughs had 40% mc and were tested at 25°C and 0.1% strain.

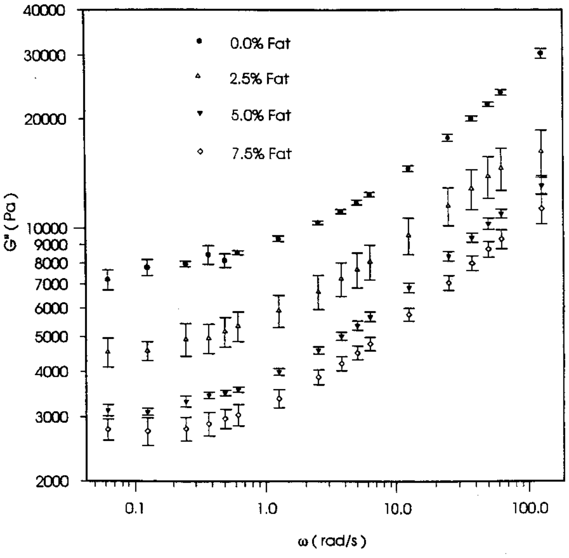

Fig. 6. Effect of frequency on G'' for wheat flour doughs with different fat content. All doughs had 40% mc and were tested at 25°C and 0.1% strain.

Time-Lipid Superposition

The DMA results indicate that added fat exerts a plasticizing effect in this frequency range, which is similar to added water or increased temperature. The fact that the slopes were essentially constant for the four doughs examined here indicated that the curves for G' and G'' could be superimposed by shifting along the frequency axis. The shifted curves for G' and G'' are shown in Fig. 7.

Shift factors (Table VI) for the effect of added shortening were calculated using 0.0% fat as the reference fat content. A shift factor (a_F) was determined using the following equation:

$$\log a_F = \log \omega_s - \log \omega = \log (\omega_s/\omega) \quad (8)$$

where ω_s is the frequency of a point on the reference (0 % added shortening) curve with a specific G' or G'' value, and ω is the frequency of a point with the same G' or G'' value on a curve for a different fat content. The shift factors used for G' and G'' are plotted as a function of fat content in Fig. 8. Based on the shape of this curve, shift factors were modeled with a Williams-Landel-Ferry (WLF) equation (Ferry 1980b):

$$\log a_F = -C_1(F - F_o)/(C_2 + F - F_o) \quad (9)$$

where F is the added fat content (%), F_o is the reference added fat content (0%), and C_1 and C_2 are constants. The parameters, C_1 and C_2 were calculated using 0.0% fat as the reference fat content and were 4.15 and 8.20, respectively. The success of Eq. 9 in fitting the shift factors further suggests that the added lipid does act as a compatible plasticizer for gluten for the amounts used here and supports the concept of time-lipid superposition. Kalichevsky et al (1992) have previously reported that fats and emulsifiers have a plasticizing effect on gluten, in that they decrease the modulus in the glass transition region, even though they do not greatly influence the temperature or water content of the transition itself. Although the underlying molecular basis of this response cannot be determined from these experiments alone, it seems likely that the major effect is a reduction in the number of effective crosslinks in the gluten, which is reflected in the lower power law intercept values.

DISCUSSION

Apparently, added fat can be used to augment the plasticizing effect of water, perhaps without causing excessive stickiness that might negatively affect sheeting processes. However, this effect of plasticization by lipid appears to saturate at some level of added lipid (~5%). Matz (1992) refers to the fact that only a certain amount of shortening can be incorporated into a dough before the product will look and feel greasy. It may be that only that part of the added lipid that becomes an integral part of the dough matrix, by whatever mechanism, can exert a plasticizing effect. Kalichevsky et al (1992) also surmised that added lipids are probably not highly compatible with gluten due to their high molecular weight, which would limit their ability to plasticize gluten. These authors also point out that the hydrophilicity of an additive, relative to that of gluten, must be considered in evaluating, or predicting its plasticizing effect. So, although the plasticizing effect of shortening may be limited in higher moisture doughs, its continued use in commercial practice implies that it is nevertheless technically significant.

TABLE IV
Williams-Watts Model Parameters[a] for Stress Relaxation at 25°C for Wheat Flour Doughs with Different Added Fat Content

Added Fat (%)	τ_1	$<\tau_1>$	β_1	τ_2	$<\tau_2>$	β_2
0.0	15.19	106.81	0.32	0.57	0.81	0.63
2.5	16.95	217.93	0.28	0.61	0.80	0.68
5.0	16.89	260.90	0.27	0.68	0.81	0.75
7.5	21.59	233.77	0.29	0.78	0.82	0.82

[a] τ_i = Characteristic times (sec), $<\tau_i>$ = average relaxation times (sec), β = width of distribution of relaxation times within a mode.

TABLE V
Power-Law Parameters Describing Frequency Sweeps at 25°C for Wheat Flour Doughs with Different Fat Content

	Added Fat (%)			
	0.0	2.5	5.0	7.5
Storage modulus (G')				
G_o' (kPa)	26.47	17.08	12.16	11.03
n'	0.21	0.21	0.21	0.19
Loss modulus (G'')				
G_o'' (kPa)	9.89	6.17	4.28	3.65
n''	0.19	0.19	0.20	0.20

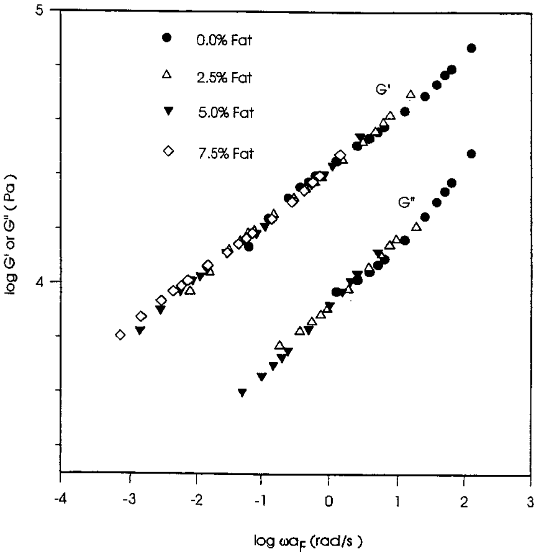

Fig. 7. Master curves of storage modulus (G') and loss modulus (G'') for wheat flour doughs with different fat content. All doughs had 40% mc and were tested at 25°C and 0.1% strain; a_F is the shift factor for the effect of fat content; 0% added fat is the reference dough.

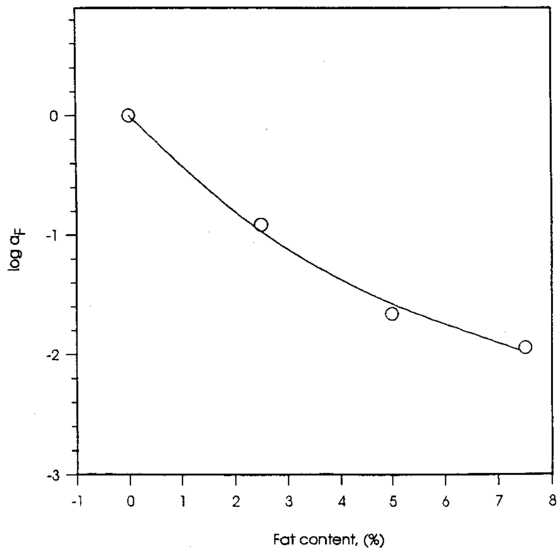

Fig. 8. Shift factor a_F as a function of fat content from 0.0% (reference) to 7.5%, for the wheat flour doughs. Curve fit represents Eq. 9 with C_1 = 4.15 and C_2 = 8.20.

The combination of SR and DMA results, interpreted with the aid of the WW model has proved useful in analyzing the effect of added fat on the rheological properties of doughs. It has been suggested here that the fast-relaxing element of the WW model may correspond to an uncrosslinked fraction of gluten. This idea is supported by the work of Bohlin and Carlson (1981), where a cooperative theory of flow was used to analyze stress relaxation results at 24°C for wheat flour dough (apparently 40% moisture content, w/w) and its corresponding gluten (63% moisture content, w/w). The observed 50% relaxation time was typically 1.5 sec for both dough and gluten, indicating that the short-time relaxation behavior of a dough can be accounted for by gluten alone. The fast-relaxation process, which occurred over a time period of 0.1 to 10 sec for both dough and gluten, was characterized by a coordination number of ~4 and did not appear to be influenced by the type of flour used or by the conditions used for dough and gluten preparation (Bohlin and Carlson 1981).

The latter conclusion was based on a limited analysis of other researchers' data, which we have verified by means of additional results (Smith et al 1970, Abdelrahman and Spies 1986, Dreese et al 1988, Noel and Brownsey 1990, Amemiya and Menjivar 1992), where *z* was obtained as the reciprocal of the power law slope for G'. In Mita and Bohlin (1983), this fast-relaxation process was attributed to the relaxation of non-close-packed fibrils, (uncrosslinked), which have a theoretical coordination number of 4. Thus, the presence of a short-time relaxation process of coordination number of ~4, which has been attributed to uncrosslinked protein fibrils, might be common to all glutens and doughs. Thus, the assignment of the fast relaxing element of the WW model to an uncrosslinked protein fraction seems plausible. This idea is further supported by the shape of the curves for tan δ shown in Fig. 9, which are characteristic of uncrosslinked polymers that exhibit entanglement coupling.

TABLE VI
Values of Fat-Content Shift Factors (a_F) for G' and G''[a]

Fat Content (%)	a_F
0.0	1.0
2.5	0.1219
5.0	0.0220
7.5	0.0114

[a] With 0.0% fat content as the reference (calculated from G' curves).

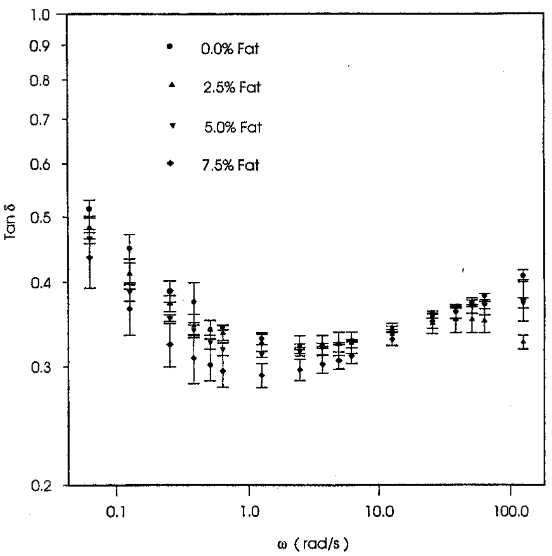

Fig. 9. Effect of frequency on tan δ for wheat flour doughs with different fat content. All doughs had 40% mc and were tested at 25°C and 0.1% strain.

It is interesting to note that virtually all published results concerning the effect of formulation or process on the rheological properties of doughs obtained using small-deformation rheological analyses are identical. The result is a family of curves with the same frequency dependence,shifted along the frequency axis. Are these all manifestations of the same underlying phenomenon? For example, Noel and Brownsey (1990) reported that the power law frequency dependence of G' for seven different glutens was 0.25 ($z = 4$); however, each gluten sample was shifted in time along the frequency axis. Those authors also tested several of the gluten samples with stress relaxation. They did not discuss those results in detail, but it was obvious that the gluten sample with the lowest power law intercept value showed the slowest rate of stress relaxation, while the gluten with the highest power law intercept by DMA showed the fastest rate of stress relaxation. Thus, the relative long-time relaxation behavior of those glutens was apparently related to their short-time elastic modulus. This would be qualitatively similar to the results found here, where added fat had a plasticizing effect as measured by DMA but also resulted in slower relaxation at long times. Clearly, power law intercepts from DMA experiments over the typical frequencies used are not sufficient to characterize the viscoelastic behavior of doughs, since they do not provide any information on viscous flow. The loss modulus (G'') in this frequency range may only reflect dissipative processes of smaller polymer chain segments, such as between crosslinks or entanglements.

CONCLUSIONS

The results shown here indicate that added shortening present during the mixing of wheat flour dough, acts as a plasticizer of the dough's short-time elastic properties. Simultaneously, it also decreases the rate of relaxation at longer times, at least up to 5% added fat. To our knowledge, this has not been reported before. Whether there is a direct cause and effect between these two observations cannot be determined from this work alone. Nevertheless, this result may be useful in interpreting results of published studies, for which correlations have been attempted between viscoelastic functions obtained at short times only, and longer time phenomena such as the oven rise of bread or the spread of cookies during baking. These results should also complement published work regarding the relationships between the chemical aspects of gluten or doughs, and functionality.

The WW model, commonly used for describing the stress-relaxation data of plastic polymers was successfully used here for doughs, apparently for the first time, and indicated the presence of only two predominant relaxation processes widely separated in time. Which component is observed will depend upon the time frame of the experimental measurements and the process time. As compared to the four-element Maxwell model, the WW model provides an average relaxation time and indication of the polydispersity for each relaxation mode. These model parameters should be more useful in the design and interpretation of sheeting, mixing, and extrusion processes for doughs where viscoelastic effects need to be considered than the rather arbitrary model parameters of viscoelastic models based on mechanical elements. Additional experimental work is needed to determine the relationship, if indeed any exists, between the empirical WW model relaxation modes and their associated model parameters, and the molecular basis for the development of doughs.

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