

# Use of the Rubber Elasticity Theory to Characterize the Viscoelastic Properties of Wheat Flour Doughs

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ABSTRACT

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The viscoelastic properties of durum wheat flour doughs were measured using the extensigraph in uniaxial extension and the Rheometrics mechanical spectrometer in oscillatory shear. The research examined the effect of increasing density of cross-links on rubber elasticity in these systems. The stress-strain behavior of durum wheat flour dough was not well simulated by Mooney-Rivlin type nonlinear elasticity. Addition of increasing amounts of iodate made the dough show appreciable strain thickening behavior, approximating the behavior of natural rubbers. The estimated apparent molecular weight between cross-links ranged from 10,500 to 16,000,

much larger than that of rubbers, for which values are in the range of 500–1,000. When the Mooney-Rivlin equation was tested, it appeared to approximate only moderately well the extensional behavior of iodate-added wheat flour doughs at finite but low extensions, where the finite extensibility of chains is not a factor. It is hypothesized that the cross-linked network is highly diluted with hydrogen and hydrophobic bonds that limit the applicability of rubberlike elasticity theories. Increasing the cross-linked density using iodic acid developed matrices that moved the behavior of durum flour doughs closer to Mooney-Rivlin behavior.

The rheology of wheat flour dough has been a topic of real interest to cereal chemists for several decades. The rheological properties of doughs are recognized to be central to the successful manufacturing of bakery products. Even though the rheology of dough has been much studied, the challenge of understanding the physical properties that control flow and deformation remain. The addition of water to wheat flour and a sufficient amount of mechanical input produce a cohesive dough. A prime contributor to the physical properties of wheat flour dough is the gluten complex. The latter is essentially composed of two classes of proteins, gluten and gliadin, along with two others of lesser significance, the albumins and the globulins (Dus 1997). During mixing, the gluten matrix forms a continuous phase that surrounds the starch granule and generates a three-dimensional network (Moss 1974).

The structure of the interrupted matrix of gluten is dependent upon how gliadin and glutenin associate with each other. Bloskma (1962) was the pioneer in the measurement of viscoelastic properties of wheat flour doughs using creep tests. Hibberd and Wallace (1966) examined the viscoelastic properties of wheat flour doughs using small-amplitude oscillatory measurements. Bushuk et al (1980) studied fractions of glutenin and showed that glutenin is a complex of both covalently and noncovalently linked components. Inda and Rha (1982) examined the effect of secondary bonding modification on the tensile behavior of wheat gluten.

Quantitative characterization of rheological properties of wheat flour and gluten doughs have been difficult because of their complicated strain-dependent (nonlinear) viscoelastic behavior. Bagley et al (1988) simulated dough rheological properties in uniaxial compression using the upper convected Maxwell model. Dus and Kokini (1990) characterized the nonlinear viscoelastic properties of hard and soft wheat flour doughs using the Bird-Carreau constitutive model. Wang and Kokini (1995) simulated both shear and extensional properties of gluten doughs using the Wagner model, and Huang and Kokini (1993) measured the biaxial extensional properties of wheat flour doughs.

Mechanical or rheological measurements are used at numerous points in the development of new products and processes, during the optimization stage and during manufacture to ensure consistent production. Many expectations exist for dough rheology, but the understanding and ability to reliably measure the material properties of dough lag far behind those expectations (Rasper 1993).

The statistical theory of rubber elasticity has the potential to offer quantitative characterization of wheat flour doughs. It is based on the concepts of random chain motion and the restraining power of cross-linking. Three conditions must be satisfied: 1) the presence of long-chain molecules, with freely rotating links (Gaussian chains); 2) weak secondary forces between the molecules; and 3) an interlocking of the molecules at a few places along their length to form a three-dimensional network that links all molecules together so that they can no longer move independently as in a liquid.

When all these conditions are met, an equation describing the relationship between the extensional force ( $f$ ) exerted on the material and the extension  $\lambda$ , defined as the extension ratio ( $L/L_0$ ), where  $L_0$  is the original length:

$$f = G(\lambda - 1/\lambda^2) \quad (1)$$

$G$  is the elastic constant, which is dependent on the structure of the material. It must also be noted that  $f$  is the force per unit cross-section, where the cross sectional is measured in the unstrained state. This theory is valid as long as the finite extensibility of chains is not a factor; for very large extensions, where rubber is observed to show highly strain thickening behavior, the effect of the finite extensibility of the chains must be taken into account (Treolar 1975).

Mooney developed a modification of the Neo-Hookean model to extend its applicability to larger deformations in the range where finite extensibility of the chain is not a factor (Flory 1953). In the Mooney concept, the relationship between tensile stress and the extension ratio  $\lambda$  is given as:

$$f = 2[\lambda - (1/\lambda^2)] [C1 + C2/\lambda] \quad (2)$$

This equation contains two empirical constants,  $C1$  and  $C2$ ; the formula is derived from statistical theory. Equation 1 corresponds to the particular case in which  $C2 = 0$  and  $C1 = G/2$ . Thus, the three general conditions quoted previously for rubberlike elasticity must be satisfied. To evaluate the two constants  $C1$  and  $C2$ , it is possible to rewrite the equation in the form:

$$f/[2(\lambda - 1/\lambda^2)] = C1 + C2/\lambda \quad (2a)$$

In this case, a plot of  $f/[2(\lambda - 1/\lambda^2)]$  versus  $1/\lambda$  should yield a straight slope of  $C2$  at extensions in the range of 0.85–0.5, and the value is equal to  $C1 + C2$  on the vertical axis at  $1/\lambda = 1$ . This analysis is valid at finite but small extensions and in the range where the finite extensibility of the chains is not a factor. This happens usually for  $1 < \alpha < 4$ . Typical plots of this kind for a series of vulcanized rubber compounds show that the constant  $C1$  varies widely according to the degree of vulcanization while  $C2$  remains approximately constant (0.10 N mm<sup>-2</sup>). This suggests that  $C1$  is a function of the network structure while  $C2$  has some independent origin.

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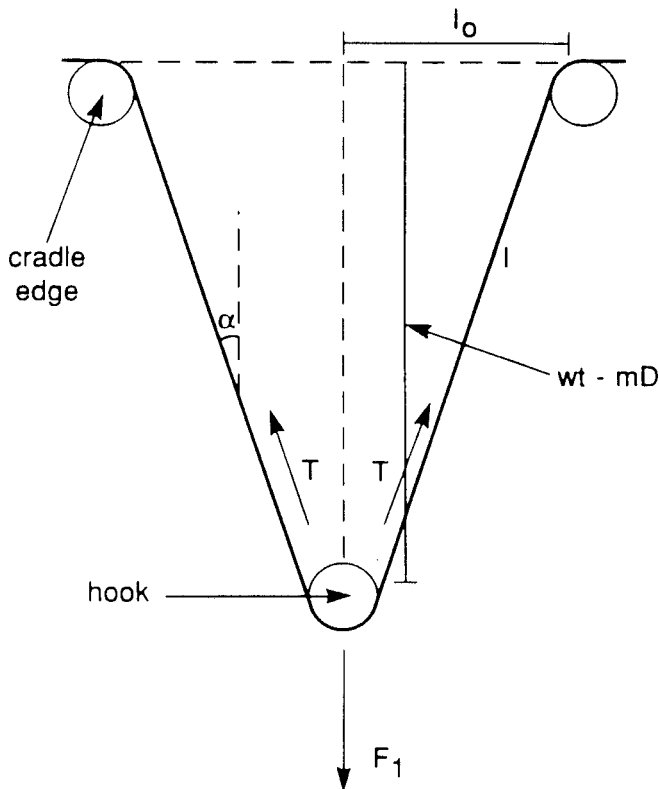
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While these ideas have been extensively tested with synthetic polymer networks, they have not been adequately investigated in relation to biological cross-linked networks like wheat flour doughs and doughs modified with oxidizing agents such as iodates. Bagley et al (1985) examined the applicability of the Mooney-Rivlin equation in torsional oscillatory flow for starches. While there seemed to be good prediction of the data using the equation, their attempt was limited to the linear viscoelastic range and was of marginal usefulness.

Moss (1974) demonstrated that in well-developed wheat flour doughs, gluten is a three-dimensional continuous network of proteins bonded together by interprotein disulfide bonds (Dus 1997). In fact, sulfhydryl reagents provide stability to dough by immobilizing parts of protein chains and thereby facilitating formation of disulfide bonds and hydrophobic interaction. The ungelatinized starch is suspended in the continuous protein network. Iodate, a maturing agent, when mixed with doughs, oxidizes the sulfhydryl groups of flour proteins and promotes the formation of disulfide bonds. It could therefore be expected that, as the cross-link density of the network increases, the resulting matrix would begin to demonstrate nonlinear elastic effects consistent with Mooney-Rivlin type rubber elasticity.

This study attempted to provide some elucidation to the applicability of the rubber elasticity theory to characterize the rheology of durum flour doughs.

The objectives of the research were twofold: 1) to use the theory of rubber elasticity to estimate the molecular weight between cross-links in wheat flour as a function of the addition of iodate; and 2) to evaluate the ability of the Mooney-Rivlin equation to predict stress-strain behavior in dough as the cross-link density of the dough was increased using a cross-linking agent, iodic acid. This study was also designed to develop inferences about the structure of the three-dimensional network in durum flour dough during extension.



**Fig. 1.** Geometry of test piece during stretching.  $l_0$  = half the distance between the cradle edges,  $\alpha$  = angle between the string of dough and the vertical,  $w$  = speed of the hook,  $t$  = time interval during stretching,  $m$  = displacement of the cradle per unit deflection, in extensigraph units,  $T$  = stretching force in the strings of dough,  $F_1$  = stretching force on test piece. (Reprinted by permission from Rasper and Preston [1991]).

**Flour, Reagents, and Moisture Content**

Flour from durum wheat (a tetraploid wheat) was obtained commercially (lot no. HAO2127, Dricolls Food Service, Carlstadt, NJ). The protein content was  $13.15 \pm 0.3\%$ ; the moisture content was  $13.16 \pm 0.2\%$ ; the crude fat was  $1.3 \pm 0.05\%$ , and total ash was  $0.37 \pm 0.05\%$ . Iodic acid (assay >99.5%) and gluten (80% protein, 7% fat) was obtained from Sigma Chemical Co. (St. Louis, MO).

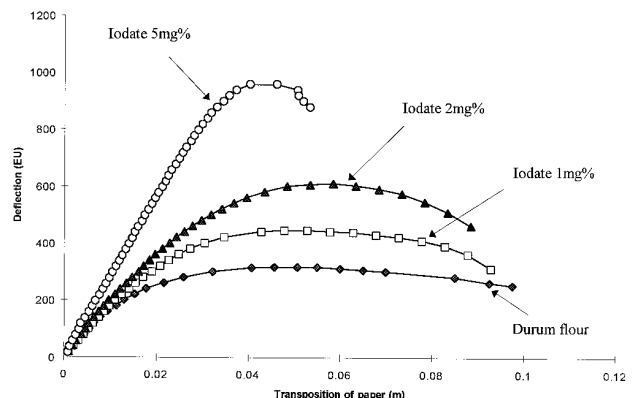
Iodic acid was diluted in distilled water, to obtain solutions with concentrations of 592 mg/L, and 1.184 and 2.960 g/L. Portions (5 mL) of these solutions were used to get, respectively, 1, 2, or 5 mg of iodic acid per 100 g of flour.

The moisture content of the durum flour was determined by Approved Method 44-19 (AACC 1995). Flour ( $2.0 \pm 0.1$  g) was transferred to tared aluminum pans with covers. Sample weight was recorded after subtracting tare weights. The dishes were uncovered and transferred to an oven at  $135^\circ\text{C}$  for 2 hr. Then, the dishes were covered, removed from the oven, and transferred to a desiccator. After reaching room temperature, the samples were weighed. Moisture content (13.06%, wb) was determined from weight loss.

**Preparation and Characterization of Wheat Flour Doughs Using the Farinograph**

Approved Method 54-10 was used for reproducible dough preparation with the same initial consistency (AACC 1995). The test assures mechanically homogenized and formed samples. The dough was prepared using a Brabender Farinograph so that its resistance was always equal to 850 BU. This value was kept constant in all of the experiments to give maximum reproducibility. To obtain doughs with a consistency of 850 BU, 165, 165.2, 166.1, and 167.2 mL of water was added. When iodate was used, 1, 2, or 5 mg was added to 100 g of flour. Thus, all of the samples had the same consistency and did not stick on the mold of the extensigraph. The necessary amount of water was added to flour and reagents and was mixed for 2.5 min using the 300-g bowl of the farinograph.

Oxidation by cross-linking agents is rapid and complete when dough is mixed for 2.5 min. After the dough was removed from the farinograph bowl, it was allowed to react for 10 min in the fermentation cabinet. To ensure reproducibility in the extensigraph studies, Approved Method 54-21 was used (AACC 1995). To ensure high quality and reproducibility of the data, experiments were repeated nine times under the same experimental conditions. Pieces of dough that weighed 150 g were rounded 20 times and molded into dough cylinders. They were immediately placed in fermentation cabinets at  $30^\circ\text{C}$ . The samples were allowed to relax for 45 min and then were stretched. The resting period is necessary for relaxation of the stresses in the dough.



**Fig. 2.** Extensigraph with different concentration of iodate. EU = extensigraph units.

### Preparation of the Dough for Mechanical Spectroscopy

The necessary amount of distilled water was added to the durum flour, and the dough was mixed for 4 min to obtain a cohesive dough. Then, the dough was shaped in the form of cylinders. Sample dimensions were  $2.0 \pm 0.3$  mm in height and  $25.0 \pm 0.2$  mm in diameter. Samples were allowed to relax for at least 1.5 hr at room temperature before being tested. Measurements were conducted in triplicate with 40% moisture doughs, at room temperature.

The parallel plate geometry of the mechanical spectrometer (800, Rheometrics, Piscataway, NJ) with 25-mm diameter plates was used for rheological measurements. Strain sweeps were conducted to determine the linear viscoelastic region. Frequency sweeps were conducted in the linear region in the frequency range of 1–100 rad/sec.

### Conversion of the Extensigrams into Stress-Strain Curves

The conversion of extensigram readings to stress-strain curves followed the procedure elaborated by Rasper (1975). In this analysis, the dough is considered a straight line with a length of  $2 L_0$  determined by the distance between the edges of the cradle. During the stretching, the test piece assumes a “V” shape. At time  $t$  and deflection  $D$ , the movement of the hook equals  $wt$  and that of the cradle equals  $mD$ , where  $w$  = speed of the hook and  $m$  = displacement of the cradle per unit deflection (Fig. 1). The deflection of the measuring system is caused by the resistance of the tested dough to stretching. The extension ratio is then given by:

$$s = \lambda = L/L_0 = \{1 + [(wX/v - mD)/L_0]^2\}^{0.5} \quad (3)$$

where  $X$  = transposition of the chart in metric units and  $v$  = speed of the chart paper. The tensile stress,  $f$ , in the strings is given by the relationship:

$$f = F_1(\lambda)/(2A_0) * \lambda(\lambda^2 - 1)^{1/2} \quad (4)$$

where  $F_1$  = the vertical downward force of the hook and  $A_0$  = cross-sectional area of the test piece before stretching (Rasper and Preston 1991). Clearly, the fact that the stress ( $f$ ) is based on the cross-sectional area in the unstrained state is a limitation of this research.

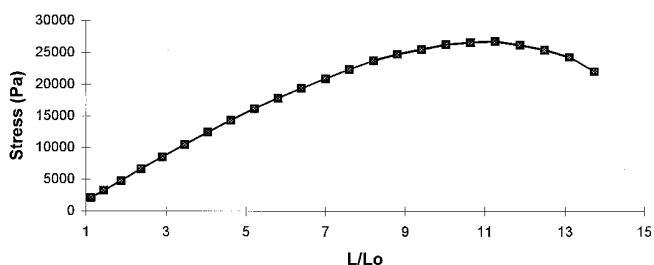


Fig. 3. Sample of tensile stress versus extension ratio derived from extensigrams using durum flour.  $L/L_0$  = extension ratio.

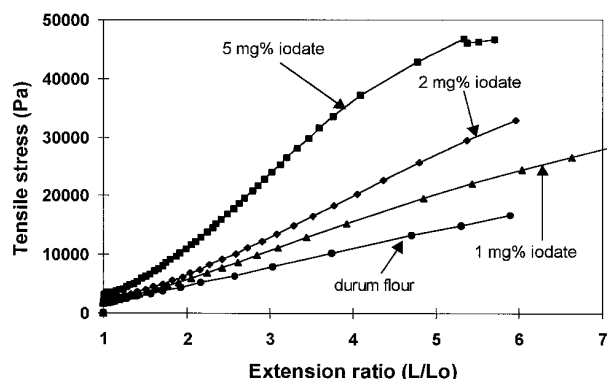


Fig. 4. Tensile stress versus extension ratio derived from extensigrams for durum flour with different concentrations of iodate.

### Determination of Molecular Weight Between Cross-Links Using the Spectrometer

The molecular weight between cross-links ( $M_c$ ) was calculated using the equation:

$$M_c = \rho R T / G' \quad (5)$$

where  $G'$  is the plateau value of the storage modulus over the frequency range selected, and where  $G'$  is essentially constant;  $\rho$  is the density of the material,  $R$  is the gas constant, and  $T$  is the absolute temperature.

To measure density, the dough was tightly packed in a mold with a height of 2 mm and a diameter of 25 mm. The sample was carefully removed from this mold and weighed with an analytical balance (Mettler, Highstown, NJ). The ratio of mass to volume gives the density. Since the  $M_c$  calculations are essentially approximate, we were satisfied with the accuracy we were getting from density measurements, which was better than 3.5% in all cases.

## RESULTS AND DISCUSSION

### Extensional Measurements with Durum Flour

The raw data obtained with the extensigraph for durum flour and for iodate-added durum flour are shown in Fig. 2. This data was converted to stress-strain values using the previously described method of Rasper (1975). An example of a stress-strain curve derived from data for durum flour is shown in Fig. 3. The application of  $\geq 2,000$  Pa of stress is necessary to start the deformation of samples, consistent with the findings of Glucklich and Schelef (1962). The fact that a high apparent yield stress is needed to initiate deformation and flow indicates the presence of a network. It is noteworthy, however, that even though a high yield stress was needed to initiate deformation and flow, the dough was able to flow. This

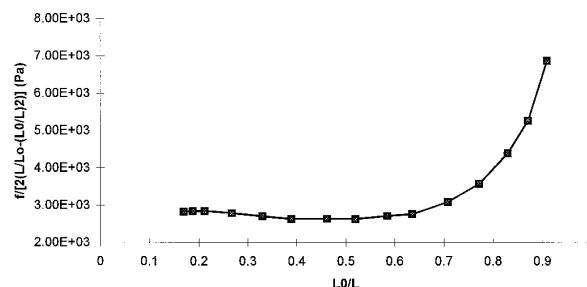


Fig. 5. Mooney-Rivlin plot for durum flour.  $L_0/L$  = extension ratio.

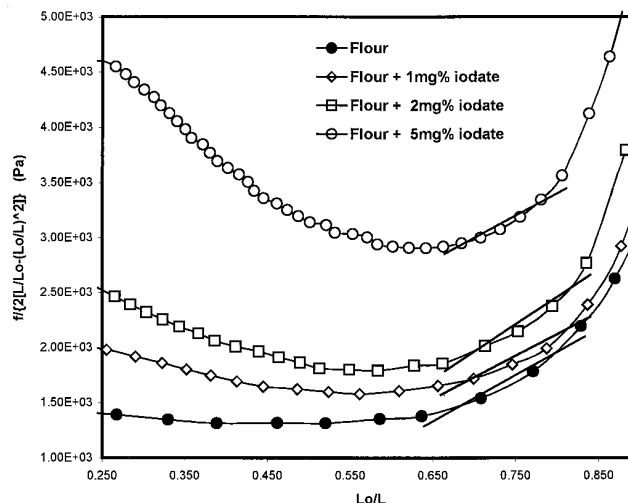


Fig. 6. Mooney-Rivlin plot for durum flour with different concentrations of iodate.

fact alone points to a weakly held network, unlike rubber, in which the extensive cross-linking prevents flow. Wheat flour dough is a two-phase system in which starch is suspended in a relatively weak gluten network. The weakly cross-linked network exists only in the gluten phase; the starch phase does not contribute to the effects caused by the cross-linking observed in the gluten network.

In the initial phases of deformation, stress varies linearly with strain. Stress-strain curves that compare the rheological properties of durum flour with those of iodate-added durum flour are shown in Fig. 4. The addition of increasing amounts of iodate increases the initial modulus and makes the curve nonlinear.

After reaching strains of approximately 700% ( $\lambda = 8$ ), the dough reached a plateau, and it broke at larger strains. In the case of rubber, it is well known that small deformations need the application of relatively small stresses, while very large stresses are necessary for deformations larger than 400% ( $\lambda = 5$ ) (Sperling 1986). Rubber show strain thickening behavior, while all the doughs studied here showed slight strain thickening behavior followed essentially by strain thinning behavior. This suggests that the network structure in dough is not able to support the stresses applied during the experiment, which results from a relatively small number of chemical cross-links and a high density of relatively weaker hydrogen bonds and hydrophobic interaction that hold the network together.

In contrast, natural rubbers have a high density of cross-links, which are able to support much larger stresses. The bonds are brought to their equilibrium stretching point, where their ability to further extend becomes limited, and the intensity of applied stress needs to become larger to achieve the higher strains, thus resulting in strain thickening behavior. It is interesting to note that, as the concentration of iodate is increased, resulting in an increased number of cross-links, the dough increasingly shows strain thickening behavior and begins to approximate the behavior of a highly cross-linked rubber.

The results in Fig. 2 show that all iodate-treated doughs show an increase in resistance to extension and a decrease in extensibility, in comparison with the control (durum flour). Iodate influences the molecular cohesion of the dough and the resulting extensional rheological properties. Indeed, iodate exerts its effect by oxidizing sulfhydryl groups, thus preventing reduction and interchange of disulfide bonds in gluten proteins. It is already well known that some intramolecular disulfide bonds are changed to intermolecular disulfide cross-linkages through the mediation of very small amounts of thiol groups. Intermolecular disulfide bridges also confer toughness and greater resistance to extension to the dough (Blokmsa and Bushuk 1988).

Stress-strain curves of durum dough change dramatically at a concentration of 5% iodate (Fig. 4). Although this result is well

known, our major focus here is on the shape of the curve and what it means in terms of rubberlike behavior of dough. The nonlinear deformation at high stresses is due to strain hardening. Below 5% iodate, the dough behavior does not show strain hardening. Tschoegl et al (1970) observed that at 5°C there is a distinct strain hardening while, at temperatures above 25°C, no strain hardening behavior is evident. Their observation shows the impact of hydrogen and hydrophobic bonds whose strength is dominated by temperature. In contrast, our results focus on the effect of cross-linking at temperatures where, according to Tschoegl et al (1970), the major impact of hydrogen and hydrophobic bonds is significantly reduced. Our experiments were carried out at 30°C.

The application of the Mooney-Rivlin equation to the stress-strain data of durum produced the plots in Fig. 5. For small extensions, up to  $1/\lambda = 0.85$ , a straight line is approximated. Durum behaves as a Mooney-Rivlin material only in a very narrow range during uniaxial extension experiments.

When the Mooney-Rivlin equation was tested with the iodate-added doughs (Fig. 6), it became apparent that the expected linearity in the  $L_0/L$  range of about 0.6–1.0 was only roughly observed. By applying a linear regression on the Mooney-Rivlin curve in the  $L_0/L$  range of 0.65–0.84, the constants C1 and C2 can be obtained according to Equation 2a (Fig. 7). The values of C1 and C2 are reported in Table I. The variation of C2 values showed no trend with the addition of different levels of iodate to durum flour. This is expected since this constant is independent of degree of cross-linking. The variability observed could be due to the difficulty in determining the linear portion of the Mooney-Rivlin curve. On the other hand, C1 tended to increase with iodate concentration, with the exception of durum flour containing 2 mg% iodate. This trend for durum flour was expected since, for vulcanized rubbers, C1 is a function of the degree of vulcanization.

It would appear that the Mooney-Rivlin concept does not simulate the data well because the dough is, in effect, linear elas-

TABLE I  
Mooney-Rivlin Constants C1 and C2 for Different Iodate Concentrations in Durum Flour

Type of Dough	C1 (kPa)	C2 (kPa)	R <sup>2</sup> <sup>a</sup>
Durum flour	-1.323	4.136	0.94
1 mg% iodate	-0.975	3.883	0.90
2 mg% iodate	-1.563	5.043	0.94
5 mg% iodate	-0.039	4.341	0.93

<sup>a</sup> For regression lines used in the calculations of C1 and C2.

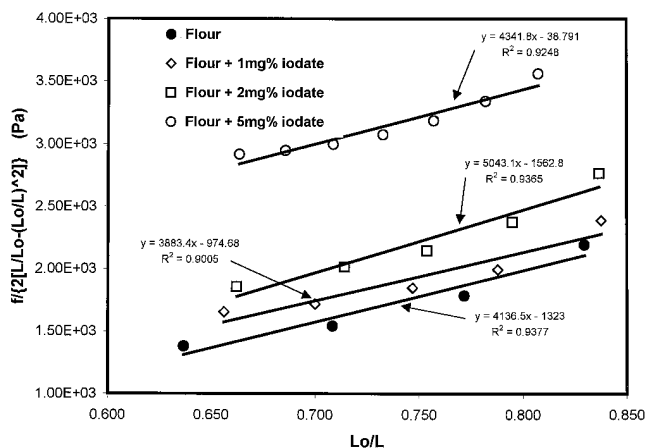


Fig. 7. Linear regression on Mooney-Rivlin curves to determine constants C1 and C2.

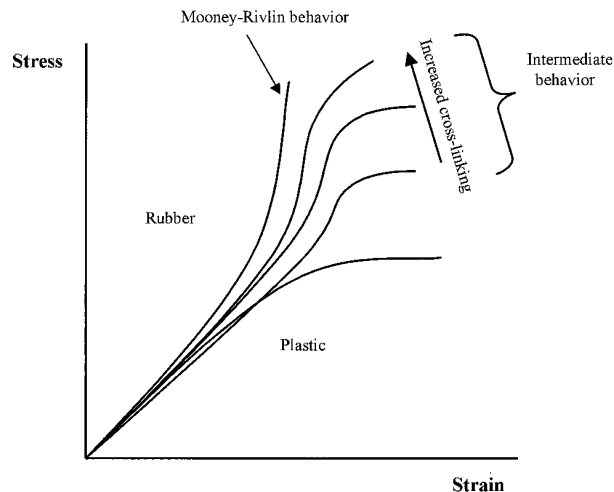


Fig. 8. Effect of cross-linking on stress-strain curves of solid materials.  $L_0/L$  = extension ratio.

tic in extension. At a small extension ratio, this is simply an artifact of the initial high stress needed to initiate the deformation, which obscures the nonlinearity at extension ratios near 1. The fact that dough appears to show linear elastic behavior is simply an artifact of the experiment.

As the concentration of iodate is increased, strain hardening begins, thus approximating Mooney-Rivlin behavior. It therefore appears that the Mooney-Rivlin equation provides only a very rough approximation for data in the nonlinear viscoelastic region at relatively small extension ratios. This is in contrast to the data of Bagley et al (1988) with starch suspensions, which suggested that the Mooney-Rivlin concept would be closely followed by starches. Close examination of their data, however, clearly shows that their test was limited to the linear viscoelastic region, where this comparison has only marginal usefulness.

The presence of yield stresses in dough does signify the presence of a network structure. In fact, in rubber, the yield stress approaches infinity. Behavior intermediate between rubber elasticity and plastic flow is observed for dough. Mooney plots show intermediate, weak Mooney-Rivlin behavior in the yield region (that is, the region below the yield stress). In Fig. 8, stress ( $\tau$ )-strain ( $\lambda$ ) curves are seen, where typical initial Hookean behavior followed by plastic flow (as in metals) is plotted. Rubbers show the other extreme; they become strain hardened at relatively large extensions and do not flow. Doughs, however, show a very small range of weak, rubberlike behavior, which becomes more pronounced as the protein network is more and more cross-linked and its concentration increases. It is clear that intermediate rubberlike behavior is observed for dough, such as that shown in Fig. 8.

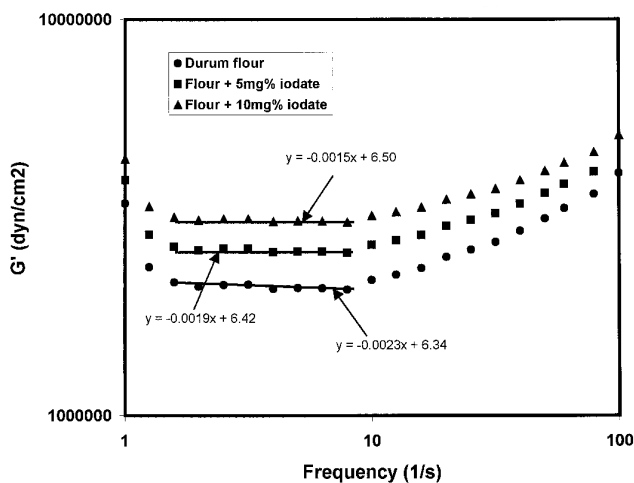


Fig. 9. Effect of iodate on the magnitude of the storage modulus  $G'$ .

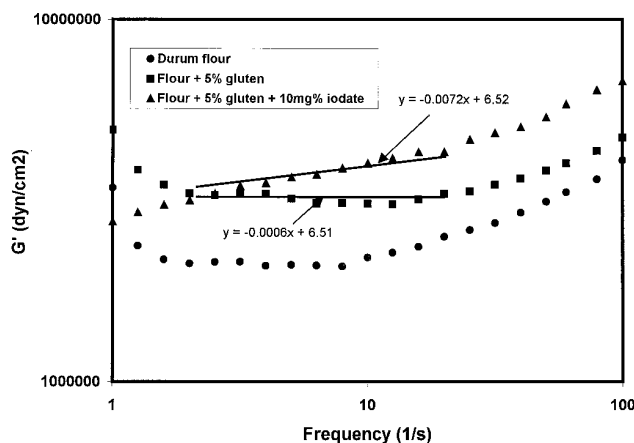


Fig. 10. Effect of gluten on the magnitude of the storage modulus  $G'$ .

### Estimation of the Apparent Molecular Weight Between Cross-Links

The difference in the behavior of doughs and rubbers can be easily explained from a molecular point of view. In cross-linked rubbers, the  $M_c$  is in the range of 500–1,000 g/mol (Sperling 1986). In wheat flour doughs, the number of cross-links per molecule is not high enough to simulate rubberlike behavior. Another important consideration is related to the amount of protein. The elastic behavior of dough results largely from the protein fraction of the flour. Since the protein content is usually in the range of 10–14%, the network is weak because starch is suspended in the protein matrix (Dus 1997). Bagley et al (1988) determined that if the protein content is increased in the dough, the dynamic mechanical properties increase.

Results of the small amplitude measurement are shown in Figures 9 and 10 for  $G'$ .  $G'$  shows a weak dependence on frequency, allowing the use of the rubber elasticity theory to estimate molecular weights between cross-links. Consistent with prior results in Fig. 4, the durum flour alone has the lowest  $G'$  value for all the frequency range studied and also deviates the most from rubberlike behavior. The introduction of increasing levels of iodate and gluten increases the value of the modulus, as expected. The addition of both iodate and gluten also reduces the frequency dependence of the modulus and allows the use of the rubber elasticity theory as an approximation to obtain  $M_c$ .

$G'$  values are also shown in Fig. 11. Curves of  $G'$  versus frequency show the characteristic minimum observed for rubberlike materials.

The change in  $M_c$  of doughs subjected to different concentrations of iodate and/or gluten is shown in Table II. As expected,  $M_c$  kept decreasing from the initial value, which is an indication of the existence of an increasingly cross-linked network. The appar-

TABLE II  
Effect of Iodate Concentration and Gluten Content on Molecular Weight Between Crosslinks ( $M_c$ )

Concentration of Cross-Linking Agent	$G'$ (dyn/cm <sup>2</sup> )	$M_c$ (g/mol) <sup>a</sup>
Durum flour (F)	$2.164 \times 10^6$	16035
F + iodate 5 mg%	$2.665 \times 10^6$	13020
F + iodate 10 mg%	$3.162 \times 10^6$	10974
F + gluten 5%	$3.247 \times 10^6$	10686
F + iodate 10 mg% + gluten 5%	$3.296 \times 10^6$	10527

<sup>a</sup> Calculations based on a density of 1.4 kg/liter,  $R = 8.314 \times 10^7$  dyn/cm/mol-K and a temperature of 298 K.

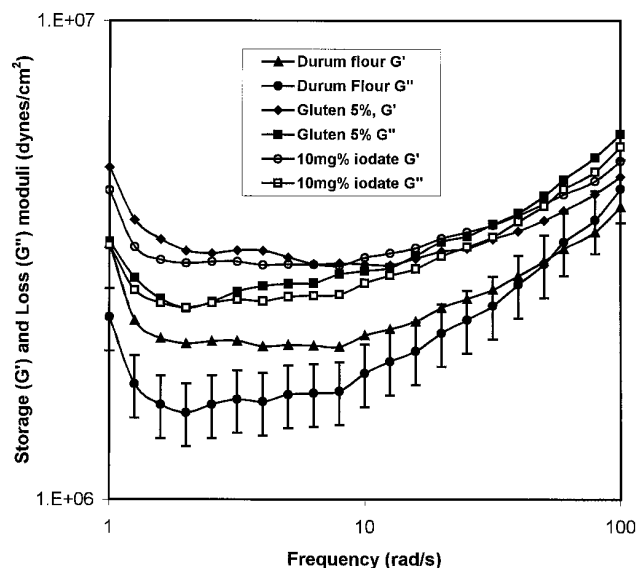


Fig. 11. Frequency sweeps for durum flour doughs.

## LITERATURE CITED

ent  $M_c$  value for durum flour dough was about 16,000. At the other extreme, the addition of 10% iodate and 5% gluten reduced the apparent  $M_c$  value to about 10,500, showing that the number of elastically active network junctions go up significantly with the addition of gluten and iodate. The  $M_c$  values obtained for durum flour are much higher than those for natural rubber, where the  $M_c$  values are in range of 500–1,000, and the number of cross-links is proportionately smaller in wheat flour doughs.

Bushuk et al (1980) suggest that secondary bonding interactions (hydrogen and hydrophobic bonds) in dough make a significant contribution to the rheological properties. They observed that secondary bonding interactions between different protein subunits in gluten were responsible for the unique structure and physical properties of gluten. These bonds allow for protein subunits to form an elastic network, imparting a three-dimensional structure to gluten and thus to doughs as well. The research in this article agrees with the results of Bushuk et al (1980) and, in addition, obtained an estimate of  $M_c$  using rubber elasticity theory to demonstrate the relatively low density of cross-links. At the same time, the presence of large secondary bonds has been suggested as the reason for the discrepancy between the experimental data in uniaxial extension and the predictions of the Mooney-Rivlin equation.

Two major assumptions about rubber elasticity are only approximately justifiable. First, the chains are clearly not Gaussian because there are well-known restrictions in bond angles. Second, the secondary bonding interactions are supposed to be weak and yet they are a major contributor to the rheology of the dough. The high density of hydrogen and hydrophobic bonds clouds the contribution of cross-links to the elasticity of the network.

## CONCLUSIONS

This report examined the applicability of rubberlike concepts to dough. The stress-strain behavior of durum wheat flour dough was not well simulated by Mooney-Rivlin type nonlinear elasticity. The addition of increasing amounts of iodate made the dough show appreciable amounts of strain thickening behavior, approximating the behavior of natural rubbers. The estimated apparent molecular weight between cross-links ranged from 10,500 to 16,000, which is much larger than that of rubbers, whose values are in the range of 500–1,000. When the Mooney-Rivlin equation was tested, it appeared to only moderately well approximate the extensional behavior of wheat flour doughs with added iodate—and only at finite but low extensions where the finite extensibility of chains is not a factor.

## ACKNOWLEDGMENTS

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