

Dynamic Viscoelastic Behavior of High-Pressure-Treated Wheat Gluten

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ABSTRACT

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The effects on the viscoelastic behavior of hydrated wheat gluten after treatment at different pressures (200–800 MPa), temperatures (20, 40, and 60°C), and holding times (20 and 50 min) were investigated by controlled stress rheometry. Because of the wide range of properties, four different torque amplitudes were used (0.5, 1.00, 3.00, and 6.00 mNm). Significant effects on rheological properties were observed, except when samples were

analyzed at 0.5 mNm (limited heat and pressure treatments). Both storage modulus (G') and loss modulus (G'') were more affected by temperature than pressure. The holding time had substantial effect on the slopes of both moduli at mild treatments; for the more severe treatments, the intercepts of the storage moduli in particular were extensively affected.

High-pressure treatment induces structural changes in food macromolecules such as protein that result in changes in functionality (Ledward 1995). Noncovalent bonds such as hydrophobic interactions, hydrogen bonds, and electrostatic interactions are all affected by high pressure, but covalent bonds remain intact (Cheftel 1992, Heremans 1992, Ledward 1995). This may result in protein unfolding (partial denaturation), dissociation of noncovalently linked oligomeric structures into subunits, and dissociation of carboxyl groups of amino acid side chains. In many cases, aggregation to form a gel network occurs (Ledward 1995). The formation of hydrogen bonds (Defaye and Ledward 1995) and weakening of hydrophobic interactions are important in dictating protein conformational changes in pressure-treated samples. Pressure-induced gels are different from those induced by heat. The gels tend to be glossier, smoother, softer, and possess greater elasticity (Mertens et al 1993).

The viscoelastic properties of gluten are affected by the structural properties of the gliadin and glutenin subfractions and the interactions between them. Hydrogen bonds are particularly important because of the of glutamine residues, but hydrophobic interactions as well as covalent disulfide bonds linking glutenin subunits into polymeric structures are also important (Tatham 1990, Schofield 1994). It is widely accepted that disulfide cross-linked glutenin polymers are responsible for the elastic character of gluten, whereas the gliadins are responsible for its viscous properties. The nature of the individual glutenin subunits, especially the high molecular weight glutenin subunits (HMW-GS), appears to be important in determining gluten functional properties (Tatham 1990, Schofield 1994). Evidence has also been presented indicating that the glutenin-to-gliadin ratio also affects gluten rheological behavior (Khatkar et al 1995).

Most studies concerned with the effects of physical variables on gluten rheological and functional properties have examined the effect of heat, especially in relation to the loss of baking quality, that occurs when gluten is heated at $>50^{\circ}\text{C}$ (Schofield et al 1983, Weegels et al 1994). Examination of the dynamic rheological properties of gluten have shown that both the storage modulus (G') and the loss modulus (G'') are increased as a result of heating, indicating an increase in the cross-link density of the system's rheology (Legrys et al 1981, Schofield et al 1984). This is consistent with observations that gluten protein extractability decreases after heating (Pence et al 1953, Booth et al 1980, Jeanjean et al 1980, Wrigley et al 1980). Electrophoresis and gel-filtration chromatographic analysis of the extracted protein has shown that glutenin is affected at a

lower temperature than gliadin. The ω -gliadins, which are deficient in sulfur amino acids, are not affected. The increase in extractability that occurs when reducing agents are added to the system implies that the heat-induced changes in these gluten are related to changes in disulfide bonding (Jeanjean et al 1980, Wrigley et al 1980). Measurement of free sulfhydryl groups in SDS-extracted and SDS-inextractable protein using radio-labeled iodoacetamide indicated that there was no increase in the number of disulfide bonds when gluten was heated, suggesting that the cross-linking changes caused by heating were due to disulfide bond rearrangement (Schofield et al 1983). In contrast, more recent research in which sulfhydryl groups and disulfide bonds were quantified by a S,S'-dithio-bis-(2-nitrobenzoic acid) procedure, indicate that the ratio of sulfhydryl groups to sulfhydryl groups plus disulfide bonds declined on heating at moisture contents similar to that used in the present work, suggesting that sulfhydryl groups are oxidized to disulfide bonds on heating (Weegels et al 1994). Despite some inconsistencies, the research clearly demonstrated that the changes in gluten rheological properties and functionality are related to modification of disulfide cross-linking. It should be noted, however, that this may not be the sole cause of such changes. There has been little related research on the effects of high pressure on the properties of cereal flours, dough, or the major chemical components of cereal flours. The gelatinization properties and susceptibility to amylase digestion of pressure-treated starch has been examined (Thevelein et al 1981, Hayashi et al 1989), as has the effect of pressure on α -amylase activity in barley and wheat flour (Gomes and Ledward 1998).

As an alternative to heat treatment, gluten might be modified by different pressure and temperature regimes, which could potentially lead to novel textures and products

MATERIALS AND METHODS

Preparation of Hydrated Wheat Gluten

Commercial vital wheat gluten was obtained from Cerestar Deutschland GmbH (Barby, Germany). The gluten was mixed with 1.5 times its weight of distilled water in a Z-blade mixer (Morton Machine Co. Ltd., Wishaw, Scotland) operating at high speed for 100 sec and then at low speed for a further 200 sec. The resultant hydrated gluten had a moisture content of $\approx 62.5\%$ (w/w) which is similar to the moisture content of freshly isolated gluten. The gluten doughs were then divided into 100-g portions and rolled tightly into a cylinder shape so that they could be fitted in a lubricant-free condom. The samples were then treated at the appropriate temperature and pressure for 20 or 50 min, removed from the condom, and stored at 4°C in polyethylene bags for 15 hr to allow any residual stress to relax before the dynamic rheological properties were measured at 25°C .

High-Pressure Treatments

The 100-g gluten samples were subjected to pressures of 200–800 MPa at temperatures of 20, 40, and 60°C for 20 or 50 min as

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described previously (Defaye et al 1995). The pressure cell was maintained at the appropriate temperature by circulating water, and the pressure was applied within 2 min. Thus, temperature equilibration occurred concomitantly with pressure treatment. The rate of pressure increase was ≈ 250 MPa/min. During high-pressure treatment, an adiabatic increase in temperature occurs. At ambient temperature, the monitored cell temperature increased by $\approx 15^\circ\text{C}$ in the first 3 min on reaching 800 MPa, but decreased to the initial temperature over the next 4 min. Proportionately smaller increases were observed at lower pressures and higher temperatures (Defaye et al 1995).

Rheological Measurements

A controlled stress rheometer (Rheo-Tech International Ltd., Royston, England) was used to measure the dynamic viscoelastic properties of the gluten samples. The testing conditions were chosen so as not to exceed the linear viscoelastic behavior of the sample; that is, so that there was no evidence of structural breakdown from the preliminary stress amplitude scans (Figs. 1 and 2). A parallel-plate measuring geometry was used (20 mm diameter) with a gap width of 1 mm. Samples were loaded onto the rheometer and allowed to equilibrate to the measuring temperature ($25 \pm 1^\circ\text{C}$, ≈ 5 min). The edges of the sample were coated with a light silicon oil to prevent drying out (< 1 cp). Storage (G') and loss (G'') moduli were obtained over a frequency range of 1–10 Hz. Owing to the varying physical characteristics of pressure-treated glutes, it was not possible to perform all measurements under the same torque conditions. Hence, the dynamic rheological analyses were conducted using four separate torque amplitudes (0.5, 1, 3, and 6 mNm). This ensured that all testing was nondestructive and conducted in the linear viscoelastic range of each sample.

Statistical Analysis

The treatment combinations studied were pressure (200, 400, 600, and 800 MPa), temperature (20, 40, and 60°C), and holding time (20 and 50 min). After subjecting the samples to the various treatments, the dynamic rheological measurements were conducted on four replicate samples from two separate experiments ($n = 8$). Native (untreated) samples were also analyzed at the same time. Both storage (G') and loss (G'') moduli were analyzed for significant differences within each of the groups. Linear regression analysis was used to determine the slopes and intercepts (at 0 or log 1 frequency) of all G' or G'' as a function of frequency. This treatment was used to locate the data on the overall moduli scales for comparative purposes, no rheological function is implied. The slopes and intercepts were used in one-way multivariate analysis

of variance (MANOVA) (Mead 1992) to estimate the differences among treatments in each data set. Unplanned and planned treatments (the significance within pairs of holding time) had multiple comparisons analyzed by Duncan's new multiple range test and orthogonal comparison, respectively (Steel et al 1980, Ouppadisakul 1984). All statistical analyses were computed using the Statistical Analysis System (SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

The results obtained in this study, may be regarded as a first step in applying more extensive rheological techniques to a complex food and biological system. However, it must be appreciated that while dynamic rheological measurements have been obtained, they are only representative of a relatively small part of the material's full spectrum of mechanical behavior. Although limited in range, these measurements give an insight into the nature of the material (as a weak viscoelastic system). They do not, however, represent a fundamental study into the nature of gluten itself or of the pressure-treated samples. Such fundamental studies require a much more extensive examination of the polymeric systems under test.

The data described represents only a fraction of the possible mechanical spectrum, and while it was possible, using the rheometer described, to access lower frequencies (down to 0.01 Hz), during the extra time taken for measurement, crusting of the sample edges occurred due to drying of the sample. Similar problems were apparent if the measurement temperature was raised (as would be required to conduct time and temperature superimposition of the data).

In consideration of the data, it should be noted that there are several reports proposing the mathematical fitting of certain models to this type of data to assess the effects of pressure on polymeric systems (Moonan and Tschoegl 1983). However, in view of the limited nature of the data (one-tenth), this type of approach was considered inappropriate in this case. All of the data plots of moduli V frequency obtained could be described as being characteristic of weak viscoelastic materials. These varied essentially only in their absolute values and their rate of change of value with frequency. It was considered that these two characteristics could best be assessed by considering a derived intercept (modular value at 1 Hz) and slope (change of modular value with frequency). In this sense, the intercept would represent the overall strength of the material under test, and the slope would represent any change in liquid V gel character (increasing slope indicating an increase in liquid-like behavior). There is no suggestion that such a treatment of the data represents a model fit.

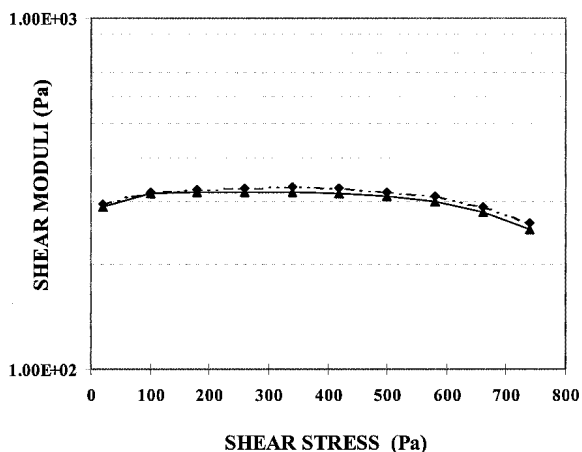


Fig. 1. Stress amplitude sweep at frequency 1 Hz of high-pressure-treated gluten samples at 200 MPa, 20°C , and 50 min. Solid line = G' and dotted line = G'' .

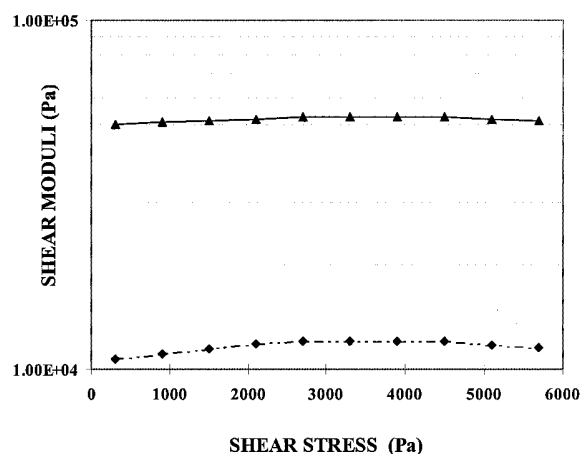


Fig. 2. Stress amplitude sweep at frequency 1 Hz of high-pressure-treated gluten samples at 800 MPa, 60°C , and 50 min. Solid line = G' and dotted line = G'' .

The variable nature of commercial vital wheat gluten and the gluten doughs prepared from it (even under standardized mixing conditions) required the application of some statistical treatment to assess any differences between the sample groups (Table I). While it would have been possible to apply such a statistical approach to the parameters of a model fit, the limited nature of the data presented in this study (one-tenth) would make such a treatment suspect.

The gluten samples treated under different pressure, temperature, and time regimes were initially assessed as a function of stress amplitudes to determine the region of linear viscoelastic behavior relating to each group of samples (Figs. 1 and 2). As the treated samples varied considerably in their final rheological properties, different stress regimes were used to measure each group. The increasing stresses needed to make suitable measurements indicate the overall increase in structure with increasingly severe treatments (Table I). In addition to this increasingly elastic behavior, several interesting differences were observed within the test groups.

In general, the coefficient of variation of the entire analysis fell into a wide range (4.5–28%), and their variations are reported as standard error in Table I. MANOVA of the data for the various test groups showed that, for all groups analyzed, except those measured at 0.5 mNm (low pressure-low temperature), there are significant differences ($P \leq 0.001$) within each individual group. The four statistical assessments (Wilk [λ], Pillai [trace], Hotelling-Lawley [trace], and Roy [greatest root]) showed good agreement, the differences not being dependent on each other. For those analyzed at 0.5 mNm, the differences in G' were caused by the changing slopes as well as the intercepts. The first three testing methods in this design had probability (P) values 0.05–0.08, whereas the Roy's greatest root had a P value of 0.01. For G'' , the

P values of the intercepts are substantially lower than the slopes (0.08 and 0.78, respectively). Overall, no evidence of significant difference of G'' in this data set is shown by the four statistical assessments ($P \geq 0.05$).

Figures 3 and 4 show a summary of the results obtained for the rheological properties of gluten subjected to the various pressure-temperature-time regimes. All samples in the 0.5 mNm group showed similar behavior with relatively high values for their slopes and low values for their intercepts. Even though there was some evidence from statistical analysis of the data that the intercepts and slopes were slightly different (the G' intercepts and slopes of control or native samples and treatment at 200 MPa, 40°C, 20 min, and G'' intercepts of treatment at 200 MPa, 20°C, 50 min; 200 MPa, 20°C, 20 min; and 200 MPa, 40°C, 20 min), these were masked since the orthogonal comparison of control samples against other treatments in the same data set showed no significant difference ($P \leq 0.05$) for all data sets within this torque amplitude, indicating no significant changes in sample structure. In contrast, data obtained at higher temperature (200 MPa, 60°C) show an increase in both G' and G'' intercepts and slightly decreasing slopes (Table I, Figs. 3 and 4) but the loss tangent ($\tan \delta$) was still high. These suggest an overall increase in liquefaction of the structure (Morris et al 1980).

In general, the control samples showed essentially viscous liquid-like behavior with a strong frequency dependence of the moduli with $\tan \delta$ values approaching unity. There is little evidence of gel-like behavior. In addition, samples treated at low pressure (200 MPa) and low temperature had properties similar to those of the control (untreated) gluten but with reduced overall interaction (lower values of G' and G'') and also an increase in liquid-like behavior (increased $\tan \delta$ values). This is a typical characteristic of an essentially viscous system (Ferry 1980).

TABLE I
Multiple Comparisons of Viscoelastic Properties of Glutens Subjected to Different Pressure, Temperature, and Time Regimes Within Each Individual Group

Pressurization Conditions			Rheology	Means of Storage Moduli		Means of Loss Moduli	
Pressure (MPa)	Temperature (°C)	Time (min)	Torque Amplitude (mNm)	Intercepts (kPa)	Slopes	Intercepts (kPa)	Slopes
0.1	20	0	0.5	0.38c ^a	2.67b	0.34y,z	2.84n
200	20	20	0.5	0.39c	2.78b,a	0.28z*	2.88n
200	20	50	0.5	0.34c,d	2.60b	0.43y*	2.62n
200	40	20	0.5	0.15d	3.09a	0.26z	2.73n
200	40	50	0.5	0.18c,d	2.87b,a	0.31y,z	2.79n
				SE = 0.11	SE = 0.19	SE = 0.047	SE = 0.22
200	60	20	1	0.84y	1.88f	1.12g,h	1.98r,s
200	60	50	1	0.81y	1.98e,f	1.39g	2.03r,s
400	20	20	1	0.55y	2.10e,d**b	0.67h	2.01r,s***
400	20	50	1	0.76y	2.42b,a**	0.72h	2.57p***
400	40	20	1	0.57y	2.35b,a,c*	0.61h	2.35q**
400	40	50	1	0.56y	2.14e,d,c*	0.71h	2.10r**
600	20	20	1	0.57y	2.23b,d,c	0.75h	2.13r**
600	20	50	1	0.67y	2.17e,d,c	1.13g,h	1.85s**
800	20	20	1	0.73y***	2.45a**	0.64h**	2.48p,q***
800	20	50	1	1.46z***	2.19e,d,c**	1.42g**	2.10r***
				SE = 0.21	SE = 0.14	SE = 0.27	SE = 0.10
400	60	20	3	14.86d***	1.02b	5.11g***	1.41n,o
400	60	50	3	36.50c***	0.95b	8.40f***	1.35o
600	40	20	3	6.08e	1.48a	2.91h*	1.80m*
600	40	50	3	9.99e	1.37a	4.03g*	1.58m,n*
				SE = 4.30	SE = 0.10	SE = 0.59	SE = 0.11
600	60	20	6	37.65e***	0.32b	10.44j*	0.69r
600	60	50	6	49.18d***	0.32b	14.13k*	0.81r,q
800	40	20	6	13.84g**	0.86a***	5.51h	1.34p***
800	40	50	6	20.59f**	0.50b***	6.84h	0.92q***
800	60	20	6	46.51d**	0.37b	13.37k	0.70r
800	60	50	6	54.43c**	0.36b	14.50k	0.73r
				SE = 3.54	SE = 0.13	SE = 1.44	SE = 0.07

^a Means followed by the same letters within each data grouping are not significantly different, $P \leq 0.05$ (analyzed using Duncan's multiple range test).

^b Means of samples treated at different holding times (20 and 50 min) having asterisks *, **, or *** are significantly different at $P \leq 0.05$, $P \leq 0.01$, or $P \leq 0.001$, respectively (analyzed using orthogonal comparison).

When considering gluten treated at 400 MPa, 20 and 40°C, both G' and G'' intercepts showed no significant difference (Table I), only the treatment at 400 MPa, 40°C, 50 min, had slightly lower G' and G'' values (Fig. 4) because these data sets were measured at higher stress amplitude than the control gluten. These are also an indication of melting out (Funt Bar-David et al 1975) that might be due to the weakening of noncovalent bonds such as hydrophobic or electrostatic interactions (Heremans 1995, Ledward 1995) as a result of high amounts of proline, glycine, and leucine which are the major contributors to the hydrophobic interactions present in gluten (Hoseney et al 1990, Zayas 1997). Again, there was no evidence of the formation of a new or different rheological system (the shape of the plots remained essentially unchanged). It has been observed, for example, that oligomeric proteins are dissociated by relatively low pressure (<200 MPa), whereas unfolding of single-chain proteins only occurs at >300 MPa (Masson 1992). When gluten samples were subjected to the same pressure (400 MPa) but elevated temperature (60°C), G' and G'' increased considerably, with G' being substantially higher than G'' overall in the measured frequency range. The slopes were also markedly decreased, particularly G' (Table I, Figs. 3 and 4). This suggests increased structuring (enhanced moduli) with increasing temperature and time. Such behavior is a typical of a slightly cross-linked polymer network (Ferry 1980).

For gluten treated at 600 MPa, the G' and G'' data were allocated to three separate stress-amplitude groupings with increasing temperatures of 20–60°C (Table I). The characteristics of gluten treated at 20°C were similar to those treated at 400 MPa, 20 and 40°C, although the G' and G'' intercepts were higher than in the previous plots and had apparently lower $\tan \delta$ values. These might be an indication of a temporarily built-up structure caused by entanglements as molecules loosely entangle each other by hydrogen

bonds (Kaufman et al 1986) without forming crossed loops on the others (Funt Bar-David et al 1975). Hydrogen bond formation is enhanced by high pressure (Messens et al 1997). Gluten pressure-treated at 600 MPa, 60°C, gave G' and G'' intercepts that were both substantially higher than those treated at lower temperatures. Also, the slopes and $\tan \delta$ values were markedly decreased, indicating weak viscoelastic gels were formed (Ross-Murphy 1984). This suggests that high pressure and temperature treatment of gluten produces a very different rheological system to that formed under milder conditions. Heat-set gluten networks appear to be sufficiently close to a rubber-like state for them to be sensitive to changes in cross-link density (Attenburrow et al 1990). For rubber networks, an increase in the cross-link density increases the modulus (in proportion to the reciprocal of the distance between cross-links) (Treloar 1958).

Samples pressure-treated at 800 MPa, 20°C, gave intercepts, especially those treated for 50 min, that were much higher than the others in the same data set (1 mNm) (Table I), suggesting a less liquid behavior and some entanglement on increasing the holding time. These might be due to the formation of hydrogen bonds because glutamine is the most prevalent amino acid in gluten (He et al 1990, Lasztity 1980, Kaufman et al 1986). In addition, electrophoregrams revealed evidence of hydrogen bond formation in the high-pressure-treated gluten samples (Apichartsrangkoon et al 1998). Those pressure-treated at 800 MPa, 40 and 60°C, gave G' and G'' plots in the same grouping (6 mNm), but the intercept values were considerably increased (Table I) and the slopes were much lower. Both G' and G'' showed only limited frequency dependence. These substantial changes again suggest an overall increase in structuring with increasing severity of treatment. The relative changes in the values of the G'' and G' data result in

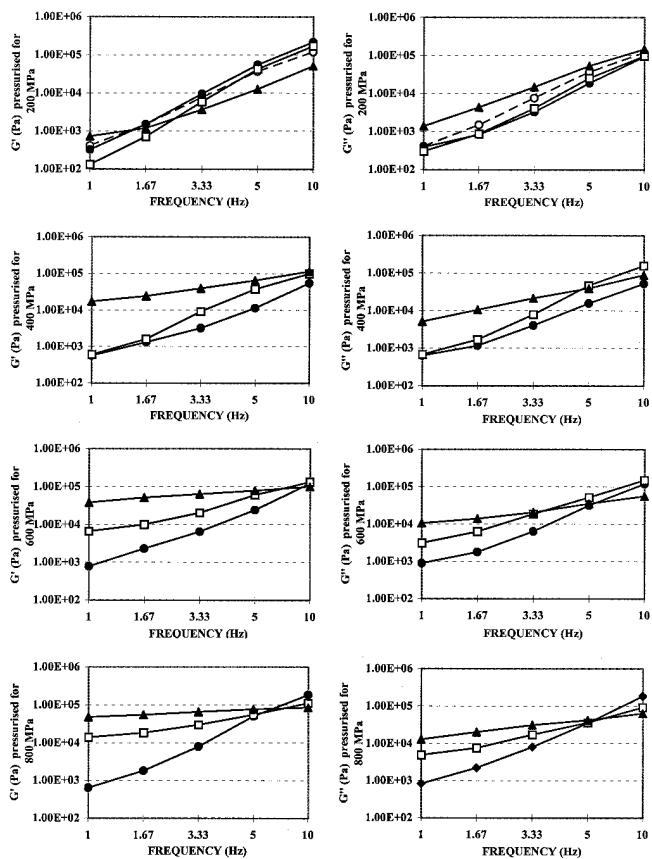


Fig. 3. Initial assessment of storage modulus (G' , left column) and loss modulus (G'' , right column) as a function of frequency for samples pressure-treated at 200–800 MPa for 20 min. ○, Native gluten; ●, gluten treated at 20°C; □, gluten treated at 40°C; ▲, gluten treated at 60°C.

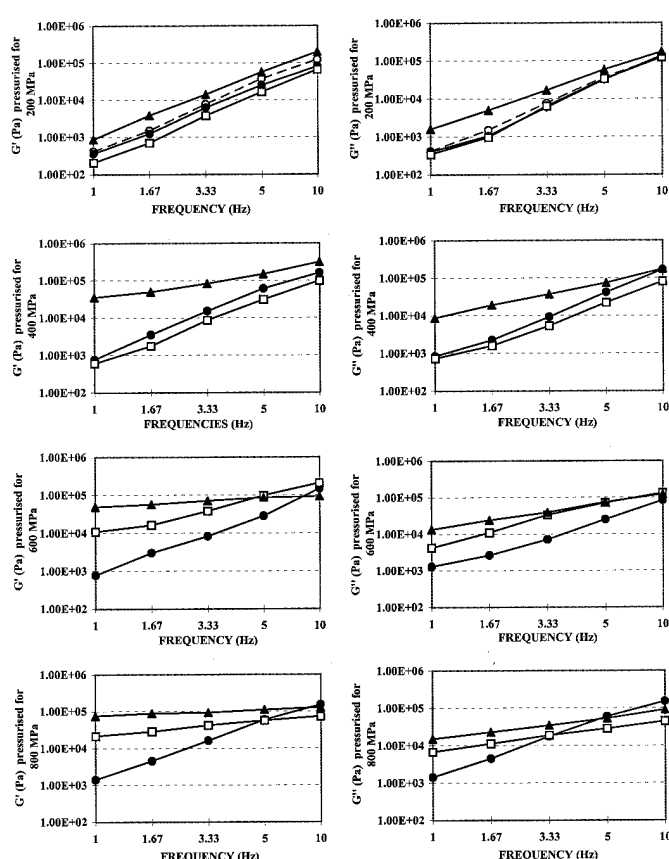


Fig. 4. Initial assessment of storage modulus (G' , left column) and loss modulus (G'' , right column) as a function of frequency for samples pressure-treated at 200–800 MPa for 50 min. ○, Native gluten; ●, gluten treated at 20°C; □, gluten treated at 40°C; ▲, gluten treated at 60°C.

apparent decreases in the $\tan \delta$ values. This suggests that irreversible alterations in the structural properties of the gluten proteins occurred at high pressure and temperature. It is apparent that, for these severe treatments, the effects of temperature as well as pressure helped to create the final structure. Apichartsrangkoon et al (1998) showed that disulfide and hydrogen bonds are probably involved in pressure-induced gluten gels, and it is also known that, in the presence of oxygen, sulfhydryl groups may be oxidized to form disulfide bonds under pressure (Gomes and Ledward 1996). Heat-treatment of hydrated gluten causes increased G' and G'' values, indicating an increase in the number of rheologically effective cross-links (LeGrys et al 1981, Schofield et al 1984). At temperatures of 50–75°C, predominantly glutenin appears to be affected, but at higher temperatures gliadins are also involved (Jeanjean et al 1980, Wrigley et al 1980, Schofield et al 1983).

In general, samples treated at 200 MPa, 20°C, behaved slightly differently from those treated at 800 MPa, 20°C, and showed higher slope values (Figs. 3 and 4). This might be due to the range of pressures used, allowing insufficient time and kinetic energy for the macromolecules to rearrange their structures, but this effect was not evident when high temperature was incorporated. The overall picture is one of increasing elasticity with increasing severity of treatment.

Considering the two holding times, both intercepts and slopes displayed only slight differences (Figs. 3 and 4). However, to clarify these effects, the data were analyzed by orthogonal comparison (Table I). For the samples analyzed at 0.5 mNm, the G'' intercepts of those treated at 200 MPa, 20°C, exhibited some evidence of time-dependent changes. The lack of time-dependence for other data sets measured at 200 MPa, even at relatively high temperatures (60°C), suggests that a threshold pressure may be required to trigger this time-dependent response. Increasing pressure in the data set at 1 mNm showed that, except at 800 MPa, the holding time had more effect on the slopes than the intercepts, in particular on those of G'' . This tends to confirm that melting out of the structure occurs at these pressure-temperature-time regimes. Samples subjected to the highest pressure (800 MPa) and longer holding time (treatment 800 MPa, 20°C, 50 min) gave an extensive increase in structure (Table I).

The samples analyzed at 3 mNm showed that holding time apparently affected the intercepts, indicating that at these pressure-temperature regimes there was still considerable time-dependent structuring going on, especially at the higher temperature (60°C) (treatment 400 MPa, 60°C, 20 and 50 min).

Despite, or perhaps because of, the overall increase in structure observed for the samples analyzed at 6 mNm, the G' intercept data showed highly significant differences due to holding time, but there was some evidence that the slopes were different at the lower temperature (as functions of time and treatments at 800 MPa, 40°C, 20 and 50 min). This increase in time-dependence suggests an overall increase in the cross-linking of an existing system is caused by the pressure-temperature-time regime. It is likely that such pressure and temperature regimes induce unfolding of protein structures, thus permitting subsequent intermolecular interactions between exposed amino acid residues (Masson 1992), and that the number of such interactions is increased at higher pressures and temperatures. Holding time had less effect on the G'' data, except the slopes of treatment 800 MPa, 40°C, 20 and 50 min. In general, G' was higher than the G'' , and the $\tan \delta$ values were lower, indicating an overall increase in the cross-linking of the system (Ferry 1980).

CONCLUSIONS

While this work is in no sense a fundamental study of the pressure and temperature interactions of the gluten system, it represents the next stage in attempting to apply basic rheological measurements to gain an understanding of the complex inter-

actions present in such a food-based system. While there are obvious limitations in the data, such measurements offer a greater insight into the changes occurring in the system under test than either a simple penetrometer or a compression test (Apichartsrangkoon et al 1998).

At mild treatment conditions there is evidence of liquid-like behavior, and the structures of high-pressure-treated gluten samples underwent some melting out. The cross-link density increased with increasing severity of treatment. Also more solid-like behavior could be observed under these conditions. In addition, these chemical cross-links might be due to the formation of disulfide or, to some extent, hydrogen bonding as described by Apichartsrangkoon et al (1998).

Although the effects of pressure and temperature may be synergistic, the high pressure used must have a key role in the changes that are occurring. This work would suggest there is considerable scope for the development of novel textured products by high-pressure-treatment of gluten material

ACKNOWLEDGMENTS

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