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A comparison of the rheological properties of wheat flour dough and its gluten prepared by ultracentrifugation

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Abstract

Ultracentrifugation has been used as a tool for separating dough into different phases and as dough can be described as a bicontinuous system, gluten forms one phase, and starch another. The aim of this study is to investigate the possibility of using ultracentrifugation to extract gluten from dough. By using this method disadvantages such as excess washing, drying and reconstitution of dried gluten (involving a second mixing) were avoided. Gluten samples were obtained by this method (doughs differing in water content from 42.6 to 47.1%) and the rheological properties of dough and the corresponding gluten were studied in frequency sweep. The gluten coming from dough after ultracentrifugation had water contents in the range of 54.2–58.8%. An increase in water content reduced the storage modulus to a greater extent than the loss modulus for the studied dough. The gluten was not affected to the same extent by an increase in water content, as was the dough. The ratios of $G'_{\mathrm{dough}}/G'_{\mathrm{gluten}}$ and $G''_{\mathrm{dough}}/G''_{\mathrm{gluten}}$ approached the value of 1 when the amount of dough water increased. The slope of log G'' versus log ω for gluten (n''_{gluten}) were always higher than n'_{gluten}. For dough the slope of log G'' versus log ω (n''_{dough}) were on the same level or higher than (n'_{dough}). It was concluded that both the frequency dependency and the values of G' and G'' were more or less independent of water content for gluten. On the contrary dough showed a strong dependency of water content in particular for the value of G' and the frequency dependency of G'.

Keywords: Ultracentrifugation; Gluten; Dough; Water content power law parameters; Rheological properties

1. Introduction

Wheat gluten, or vital gluten, is the concentrated protein prepared from wheat flour, usually by washing the starch from flour–water dough (MacRitchie, 1984). Vital wheat gluten is of obvious benefit in increasing the strength of weak flour used in breadmaking. It also plays an important role in improving the tolerance of dough to processing and thereby improving the quality of the finished product. When wheat flour is mixed with water, the two native protein groups present—glutenin and gliadin—combine to form a viscoelastic mass: gluten. Freshly extracted gluten is a wet and gummy mass, which can be dried to form a free-flowing, light-tan colored powder containing 75–80% protein (Magnuson, 1985). Gluten is capable of forming adhesive and cohesive masses, films and three-dimensional networks, all essential to baking performance (Bloksma & Bushuk, 1988).

The common way to prepare gluten from wheat flour dough is either by hand washing or by automatic gluten washing devices. According to MacRitchie (1985), the use of 200 ml of water per 100 g flour and five separate washes can give gluten of about 70% protein content (MacRitchie, 1985). Further washes will produce higher-grade gluten, i.e. with a higher protein content, but this is a disadvantage because of the larger volumes of water that need to be removed. Although higher grades are obtained with defatted flours than with whole flours, it is usually difficult to achieve glutens with protein contents much >80% (dry weight) (MacRitchie, 1985; Kokelaar, 1994). Some occluded starch granules always remain and cannot be easily removed. Following washing out of gluten, the aqueous suspensions can be collected and centrifuged to produce water soluble (supernatant) and starch (sediment) fractions (Janssen, 1992). All fractions can then be freeze-dried, a technique that has been found to be most valuable for

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preserving the functional properties of the fractions. Janssen (1992) prepared glutens from flour using a small scale Batter process (created by Weegels, Marseille, & Hamer, 1988), which imitates the industrial separation procedure and by which a reasonable amount of flour can be separated in a reproducible way. A factor to be aware of is that a gluten of high quality can be severely damaged during the isolation procedure. Laboratory-prepared gluten almost always shows better 'vitality' than commercial gluten samples (MacRitchie, 1984, 1985). All these methods for separation of gluten are based on manipulating a flour–water dough in an excess of water to separate starch from gluten, and to recovering, refining, and carefully drying each fraction. While precise process control throughout is essential to producing quality gluten, the drying step is particularly important (Janssen, 1992; MacRitchie, 1984).

Wheat flour dough can be characterized as a viscoelastic material, combining the properties of a Hookean solid with those of a non-Newtonian viscous fluid (Faubion & Hoseney, 1990). The rheological properties of wheat flour dough are largely governed by the contribution of starch, protein and water. Small deformation, oscillatory, shear measurements have been used for several years in fundamental, non-destructive rheological characterization of wheat flour dough (Hibberd, 1970; Hibberd & Parker, 1975; Tsiami, Bot, & Agterof, 1997a,b. The magnitude of the dynamic moduli G' and G'' is strongly affected by the composition and the processing of the dough (Campos, Steffe, & Ng, 1997; Menjivar, 1990; Navickis, Anderson, Bagley, & Jasberg, 1982). Rheological studies of dough prepared from different wheat qualities have shown that dynamic measurements are affected by starch–starch, starch–protein and protein–protein interactions (Larsson & Eliasson, 1997; Petrofksy & Hoseney, 1995).

Knowledge of both the viscous and elastic properties is necessary for quality control, for understanding of processes such as baking and extrusion, and for elucidation of the interactions that occur among dough components. Gluten is largely responsible for the viscoelastic properties of flour-based doughs, and also the dynamic properties of rehydrated gluten samples. Dynamic testing of gluten and dough has been reported by several authors (Cumming & Tung, 1977; LeGrys, Booth, & Al-Baghdadi, 1981). An obstacle in performing rheological measurements on gluten is of course to prepare the gluten from dough. Ultracentrifugation has been used as a tool for separating dough into different phases and dough can be described as a bicontinuous system, where gluten forms one phase, and starch the other (Larsson & Eliasson, 1996). The aim of this study is to investigate the possibility of using ultracentrifugation to extract gluten from dough. Gluten samples were obtained by this method (from doughs differing in water content) and the rheological properties of dough and the corresponding gluten were studied in frequency sweeps.

2. Materials and methods

2.1. Flour

One wheat flour of medium baking quality (Kosack, a Swedish winter wheat, harvested in 1999) was selected for this study. The flour was milled in a Quadrumat Senior Mill to an extraction rate of 65% (Svalöf Weibull AB, Svalöv, Sweden). Chemical analysis of the flour gave the following composition on dry basis (w/w): protein 8.0% (N × 5.7), ash 0.42%, water content 14.4%, starch content 85.9% and damaged starch 4.4% (American Association of Cereal Chemists, 1994). Falling number was 333s.

2.2. Dough mixing

Wheat flour doughs were mixed in a 10 g farinograph bowl (Brabender Do. Corder, OHG, Duisburg, Germany). Flour (10 g) was mixed with distilled water to give doughs with water contents of 39.5, 42.6, 44.5, 45.5, 46.5 and 47.1% (w/w), respectively. Mixing was performed at 30 °C, 60 rpm, for 10 min. We have chosen to use a well-known mixer (Brabender farinograph), and a fixed mixing time while the water content was varied. The same approach has been used by others (e.g. Masi, Cavella, & Sepe, 1998). At least four doughs were mixed at each water content and used for ultracentrifugation and rheological tests.

2.3. Ultracentrifugation of dough

The dough sample was placed in a test tube with a diameter of 10 mm and a height of 60 mm. The doughs were centrifuged immediately after the mixing. Doughs were centrifuged for 1 h at 100,000*g* (LE 80K OPTIMA, Beckman, USA). When the wheat flour dough was subjected to ultracentrifugation, it separated into maximum five fractions: liquid, gel, gluten, starch and unseparated phase (Larsson & Eliasson, 1996). After ultracentrifugation of the dough, the liquid and gel phases were discarded and the gluten phase was carefully taken out with the help of a spatula. It must be noted that this is a critical stage for the preparation of the gluten phase. The time spent for this treatment of the gluten is critical because water evaporates during the handling of the ultracentrifuged gluten. To determine the water content, the gluten phase was dried for 1 h at 130 °C. Four replicates were made for each sample for drying. The water content of the gluten was obtained with a coefficient variation of $<3.2\%$.

2.4. Dynamic rheological measurements

By using oscillatory measurements the deformation can be kept so small that the structure of the material is not irreversibly altered during measurement. Thus, rheological parameters provide information on the structure of the material (Bloksma & Bushuk, 1988). In these tests a sinusoidally stress is applied to a test-piece and the resulting strain is measured. G' is defined as the elastic, or storage, modulus, and G'' is referred to as the viscous, or loss modulus. Dynamic oscillatory measurements were performed on a controlled stress rheometer (RTI Rheo-Tech International Ltd, Lund, Sweden). Its software was used to calculate G' and G''. All measurements were conducted at 25 °C using 15 mm diameter parallel plate geometry with a gap between the plates of 2 mm. Dough was removed from the farinograph bowl, and placed between the plates of the rheometer. In the case of gluten, the freshly prepared gluten phase was removed from the tube after ultracentrifugation, and placed in the rheometer. In order to prevent drying, a thin layer of silicon oil was spread over the dough or gluten surfaces exposed to air. Before starting any measurements, the sample (dough or gluten) was held at rest for 30 min to allow relaxation of stresses generated during sample loading. Dynamic frequency sweep tests of the doughs and glutens were carried out in the linear viscoelastic region. A frequency range of 0.1–10 Hz was applied. Values of G' and G'' measured at 1 Hz in the oscillation frequency sweep were taken as representative of all the data obtained, for easier comparison of the results. The value of stress was 2.5 Pa. The linear region varied, and was up to 6.5 Pa at the lowest water content of dough (42.6%). The applied strain was 0.001. The experiments were performed in tetraplicates. Values reported are the means of these determinations. The coefficients of variation in measured values were lower than 15% for doughs and glutens.

2.5. Calculation of power law parameters

In the present study power law constants (slopes), relating G' and G'' to frequency, were calculated using the following equations

$$G' = G'_0 \omega^{n'} \quad (1)$$

$$G'' = G''_0 \omega^{n''} \quad (2)$$

where G' and G'' represent the storage modulus and the loss modulus, respectively, n', n'' are the corresponding slopes, ω is frequency and G'_0, G''_0 are the intercepts of the power law model for frequency sweeps.

3. Results and Discussion

3.1. Ultracentrifugation of dough

During the dough mixing process, the water added becomes distributed between the flour components (pentosans, gluten, lipids, starch), and the remainder forms the liquid phase. The structural properties of these components and their water-binding capacity, coupled with the duration and intensity of the mixing, will determine handling properties and the ultimate bread quality. The separation of Kosack doughs at 39.5–47.1% water content is illustrated in Table 1. It seems that the amount of the gluten phase is increased as the dough water content is increased. At high water contents, a separation of the dough into liquid, gel, gluten, starch and unseparated phases was observed. At the water content of 39.5% the dough did not separate. The volume of the liquid phase increased as the water content of the dough increased from 42.6 to 47.1%, whereas the volume of the gel phase was not affected. The starch fraction increased when the water content increased and the gluten fraction seemed to increase somewhat. This trend was similar to earlier results on cultivar Kosack (Larsson & Eliasson, 1996).

When the water content was reduced, more unseparated dough was found at the bottom of the test tube. The volume of the gluten phase for the flour Kosack was lower in the present study (Fig. 1) than the volume reported earlier (Larsson & Eliasson, 1996). This is most likely due to the fact that the protein content (8%) of the flour from 1999 used in this study was lower than the protein content of the flour (11%) from 1995 used in the previous study (Larsson & Eliasson, 1996). Although the protein content of the flours differed, the water content of the gluten phase seemed not to be affected significantly by the year (Fig. 1). In both studies the water content of the gluten resulting after ultracentrifugation decreased when the dough water content increased.

Table 1
Volume fractions of separated phases (%)

Water content						
Separated phase	42.6	43.5	44.8	45.5	46.5	47.1
Liquid	8.8 ± 0.0	16.0 ± 0.1	16.0 ± 0.2	15.9 ± 0.1	17.5 ± 0.1	19.5 ± 0.2
Gel	7.2 ± 0.1	6.4 ± 0.2	6.1 ± 0.1	6.0 ± 0.3	6.4 ± 0.2	5.8 ± 0.1
Gluten	10.0 ± 0.2	12.6 ± 0.3	11.4 ± 0.2	12.2 ± 0.2	13.3 ± 0.2	13.5 ± 0.1
Starch	44.3 ± 0.3	53.3 ± 0.2	56.1 ± 0.4	56.1 ± 0.3	57.1 ± 0.2	57.4 ± 0.2
Unseparated dough	29.5 ± 0.2	11.6 ± 0.3	12.3 ± 0.4	9.8 ± 0.3	5.5 ± 0.2	3.6 ± 0.3

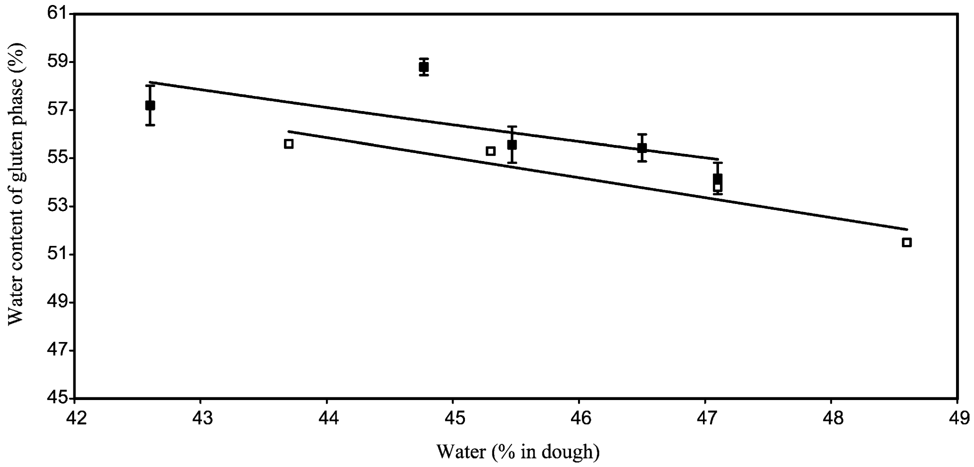

Fig. 1. Water content of the gluten phase from the Kosack wheat flour dough for the years 1999 and 1995; (■):1999 (present work), (□):1995 Larsson and Eliasson (1996).

3.2. Effect of water content on the rheological properties of gluten and dough

Rheological testing has the advantage that measurement of rheological parameters can give indication of the structure of the material being measured. It should be noted that the present gluten measurements were performed on samples derived from the corresponding dough without any other treatment than the ultracentrifugation. The effect of water content on the rheological properties of dough and the corresponding gluten was studied, and G' and G'' as a function of water content are shown for both dough and its corresponding fresh gluten in Fig. 2.

3.2.1. Effect of water content on the rheological properties of gluten

Fig. 2 shows that the values of G' and G'' for gluten decreased slightly with an increase in water content, although G'' was not affected to the same extent as G'. The data were fitted to a linear relationship for G' and G'' versus water content ($R^2 = 0.85$ and $R^2 = 0.60$, respectively). The gluten with the highest water content (58.8%) resulted in the lowest value for G' and the gluten with the lowest water content gave the highest value of G', as expected. The results obtained for the gluten phase recovered by ultracentrifugation confirm the results obtained in other studies, where gluten samples have been subjected to different degrees of manipulation. In these studies it was found that G' decreased with increasing water content of gluten (Attenburrow, Barnes, Davies, & Ingman, 1990; Dreese, Faubion, & Hoseney, 1988; Janssen, 1992). Attenburrow et al. (1990) reported values of the storage modulus of gluten in the range of 2000–8000 Pa. Dreese et al. (1988) reported that G' of gluten increased when the water content decreased in the range 46–61%, i.e. a much broader range than was studied in the present work.

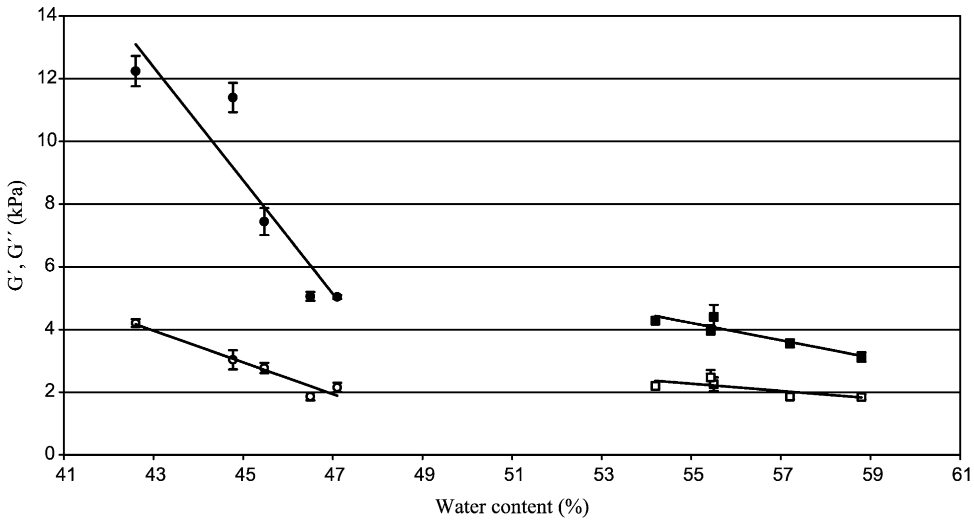

Fig. 2. Storage modulus (G') and loss modulus (G'') for dough and gluten, respectively, at different water contents. Data were obtained at a frequency of 1 Hz. G' for gluten (■), G'' for gluten (□), G' for dough (●), G'' for dough (○).

Dreese and Hoseney (1990) suggested that the differences in rheological properties between commercially produced gluten and hand washed, lyophilized gluten prepared in the laboratory were caused principally by differences in the drying procedure. The results from the present work can be compared with results from other works with different gluten preparation methods. The present results are similar to the results of Smith, Smith, and Tschoegl (1970) although they used commercial gluten. It seems that the ultracentrifugation of dough does not change the rheological properties of the gluten.

Although different wheat flours and thus different gluten qualities have been used in different studies, it is still possible to draw some conclusions when comparing the studies. A decrease in G' and G'' with increasing water contents of gluten has been observed in most studies (Fig. 2 in the present study and Dreese et al., 1988) with more or less strong dependence of G' and G'' on water content. It seems that using the method of ultracentrifugation it is possible to produce gluten with similar rheological behaviour as can be produced by other methods (e.g. hand washing).

Another method of gluten preparation involved slurring the flour with water (10:1, water–flour) and then centrifuging (Schroeder & Hoseney, 1978). In this case ultracentrifugation gives an advantage, as we can separate and study fresh gluten that have been mixed under exactly the same conditions as the corresponding dough. The gluten thus is produced by this method without rehydration and mixing of a dried powder.

3.2.2. Effect of water content on the rheological properties of dough

Fig. 2 shows that the values of G' and G'' for dough decreased as the water content increased from 42.6 to 47.1% (w/w). The data were fitted to a linear relationship for G' and G'' versus water content ($R^2 = 0.87$ and $R^2 = 0.93$, respectively). The trend that both G' and G'' decreased as water content of dough increased was in agreement with earlier studies (Dreese et al. 1988; Hibberd, 1970; Hibberd & Parker, 1975; Janssen, 1992; Kokelaar, 1994; Mani, Trägårdh, Eliasson, & Lindahl, 1992). The values of G' and G'' for Kosack doughs varied from 5 to 12.2 kPa and from 4.2 to 2.15 kPa, respectively. The values from the present work were in the same range as the values from the previously mentioned works. A comparison of results obtained for wheat flour doughs (Hibberd, 1970; Hibberd & Wallace, 1966; Masi, Cavella, & Sepe, 1998; Navickis et al. 1982; Smith et al., 1970) is complicated for several reasons. First, the wheat varieties differ among these studies. Second, the water content of the doughs did not cover the same range. For doughs, added complexities result from the unknown distribution of water between the gluten and starch phases, and the possible presence of free water (Smith et al., 1970).

3.3. A comparison of the rheological properties of dough and gluten

The water content of the gluten (coming from dough by ultracentrifugation) was higher than that of the dough in the range of water content studied (Fig. 1). When the water content of the dough increased from 42.6 to 47.1%, the water content of the gluten coming from dough after ultracentrifugation was in the range of 54.2–58.8% (Fig. 2). A comparison is made of the values of the rheological parameters of the doughs and their isolated wet gluten for all water contents. G' was greater than G'' for both dough and gluten, independent of the water content. For the studied gluten and dough, the range of water content varied 4.6 and 4.5%, respectively. In conclusion, both G' and G'' were more sensitive to water content for dough than for gluten. It is interesting to notice that both G' and G'' for dough approached the values of G' and G'' for gluten when the dough water content increased. This means that at a dough water content of 47.1% more or less the same values of the moduli were observed for the dough and its corresponding gluten with a water content of 54.2%.

The ratio of G' for dough and G' of the corresponding gluten (G'_{dough}/G'_{gluten}) is given for the investigated water contents in Table 2. The corresponding ratios for G'' are also given. The ratio G'_{dough}/G'_{gluten} decreased as the water content of dough increased, because of the more rapid decrease in G' for dough compared to G' for gluten. The same trend of decrease appeared for the ratio G''_{dough}/G''_{gluten}. The observed ratio for G' was higher than 1 for all water contents while the ratio for G'' was lower than 1 at the highest dough water contents (46.5 and 47.1%). Consequently, an increase of the water content of dough caused a change in the ratio of G'_{dough}/G'_{gluten} and G''_{dough}/G''_{gluten} and then these ratios approached the value of 1. In this case, the dough and gluten show the same rheological properties (G', G'') although the water content of dough and gluten differed.

3.4. Power law constants for dough and gluten

Frequency sweeps of G' and G'' were determined for both dough and gluten at 25 °C. The magnitude of the slope of

Table 2
The ratios between moduli of dough and the corresponding gluten at different dough water contents. Data obtained at a frequency of 1 Hz

Water content of dough (%)	Water content of separated gluten (%)	G'_{dough}/G'_{gluten}	G''_{dough}/G''_{gluten}
42.6	57.2	3.44	2.25
44.5	58.8	3.65	1.63
45.5	55.5	1.68	1.22
46.5	55.4	1.27	0.75
47.1	54.2	1.17	0.97

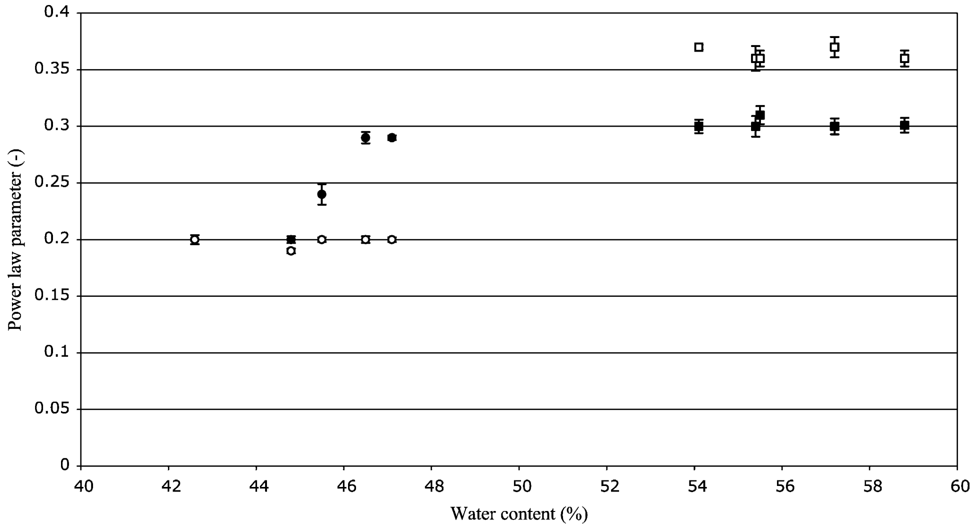

Fig. 3. Power law parameters (n' and n'') of the frequency sweep for dough and gluten in the range of water contents 42.6–58.8%. Error bars show standard deviation from mean value of at lest four measurements. Power law parameters, n' of gluten (■) and n'' of gluten (□), for n' of dough (●), for n'' of dough (○).

log G' against log ω provides useful information about the structure of the biopolymer (Ross-Murphy, 1995). Gels can be characterized as 'true gels' when log G' versus log ω or log G'' versus log ω plots give nearly zero slopes (Ross-Murphy, 1984), while for 'weak gels' and highly concentrated solutions the plots have positive slopes. According to Ferry (1980), when the slope of log G' vs. log ω (n') has a value approaching 0, the material behaves like a rubbery material, while a liquid flowing material has a slope (n') approaching 2. When a 3D network is present we expect the slope to be near zero (Gabriele, de Bruno, & D'Antona, 2001; Kokini, Cocero, Madeka, & de Graaf, 1994).

In the present work, G' was greater than G'' for both dough and gluten at all water contents. Fig. 3 gives the values of the slopes as calculated from the frequency sweeps. Linear regression of log G' and log G'' versus log ω data showed that the resulting values of n' and n$''$ for both dough and gluten were low (<0.4) for all the studied water contents, indicating the existence of a 3D network. However, these networks showed to have different responses to water. The values of n' for dough (n'_{dough}) varied from 0.20 to 0.29 as the water content was increased. On the other hand, the n'-values of gluten were independent of water content ($n'_{\text{gluten}} \approx 0.30$) and on the same level as n'_{dough} determined at the highest dough water content (Fig. 3). Increasing values of n', such as those observed for dough when water content is increased, are considered to indicate an increasing fraction of uncross linked material (Kokini et al., 1994). Moreover, the slope of log G'' versus log ω for dough (n''_{dough}) was on the same level or higher than n'_{dough}. For gluten the slope of log G'' versus log ω (n''_{gluten}) was always higher than n'_{gluten}. This indicates that G'' increased faster than G' in the frequency sweep. Thus, the frequency spectra of gluten correspond to the transition region, whereas the frequency spectra of dough correspond to the plateau (rubbery) region. A greater frequency dependence for G'' compared with G' ($n'' > n'$) have been reported also for commercial vital gluten in the study by Redl, Morel, Bonicel, Guilbert, and Vergnes (1999). However, the slope values were slightly higher ($n'' = 0.4$ and $n' = 0.33$) than those reported here for fresh gluten recovered by ultracentrifugation (Fig. 3).

Power law parameters (n' and n'') for dough in the same range as we have found in the present study have been reported previously. Frequency dependence have been reported for a soft white winter wheat and a hard red winter wheat at the dough water content of 43% where $n' = 0.28$ and $n'' = 0.27$, and $n' = 0.23$ and $n'' = 0.22$, respectively (Schluentz, Steffe, & Ng, 2000). In earlier studies by Bohlin and Carlson (1980) and by LeGrys et al. (1981) similar frequency dependence for G' ($n' = 0.27$ and $n' = 0.29$) were reported for dough. The present study also confirms the increasing frequency dependence for G' at higher dough water contents that was observed for some of the flours studied and reported on in the work by Navickis et al. (1982). The observation by Navickis et al was in contradiction to the earlier study by Hibberd where the frequency dependence of wheat flour dough was found unaffected by dough water content (Hibberd, 1970). Moreover, an increase in n' with increasing protein content of the dough have been reported by Smith et al. (1970).

3.5. Shift factors for dough and gluten

An attempt was made to obtain a unique mastercurve for dough and gluten. One advantage of the method is that the range of frequencies is extended beyond those available experimentally. Shift factors can be used to shift the frequency sweep on the *x*-axis so that the behaviour

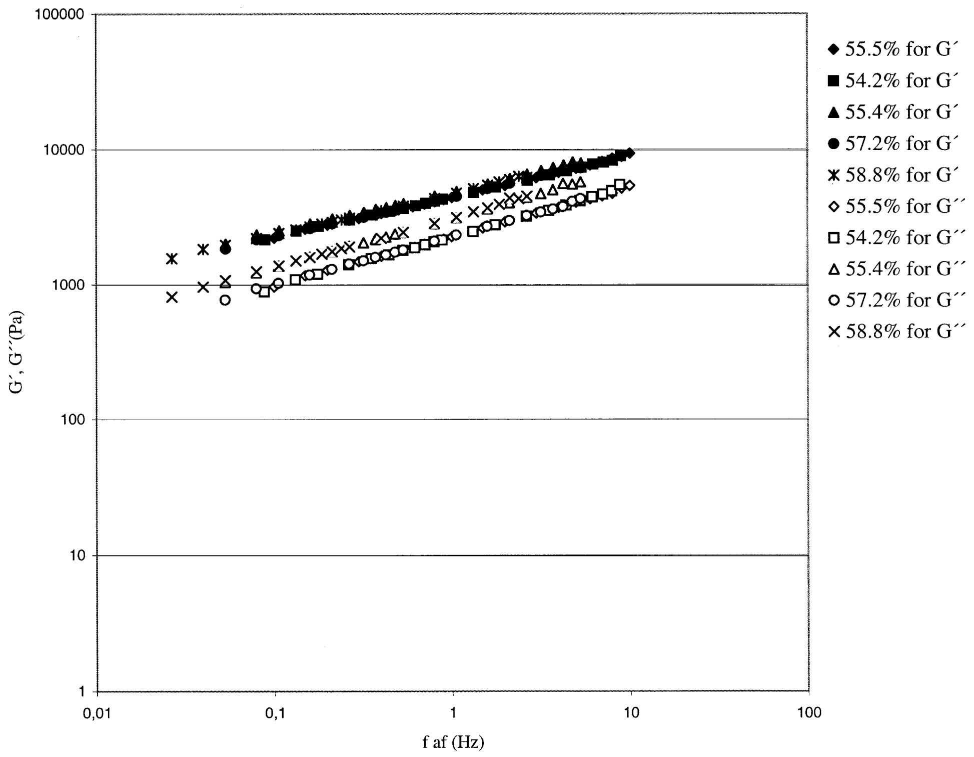

Fig. 4. Master curves of storage modulus (G') and loss modulus (G'') for gluten with different water content (55.5–58.8%). The gluten with 55.5% is the reference gluten.

at lower and higher frequencies can be studied. Figs. 4 and 5 give the superimposed curves of storage modulus and loss modulus for dough and gluten, respectively. According to Figs. 4 and 5, superposition works well for the storage modulus of dough and gluten, but does not give a satisfactory fit for the loss modulus neither of dough or gluten. According to Ferry (1980), superposition can theoretically be applied for both simple and more complex materials. Superposition for concentration has been illustrated for measurements in the transition region. However, it is not obvious that the method is successfully applied in the plateau and terminal region (Ferry, 1980). Failure of the superposition may indicate physicochemical changes in the studied material (Redl et al., 1999). Thus, successful superposition for dough and gluten would mean that similar molecular processes are taking

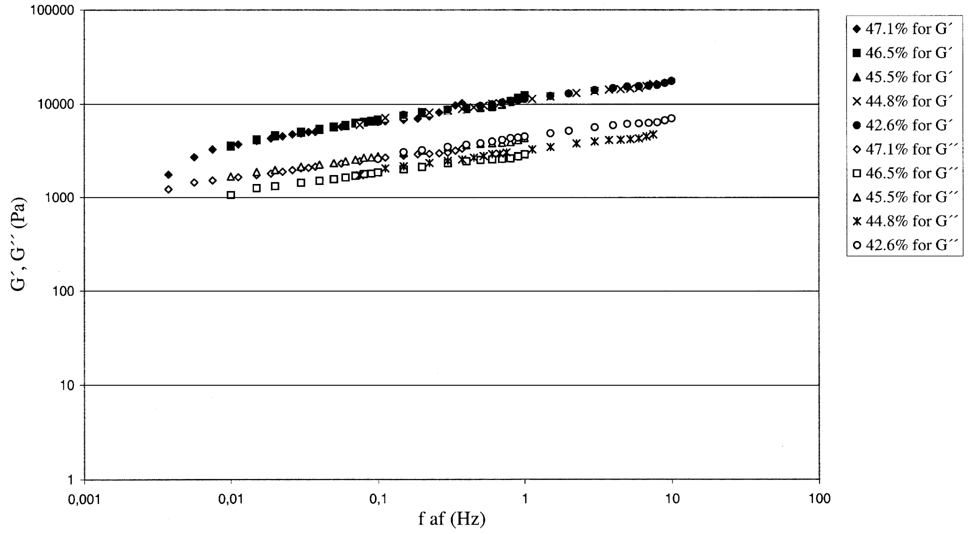

Fig. 5. Master curves of storage modulus (G') and loss modulus (G'') for doughs with different water content (42.6–47.1%). The dough with 42.6% is the reference dough.

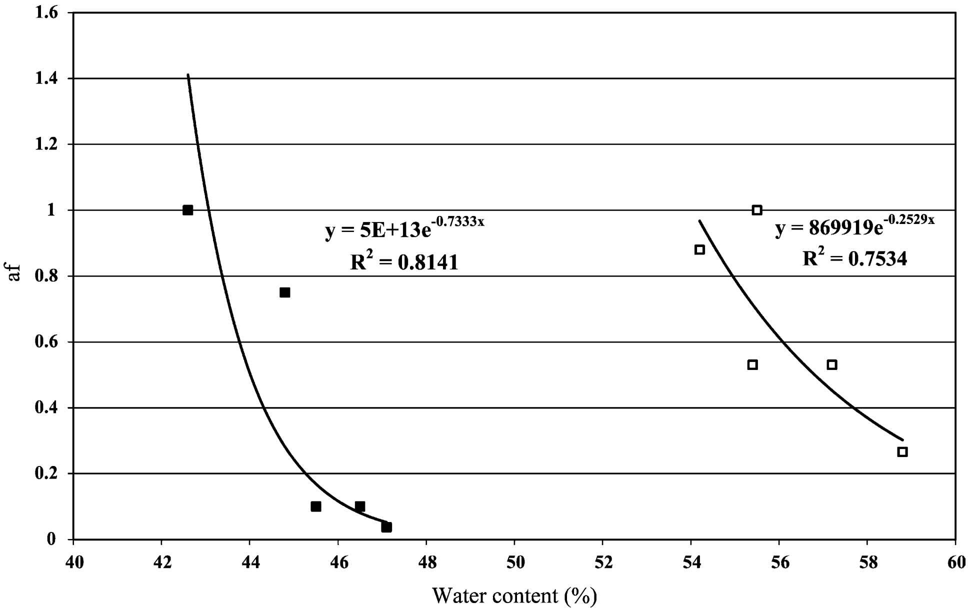

Fig. 6. Shift factor af as a function of dough water content and gluten water content. Shift factors of dough (■), shift factors for gluten (□).

place at different water contents and at different frequencies as suggested by Lopez da Silva, Goncalves and Rao (1994). The shift factors (af) for the superposition in Figs. 4 and 5 are presented as a function of water content in Fig. 6. An exponential dependency of water content for the shift factors is shown, which is stronger for dough than for gluten (Fig. 6). This may indicate that the dilution effect by water is stronger for dough than for gluten. Fu, Mulvaney, & Cohen (1997) showed the same effect for fat added on different levels.

4. Conclusions

The use of ultracentrifugation as a method for gluten preparation for further rheological studies was demonstrated. By this method disadvantages such as excess washing, drying and reconstitution of dried gluten (involving a second mixing) were avoided. The amount of water in the dough affected the water content of the gluten prepared from the dough, and, consequently, its rheological response. All the doughs and glutens behaved as viscoelastic materials at all the investigated water contents. An increase in water content reduced the storage modulus to a greater extent than the loss modulus. Gluten was only moderately affected by an increase in water content. Similarly, the different response to an increase in water content was observed for the frequency dependence of dough (n'_{dough} and n''_{dough}) and gluten (n'_{gluten} and n''_{gluten}). A strong effect of increasing the water content was observed for n'_{dough}, while n''_{dough}, n'_{gluten} and n''_{gluten} were unaffected. The frequency dependence of G'' for dough (n''_{dough}) was on the same level or lower than n'_{gluten}, where as n''_{gluten} was always higher than n'_{gluten}. This indicates that the frequency spectra of gluten represent the transition region, whereas the frequency spectra of dough belong to the plateau region.

It can be concluded that gluten could not be diluted in order to influence its rheological behaviour in the range of water contents investigated. On the other hand, a dilution of wheat flour dough obviously had a weakening effect on the rheological parameters investigated.

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References

American Association of Cereal Chemists (1994). *Approved Methods of the AACC* (8th ed) (*Method 54-21; Method 76-30A*), St Paul, MN: The American Association of Cereal Chemists.

Attenburrow, G., Barnes, D. J., Davies, A. P., & Ingman, S. J. (1990). Rheological properties of wheat gluten. *Journal of Cereal Science*, *12*, 1–14.

Bloksma, A., & Bushuk, W. (1988). Rheology and chemistry of dough. In Y. Pomeranz (Ed.), (*Vol. 2*) (pp. 131–218). *Wheat: Chemistry and technology, Pomeranz*, MN: The American Association of Cereal Chemists.

Bohlin, L., & Carlson, T. L. G. (1980). Dynamic viscoelastic properties of wheat flour dough: dependence on mixing time. *Cereal Chemistry*, *57*, 174–177.

Campos, D. T., Steffe, J. M., & Ng, P. (1997). Rheological behaviour of undeveloped and developed dough. *Cereal Chemistry*, *74*, 489–494.

Cumming, D. B., & Tung, M. A. (1977). Modification of the ultrastructure and rheology of rehydrated commercial wheat gluten. *Canadian Institute Food Science Technology Journal*, *10*, 109–119.

Dreese, P. C., Faubion, J. M., & Hoseney, R. C. (1988). The effect of different heating and washing procedures on the dynamic rheological properties of wheat gluten. *Cereal Foods World*, *33*(2), 225–228.

Dreese, P. C., & Hoseney, R. C. (1990). The effect of water-extracted solubles from gluten on its baking and rheological properties. *Cereal Chemistry*, *67*(4), 400–404.

Faubion, J. M., & Hoseney, R. C. (1990). The viscoelastic properties of wheat flour doughs. In H. Faridi, & J. M. Faubion (Eds.), *Dough rheology and baked product texture* (pp. 29–66). New York: Van Nostrand Reinhold.

Ferry, J. D. (1980). *Viscoelastic properties of polymers*. New York: Wiley.

Fu, J., Mulvaney, S. J., & Cohen, C. (1997). Effect of added fat on the rheological properties of wheat flour doughs. *Cereal Chemistry*, *74*(3), 304–311.

Gabriele, D., de Bruno, C., & D'Antona, P. (2001). A weak gel model for foods. *Rheologica Acta*, *40*, 120–127.

Hibberd, G. E. (1970). Dynamic viscoelastic behaviour of wheat flour doughs. *Rheologica Acta*, *9*, 487–500.

Hibberd, G. E., & Parker, N. S. (1975). Measurements of the fundamental rheological properties of wheat flour doughs. *Cereal Chemistry*, *52*, 1r–23r.

Hibberd, G. E., & Wallace, W. J. (1966). Dynamic viscoelastic behaviour of wheat flour doughs, Part I: Linear aspects. *Rheologica Acta*, *5*(3), 193–198.

Janssen, A (1992). *Obelisk and Katepwa wheat gluten, A study of factors determining bread-making performance*. PhD thesis, Wageningen Agricultural University.

Kokelaar, J.J (1994). *Physics of breadmaking*. PhD thesis, Wageningen Agricultural University.

Kokini, J. L., Cocero, A. M., Madeka, H., & de Graaf, E. (1994). The development of state diagrams for cereal proteins. *Trends in Food Science Technology*, *5*, 281–288.

Larsson, H., & Eliasson, A.-C. (1996). Phase separation of wheat flour dough studied by ultracentrifugation and stress relaxation. I. Influence of water content. *Cereal Chemistry*, *73*(1), 18–24.

Larsson, H., & Eliasson, A.-C. (1997). Influence on the starch-granule surface on the rheological behaviour of wheat flour dough. *Journal of Texture Studies*, *28*(5), 487–501.

LeGrys, G. A., Booth, M. R., & Al-Baghdadi, S. M. (1981). The physical properties of wheat proteins. In Y. Pomeranz, & L. Munck (Eds.), *Cereals: A renewable resource. Theory and practice* (pp. 243–264). St Paul, Minnesota: AACC.

Lopez da Silva, J. A. L., Goncalves, M. P., & Rao, M. A. (1994). Influence of temperature on dynamic and steady shear rheology of pectin dispersions. *Carbohyrate Polymers*, *23*, 77–87.

MacRitchie, F. (1984). Baking quality of wheat flours. *Advances in Food Research*, *29*, 201–277.

MacRitchie, F. (1985). Studies of the methodology for fractionation and reconstitution of wheat flours. *Journal of Cereal Science*, *3*, 221–230.

Magnuson, K. M. (1985). Uses and functionality of vital wheat gluten. *Cereal Foods World*, *30*, 179–181.

Mani, K., Trägårdh, C., Eliasson, A. C., & Lindahl, L. (1992). Water content, water soluble fraction, and mixing affect fundamental rheological properties of wheat flour doughs. *Journal of Food Science*, *57*(5), 1198–1200. see also 1209.

Masi, P., Cavella, S., & Sepe, M. (1998). Characterization of dynamic viscoelastic behaviour of wheat flour doughs at different moisture contents. *Cereal Chemistry*, *75*(4), 428–432.

Menjivar, J. A. (1990). Fundamental aspects of dough rheology. In H. Faridi, & J. M. Faubion (Eds.), *Dough rheology and baked product texture* (pp. 1–28). NewYork: AVI, Van Nostrand Reinhold.

Navickis, L. L., Anderson, R. A., Bagley, E. B., & Jasberg, B. K. (1982). Viscoelastic properties of wheat flour doughs. Variation of dynamic moduli with water and protein content. *Journal of Texture Studies*, *13*, 249–264.

Petrofksy, K. E., & Hoseney, R. C. (1995). Rheological properties of dough made with starch and gluten from several cereal sources. *Cereal Chemistry*, *72*(1), 53–58.

Redl, A., Morel, M. H., Bonicel, J., Guilbert, S., & Vergnes, B. (1999). Rheological properties of gluten plasticized with glycerol: Dependence on temperature, glycerol content and mixing conditions. *Rheologica Acta*, *38*(4), 311–320.

Ross-Murphy, S. B. (1984). Rheological methods. In H. W. S. Chan (Ed.), *Biophysical methods in food research* (pp. 138–199). London: Blackwell Scientific Publications.

Ross-Murphy, S. B. (1995). Structure–properties relationships in food biopolymer gels and solutions. *Journal of Rheology*, *39*, 1451–1463.

Schluentz, E. J., Steffe, J. F., & Ng, K. W. P. (2000). Rheology and microstructure of wheat dough developed with controlled deformation. *Journal of Texture Studies*, *31*, 41–54.

Schroeder, L. F., & Hoseney, R. C. (1978). Mixograph studies. II. Effect of activated double-bond compounds on dough-mixing properties. *Cereal Chemistry*, *55*(3), 348–360.

Smith, J. R., Smith, T. L., & Tschoegl, N. W. (1970). Rheological properties of wheat doughs. III. Dynamic shear modulus and its dependence on amplitude, frequency and dough composition. *Rheologica Acta*, (9), 239.

Tsiami, A., Bot, A., & Agterof, W. G. (1997a). Rheology of mixtures of glutenin subfractions. *Journal of Cereal Science*, *26*(3), 279–287.

Tsiami, A., Bot, A., & Agterof, W. G. (1997b). Rheological properties of glutenin subfractions in relation to their molecular weight. *Journal of Cereal Science*, *26*(1), 15–27.

Weegels, P. L., Marseille, J. P., & Hamer, R. J. (1988). Small scale separation of wheat flour in starch and gluten. *Starch*, *40*(9), 342–346.