Influence of Added Starch on Mixing of Dough Made with Three Wheat Flours Differing in High Molecular Weight Subunit Composition: Rheological Behavior

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ABSTRACT

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The effect of mixing time (6 and 20 min) and starch content were studied on doughs prepared with three wheat flours differing in high molecular weight subunit composition. Rheological measurements were performed in dynamic oscillation: frequency and strain sweeps, stress relaxation, and in large deformation viscosity measurements. The flours were diluted with starch to cover flour protein contents of 10–15%. Water was added to keep the starch-water ratio constant when doughs were prepared with different protein contents. By increasing the starch content of the doughs, the rheological properties approached those of a starch-water mixture prepared with the same starch-water ratio as in the dough. The effect of the starch granules was reinforced by prolonged mixing. This may explain the higher values of the storage modulus and relaxation times observed after 20 min of mixing. Qualities related to gluten properties, appeared more clearly in large deformation viscosity measurements.

From a rheological standpoint, wheat flour dough is a composite system comprising two dispersed filler phases (gas cells and starch granules). The gluten can be considered as a matrix for the fillers (Smith et al 1970), where the ratio of the rheological properties of the matrix and the fillers determines the behavior of the composite (Nielsen 1974). Several studies have demonstrated the effect of both starch and gluten concentration on the rheological behavior at small deformations (Hibberd 1970, Smith et al 1970, Abdelrahman and Spies 1986). It is obvious that both components contribute to the viscoelastic response. When gluten is added to a flour at a constant water level, a greater increase in the storage modulus is observed compared with starch content increase (Abdelrahman and Spies 1986). Such observations may exaggerate the influence of gluten properties on the rheological behavior. An increase in the modulus related to the protein-to-starch ratio is also strongly dependent on the dough water content (Smith et al 1970).

Wheat flour dough can be viewed as a phase-separated system where two continuous aqueous phases coexist due to the water insolubility of the developed gluten. The water-swollen protein (gluten) can be considered as interpenetrated by the starch granules, which are concentrated in a second liquid phase (Eliasson and Larsson 1993). This organization of the dough suggests consequences for the rheological behavior where the dough water content will determine the reinforcement of the fillers (starch) on the matrix (gluten) (Larsson and Eliasson 1996a).

It is generally accepted that a weakening of the gluten takes place when mixing is extended beyond the optimum. This has been explained by a reduction in the molecular weight of the proteins extracted from overmixed dough (Tanaka and Bushuk 1973, Danno and Hoseney 1982). Prolonged mixing, however, often results in an increase in the modulus measured at small deformation (Bohlin and Carlsson 1980, Amemiya and Menjivar 1992, Larsson and Eliasson 1996b). As small amplitude measurements are very sensitive to the material structure, the effect of increased mixing time is most likely related to the dough structure. The increase in storage modulus may also result from an increase in starch-protein interaction after overmixing (Amemiya and Menjivar 1992).

The present study was undertaken to compare the effect of starch, gluten, and mixing time on different rheological measurements under shear: oscillatory frequency and strain sweeps, stress relaxation, and viscosity measurements. The effect of flour protein concentration (10–15%) and mixing time was determined at constant starch-to-water ratios. To evaluate an effect of protein quality, three flours differing in high molecular weight subunit composition were used.

MATERIAL AND METHODS

Material

Three spring wheats with protein contents ranging from 14.9% to 15.2%. were used in the study. The flours, supplied by Svalöf Weibull AB, Landskrona, Sweden, were crosses between W 31169 and Nemares (Johansson and Svensson 1995). The characteristics of the flours (protein content, high molecular weight glutenin subunits, mixograph peak time, and baking performance) are given in Table I. The flours are referred to as 7516, 7531, and 7546. Native wheat starch was obtained from Lyckeby Stärkelsen AB, Kristianstad (protein content 0.3%, N × 6.25, fat content 0.2%).

Methods

Wheat flour doughs were prepared and the farinograph water absorption was determined according to Larsson and Eliasson (1996b). Flour (10 g) was mixed at 30°C with the amount of distilled water according to the farinograph water absorption (Table I). When the flours were diluted with starch, a larger amount of water had to be included to develop doughs of appropriate consistency. The amount of water added was based on the pronounced influence on the stress-relaxation modulus of the starch-water ratio (Larsson and Eliasson 1996b). Therefore the ratio of starch-to-water was kept constant. The starch content of the flours was estimated roughly as the dry flour subtracted by the protein (Table I) and lipid (≈2%) contents. At the farinograph water absorption the estimated starch-to-water ratios (s/w) of the doughs were: 1.02 (7516), 1.04 (7531), and 0.99 (7546). The flours were diluted with starch to develop protein contents of 13% (7531 and 7546) and 10% (all flours), and water was added so the estimated starch-water ratios were constant (Table II). The influence of mixing time was studied by comparing the rheological behavior of the doughs after 6 and 20 min of mixing. At least three doughs were mixed under each set of conditions and used for the rheological tests.

The rheological behavior of the doughs were studied using a rheometer (Bohlin VOR, Metric Analys, Stockholm, Sweden) in four different modes. First, a frequency sweep in the linear region (strain 0.00044) with the plate-plate geometry (15 mm diam., gap

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2 mm) was performed. After this, the same sample was subjected to increasing strain at a frequency of 0.5 Hz. The third measurement was a stress-relaxation test at a strain of 0.006 for which the cone-plate geometry (cone 30 mm diam., cone angle 5.4°, truncation 150 µm) was used. The sample subjected to stress relaxation was given a resting time of 45 min (at 30°C sealed in plastic), while the dough tested in the oscillatory mode only rested for 15 min before it was fixed in the rheometer geometry. Residual stresses were allowed to relax for a minimum of 15 min, before the strain was applied. No effect of resting time (15–60 min) on *G′* was observed for the flours. The fourth test was performed in the viscosity mode with the cone-plate geometry. The shear stress at constant shear rate (0.0585/sec) was studied. The cone was used to avoid a shear gradient being applied to the sample. This was considered important when the measurements were performed outside the linear viscoelastic region. A cyanoacrylate adhesive was used to eliminate slip according to Lindborg et al (1996). The rheological measurements were run in triplicates. In the dynamic measurements, error bars at 0.5 Hz give the maximum and minimum values of the storage and loss moduli. The reproducibility of the strain-sweep tests is shown by the error bars at the highest strain investigated. For the stress-relaxation and viscosity measurements the mean values of the relaxation times (taken as the time where 50 and 10% of the initial stress remained, $t_{0.5}$ and $t_{0.1}$, respectively) and the mean values of the peak-shear stress (σ_{max}) are shown with error bars indicating the standard deviations in the figures.

RESULTS

Mechanical Spectra

In Fig. 1A–C, the frequency sweeps of the storage and loss modulus (*G′* and *G″*, respectively) are shown for doughs mixed 6 and 20 min and prepared with flour protein contents of 10 and 15%. To keep the figures simple, the mechanical spectra of the doughs made with the flours diluted to protein contents of 13% (7531 and 7546) are excluded.

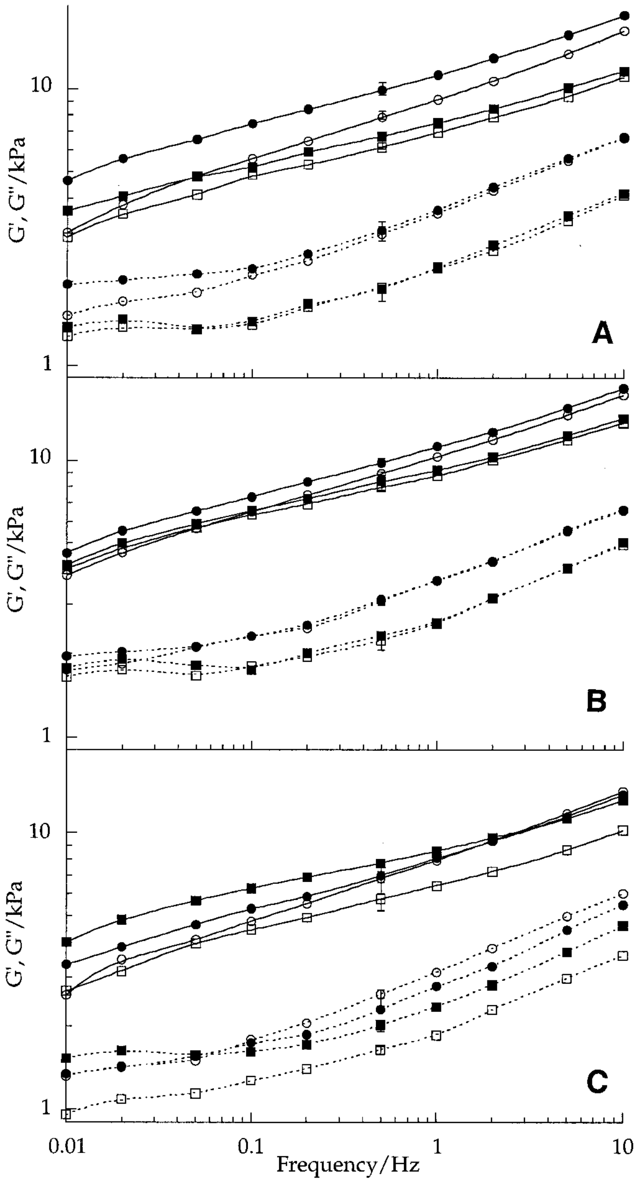

Fig. 1. Mechanical spectra of flour doughs and doughs made with flour diluted with starch (10%. flour protein content). **A,** 7516; **B,** 7531; **C,** 7546. Undiluted flour (15% protein): 6 min of mixing (○); 20 min of mixing (●). Diluted flour (10% protein): 6 min of mixing (□); 20 min of mixing (■). Storage and loss moduli: *G′* (——) and *G″* (– – – –).

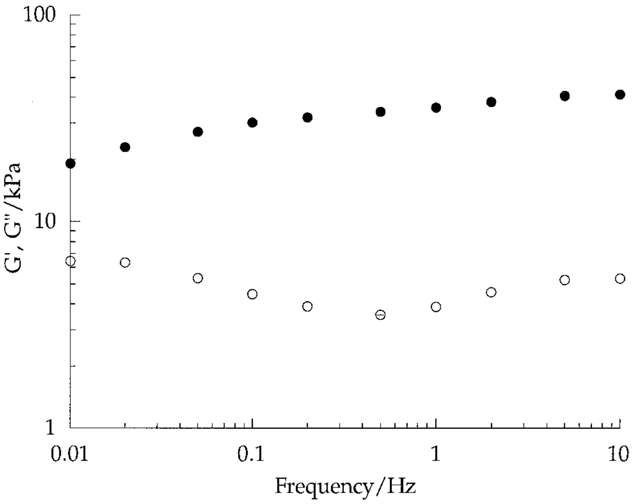

Fig. 2. Mechanical spectra of the starch-water mixture with starch-to-water ratio of 1.02. Storage and loss moduli: *G′* (●) and *G″* (○).

TABLE I
Flour Characteristics

Flour[a]	7516	7531	7546
High molecular weight glutenin subunits	2*, 7+9, 2+12	21*, 7+9, 5+10	21*, 7+9, 2+12
Protein in flour (%, dry basis)	14.9	15.0	15.2
Falling number (sec)	368	408	305
Glutogram (sec)	39.4	113.1	20.8
Bread volume (mL)	924	884	1,156
Mixogram peak development (min)	5.8	5.9	4.2
Farinograph water absorption (%, total basis)	44.90	44.34	45.52
Estimated starch-to-water ratio	1.02	1.04	0.99

[a] According to Johansson and Svensson (1995).

TABLE II
Water Content of Doughs (%, total basis) Prepared with Flours 7516, 7531, and 7546 and Starch-Flour Mixtures of Estimated Starch-to-Water Ratios

	Dough Water Content (%)		
Protein (%)	7516	7531	7546
10.0	46.50	45.97	47.23
13.0	···	45.00	46.26
15 (approx.)[a]	44.90	44.34	45.52

[a] See Table I for exact value.

When the doughs mixed for 6 min are compared, the two moduli (G' and G'') decreased somewhat as larger amounts of starch were included at a constant starch-to-water ratio (Fig. 1A–C). The frequency dependency of G'' was lower at long times (frequencies <0.1 Hz), while it increased at higher frequencies. G' was less dependent on frequency when the flours were diluted with starch. The same values of G' for the flours of 15 and 10% protein content were obtained at low frequencies, but the differences increased at higher frequencies. The mechanical spectra of the doughs prepared with a flour protein content of 13% (7531 and 7546) were recovered in between the corresponding spectra of the 10 and 15% protein flour doughs. With the 7531 flour diluted to a protein content of 13%, G' was less influenced by frequency compared with the G' of the corresponding 10 and 15% protein flour doughs (results not shown).

Figure 2 shows the mechanical spectra of a starch-water dough, mixed for 6 min. The starch-to-water ratio was the same as estimated for the 7516 flour (1.02). When all the flour was exchanged for starch, the two moduli were less frequency dependent than the moduli given by the flour doughs (Fig. 1A–C). The storage modulus reached a value of 20–40 kPa, while the loss modulus was in the same range as was observed at short times (≥2 Hz) for the flour doughs.

For the doughs prepared with the 7516 and 7531 flours and mixed for 20 min, the dilution of the flours by starch resulted in a decrease in G' over the times investigated (Fig. 1A–C). With the 7546 flour, on the other hand, no significant difference was observed beyond 0.5 Hz. At <0.5 Hz, the undiluted flour dough resulted in a lower modulus than the dough made with a flour protein content of 10%. The mechanical spectra of the 13% protein flour doughs mixed for 20 min resembled the corresponding undiluted 7531 and 7546 doughs (results not shown).

When the doughs mixed for 6 and 20 min are compared, a constant increase in G' over time was observed for all the doughs mixed for 20 min, except for the 7546 flour without starch dilution (Fig. 1C) and the dough prepared with the flour diluted to a protein content of 13% (results not shown). For these doughs, the influence of prolonged mixing appeared as a moderate increase in G' only at low frequencies. The loss modulus (G'') seemed to depend only on flour-protein content over most frequencies and not on mixing time for the doughs made with the 7516 and 7531 flours (Fig. 1A–B). However, for the 7546 flour doughs, G'' was affected both by mixing time and starch substitution (Fig. 1C).

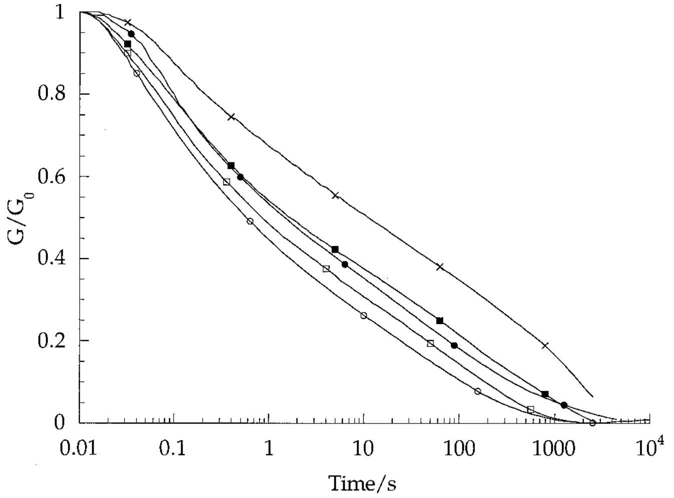

Fig. 3. Stress-relaxation measurements on 7516 flour doughs (○), doughs made with flour diluted with starch to give a flour protein content of 10% (□) and the starch-water mixture (·). Mixing for 6 min (open symbols) and 20 min (closed symbols).

Stress-Relaxation Measurements

The stress relaxation obtained with the 7516 flour is shown in Fig. 3 as an example of the influence of starch dilution and mixing time on the stress-relaxation. The modulus at time t divided by the initial modulus (G/G_0) is plotted as a function of time. Similar effects of both mixing time and starch concentration on the stress relaxation were observed for the three flours studied. By reducing the protein content from 15 to 10% by starch dilution, the stress relaxation was slowed down for all the flours but to different extents. Increased mixing time also slowed down the stress relaxation. For the starch-water mixture, the slower stress relaxation appeared early in the spectra.

Strain-Sweep Tests

The stress-strain behavior is presented in terms of the reduced storage modulus, G'/G' (strain 0.00044) as a function of strain (Fig. 4A–C). The undiluted flour doughs show a more or less linear region at strains approximately <0.001 (Fig. 4A–C). When

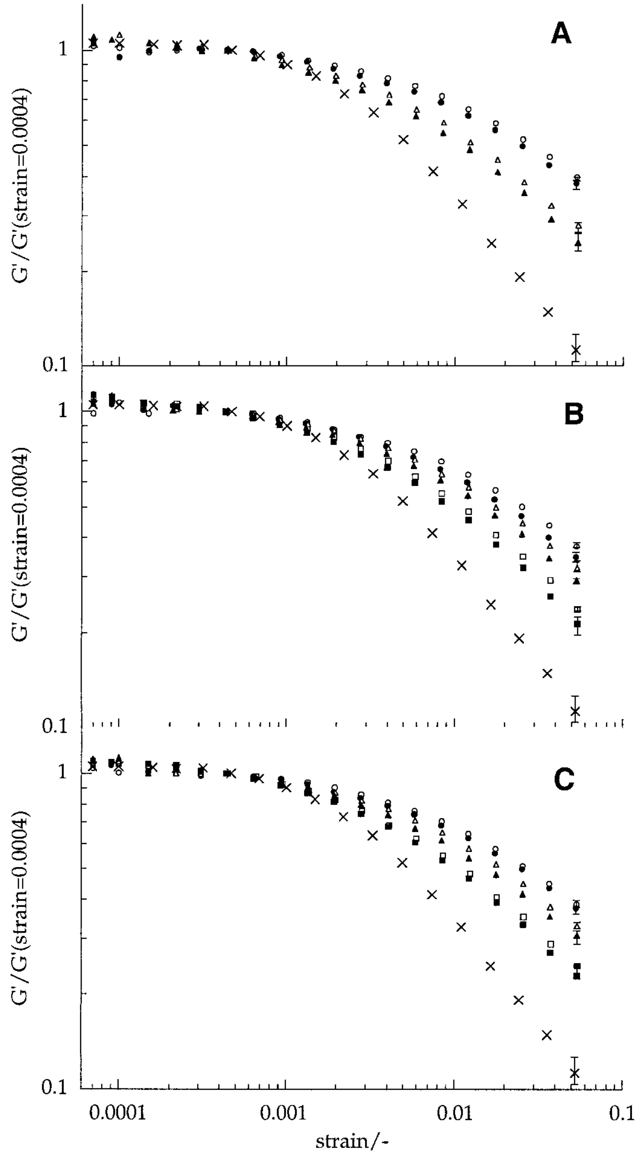

Fig. 4. Strain sweeps of flour doughs (○); doughs made with flour diluted with starch to give flour protein contents of 13% (Δ) and 10% (□); and starch-water mixture (✕). **A,** 7516 **B,** 7531 **C,** 7546. Mixing for 6 min (open symbols) and 20 min (closed symbols).

the flours were diluted with starch, the linear region decreased or *G′* was somewhat dependent on strain even at very low strain levels. The larger amount of starch also reduced the strain tolerance, observed as a stronger decrease in the reduced modulus. A reduced strain tolerance after prolonged mixing was indicated for the 7531 flour doughs but not for the other flours.

Viscosity Measurements

The shear stress (σ_{shear}) as a function of increasing strain in viscosity measurements is shown in Fig. 5A–C. When the undiluted flours were mixed into doughs for 6 min, the 7516 and 7546 doughs gave higher values of the peak-shear stress (σ_{max}) compared with the 7531 dough. For all the three doughs, the value of the peak stress (or the maximum of the stress when a well-defined peak was absent) decreased when a larger amount of starch was included. For the doughs prepared with the undiluted 7516 and 7546 flours, σ_{max} was markedly reduced after prolonged mixing. On the other hand, no effect of mixing time was observed in the viscosity measurements with the 7531 flour. When the flours were diluted with starch, the influence of extended mixing was less, if observed at all.

In Fig. 6A–D, a summary of the results is shown by the storage modulus given at 0.5 Hz, the two relaxation times ($t_{0.5}$ and $t_{0.1}$), and σ_{max} as a function of flour protein content. When the flours were diluted with starch or mixed for 20 min, similar trends were observed in relaxation times and σ_{max} for the three base flours (Fig. 6B–D). Different effects of starch dilution and mixing time, however, were observed in the storage modulus (Fig. 6A).

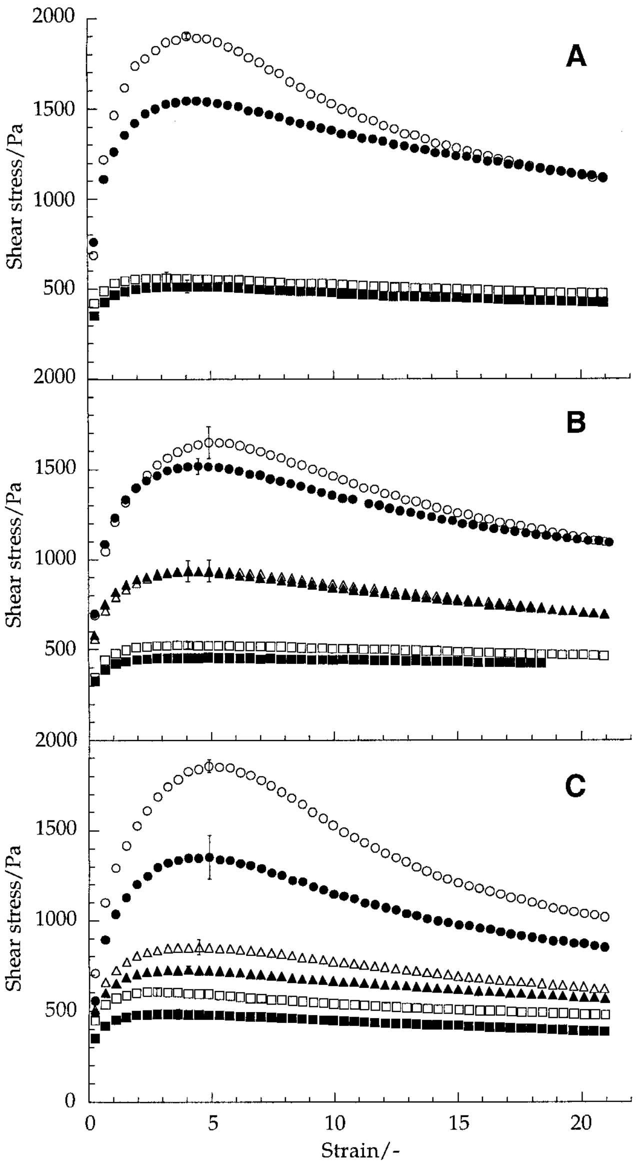

Fig. 5. Viscosity measurements on flour doughs (○); doughs made with flour diluted with starch to give flour protein contents of 13% (Δ) and 10% (□). **A,** 7516 **B,** 7531 **C,** 7546. Mixing for 6 min (open symbols) and 20 min (closed symbols).

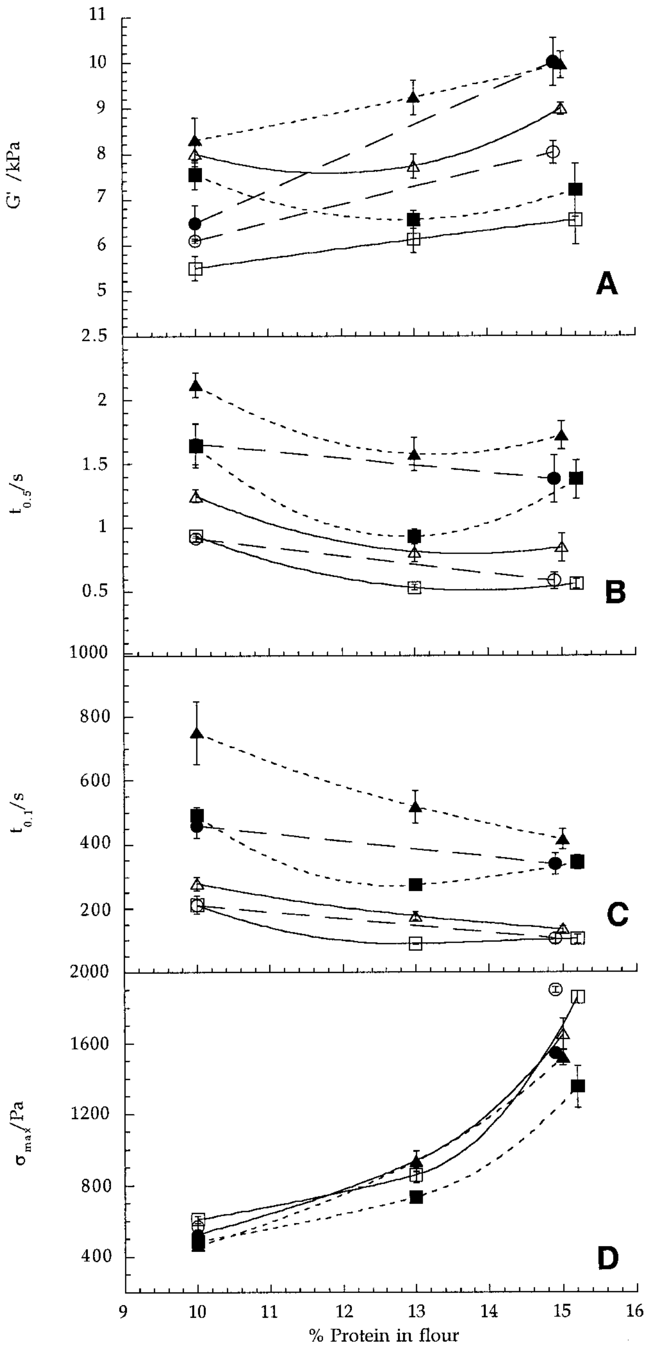

Fig. 6. Influence of protein concentration (10–15%) and mixing time on the flours 7516 (○), 7531 (Δ), and 7546 (□). Mixing for 6 min (open symbols) and 20 min (closed symbols). **A,** Storage modulus (*G′*) at 0.5 Hz. **B,** Short relaxation time ($t_{0.5}$). **C,** Long relaxation time ($t_{0.1}$). **D,** Peak-shear stress (σ_{max}).

DISCUSSION

For the present study, the dough is considered to consist of the water-swollen protein (gluten) and the starch granules concentrated in a second liquid phase, resulting in two continuous aqueous phases in the dough (Eliasson and Larsson 1993). This organization is consistent with a weakly aggregated starch structure (Matsmoto 1979) that interpenetrates the sheets of gluten in developed dough (Moss 1972).

Starch Concentration

A reduction in farinograph mixing resistance results when the starch content of a flour increases (Rasper and deMan 1980). This suggests that a lower amount of water is required for dough development at increasing flour starch contents. Considering the phase-separation behavior of dough, the simultaneous rise in starch content and decrease in added water will most likely hinder the phase separation by the absence of a continuous liquid phase (Larsson and Eliasson 1996a). Such a behavior seems disadvantageous for the dough development. In the present study, the flours were diluted with starch, and doughs were prepared with a constant starch-to-water ratio. This was done to favor phase separation and to limit effects related to a concentration of the starch-liquid phase.

At the times investigated, the mechanical spectra were recovered on the plateau zone according to Ferry (1970). When the doughs were diluted with starch to a protein content of 10%, a lower frequency dependence was observed (Fig. 1A –C). The slower decay of stress observed in the stress relaxation measurement is consistent with the effect on the mechanical spectra. This agrees with the general behavior when the filler concentration in a composite material is increased (Ferry 1970). Consequently, the resemblance to the starch-water mixture increased when the protein content of the doughs was reduced, which is indicated in both the mechanical spectrum and the stress relaxation measurement (Figs 2 and 3). Both moduli in the mechanical spectrum of the starch-water mixture show only a moderate frequency dependence. The elastic properties, however, did not persist over longer times as seen in the stress-relaxation measurement indicating a transient network. A higher storage modulus was observed for the starch-water mixture (30–40 kPa), compared with the doughs (≈10 kPa). Thus, an increase in the relative viscous properties (higher G''/G') is given by introducing gluten to the starch-water mixture.

The introduction of a larger amount of starch, while keeping the starch-water ratio constant, resulted in a lower value of the storage modulus at 0.5 Hz (Fig. 6A). These differences in G' observed for the doughs mixed for 6 min, however, decreased at lower frequencies in the mechanical spectra, and did not prevail at the longest times registered. This is in accordance with the fact that short-range interactions are more pronounced at higher frequencies (Ferry 1970). The effect of starch dilution was greatest (observed at lower frequencies) for the 7516 flour.

In stress-relaxation measurements, the influence of long-range interactions are more pronounced as the full time spectrum is covered. The stress relaxation was slowed down when the flour protein content was reduced (Figs 3 and 6B–C). The slower stress relaxation can be explained by a larger amount of weak junction zones created by the highly concentrated starch network in the starch-liquid phase. The two relaxation times ($t_{0.5}$ and $t_{0.1}$) increased strongly when the protein content of the flour decreased to 10%, but seemed to be only slightly affected by the dilution of the flour to a protein content of 13%. The differences between the three flours were only moderate, even though a slower stress relaxation (higher value of $t_{0.5}$ and $t_{0.1}$) was obvious with the 7531 flour over the protein concentrations studied.

The effect of increasing strain was investigated to study the stability of the dough structure. By including a larger amount of starch, the linear region decreased and the doughs became more sensitive to strain (Fig. 4A–C). This is in agreement with the observations on dough made by Smith et al (1970), and the general behavior upon increased strain when a larger amount of filler is introduced to a polymer matrix (Ferry 1970, Nielsen 1974). The strain sensitivity can be attributed to the effect of mechanical deformation on weak aggregates or networks that are formed by the starch granules in the concentrated starch-liquid phase. Gluten on the other hand shows a larger linear region than was investigated here (≈0.05). Strain values of 0.05–0.07 were reported in the linear region for gluten (Attenburrow et al 1990, Inda and Rha 1991, Cornec et al 1994). No differences between the flours were observed in the strain sweeps. Instead, the protein content seemed to determine how much the behavior of the dough was going to deviate from that of the starch-water mixture. This agrees with the fact that an effect on the strain tolerance is dominated by the influence of the starch structure.

The greatest influence of the dilution of the flours by starch was observed in the viscosity measurements (Fig. 5A–C). according to van den Tempel, a stress versus stain plot may be divided into three structural regions: the initial part, with a competition between structural breakdown and reformation; the overshoot peak, where the breakdown exceeds the reformation and causes rupture in weak regions; and stress relaxation beyond the stress peak (Van den Tempel 1980). The overshoot peak more or less disappeared when the flours were diluted with starch (Fig. 5A–C). The first dilution of the flour to 13% protein resulted in a pronounced decrease in the highest value of the shear stress (σ_{max}) for both 7531 and 7546. The second dilution to 10% protein only reduced σ_{max} slightly more for 7546, while it continued to decrease for 7531 (Fig. 5B–C, 6D). From these results, it can be concluded that the starch concentration strongly influenced the stress-strain behavior. It even seems like σ_{max} was dominated by an effect of starch at the lowest protein contents investigated, as no differences were observed between the flours. Lindborg et al (1997) also registered the highest peak value of the viscosity for the flour with the highest protein content.

Mixing Time

The most notable observation concerning the effect of mixing time was the different results demonstrated for measurements at small and large deformation. The value of G' increased for doughs mixed with the native flours 7516 and 7531 (Fig. 6A), whereas σ_{max} decreased for 7516 and 7546 (Fig. 6D) after prolonged mixing. This may seem contradictory, especially as depolymerization has been indicated as a reduction in the molecular weight of the proteins extracted from overmixed dough (Tanaka and Bushuk 1973, Danno and Hoseney 1982). These results may, however, be understood if the extreme difference in applied strain (0.00044 compared with ≈5) is considered. At strain values of 0.00044, the measurement is performed in the linear viscoelastic region, which imply a more or less intact sample structure. In the viscosity measurement, there was no linear relationship between stress and strain (Fig. 4). The different results at small and large deformations suggest that different structures are affected by the two measurements. Moreover, when the doughs were mixed for 20 min (independent on starch concentration) the storage modulus was less dependent on frequency (Fig. 1A–C), and the stress relaxation was slowed down, compared with the undiluted flour doughs mixed for 6 min (Fig. 6B–C). This behavior indicated that the influence of starch granules was extended over a larger time period when the doughs were subjected to prolonged mixing, similar to when the doughs were diluted with starch. Prolonged mixing fortified the effect of increasing starch concentration on the stress-relaxation times (Fig. 3 and 6B–C). This effect was greatest on the 7531 flour dough. A slower stress relaxation for the doughs mixed for 20 min may originate in a change of the microstructure during mixing. Such a change of the dough structure has been demonstrated in the microscope by Moss (1972). During prolonged mixing, the gluten sheets with starch granules in between become thinner until they eventually cover all the starch granules (Moss 1972). This means that the lamellar organization of gluten and starch is disrupted and a more homogeneous system, with respect to starch granule distribution, results after extended mixing. Also, the water distribution in the dough was influenced (Larsson and Eliasson 1996a).

Even though the influence of mixing time observed in the strain sweep test was about the same for the 7516 and 7546 flour doughs, the results obtained with the 7531 flour indicated that the strain tolerance was reduced due to overmixing in a similar way to when the flours were diluted with starch (Fig. 4B). A more homogeneous distribution of fillers in a matrix, according to Moss (1972), is however not supposed to reduce the strain tolerance in comparison to an agglomerated filler phase (Nielsen 1974). The increased influence of starch on the mechanical and stress-relaxation spectra after prolonged mixing suggested that the properties of the starch-water mixture was approached when mixing time was increased. This may be explained by the development of thinner gluten films that are less efficient in order to interfere with the properties of the starch phase compared with the thicker lamellas present in dough mixed for shorter times. A larger amount of entrapped air due to prolonged mixing may also result in a reduced strain tolerance for a composite material (Nielsen 1974).

In the viscosity measurements, the influence of mixing time was greatest on the 7546 flour doughs (Fig. 5A–C). This was observed undiluted and diluted flours. According to the mixogram, the peak development time was shorter for the 7546 flour compared with the 7516 and 7531 flours (Table I). On the other hand, according to the present investigation, the 7531 dough was hardly influenced by prolonged mixing. This may imply that the 7531 flour dough was resistant to the mechanical treatment (the low mixing speed) applied to this strong flour. In the study by Lindborg et al (1997), the strain at the peak viscosity was related to mixing time. In the present work, no such relationship was observed.

Influence of Glutenin Subunit Composition

The flours selected for the study differed in high molecular weight subunit composition (Table I). A considerable higher glutogram value was given for the 7531 flour (113 sec), compared with the other flours (20–40 sec). This shows that the 7531 gluten, comprising the 5+10 subunits, was stronger. The 7531 flour can be considered rather uninfluenced by both protein content and mixing time, judged by the mechanical spectra (Fig. 1B). On the other hand, the 7516 dough was most influenced by mixing time at the highest protein content (undiluted flour) (Fig. 1A). A greater effect of mixing time on starch dilution (low protein content) was observed with the 7546 flour dough (Fig. 1C). The storage modulus of the undiluted flour doughs mixed for 6 min (Fig. 6A) were related to the glutogram values (gluten strength). However, they were also inversely related to the farinograph water absorption, which showed that the most concentrated dough (7531) resulted in the highest modulus, and vice versa (Fig. 6A and Table I). It seems hard to tell whether the gluten strength or flour protein content dominated the effect on the storage modulus. The concentration relationship was, however, not valid after prolonged mixing, as G' of the 7516 flour increased more than it did for the others. From the strain sweep tests, no differences between the flours could be established (Fig. 4A–C).

In the stress-relaxation measurements, the doughs made with the 7531 flour resulted in longer relaxation times, especially when the protein content was reduced to 10% and the mixing time was increased. The stress-relaxation behavior of the 7531 doughs, containing the subunits 5+10, clearly differed from what was observed for the other doughs, with the subunits 2+12 (7516 and 7546). This may be compared with the considerably higher glutogram values obtained with the 7531 flour (Table I). No differences between the flours 7516 and 7546 were observed in the stress-relaxation measurements (Fig. 6B–C).

The deviating properties of the 7531 flour observed at small deformations were more pronounced in the viscosity measurement (Fig. 4A–C). No difference in peak stress (σ_{max}) was observed between the two flours containing the subunits 2+12 (7516 and 7546), for which higher σ_{max} were registered compared with the flour containing the subunits 5+10 (7531) (Fig. 4D). In the study by Lindborg et al (1997), the strongest flour, which was also the flour of the highest protein content, resulted in the highest peak viscosity. In the viscosity measurements, the 7531 flour dough was not influenced by mixing time, whereas the decrease in σ_{max} was pronounced for the other flours after prolonged mixing (Fig. 4A–C). For the 7546 flour doughs, an effect of mixing time was evident also at lower protein contents. A smaller tendency to show a distinct stress peak (undiluted flours, mixed for 6 min) was observed with the 7531 flour compared with the 7516 and 7546 flours. The broadening of the shear-stress peak may be compared with the slower stress relaxation observed for the 7531 flour doughs (Fig. 6B–C). It seems likely that the HMW subunits 5+10 conferred a too high resistance to deformation and slow stress relaxation. This may be related to a slow response to deformation during the expansion of gas cells in the breadmaking process. Thus the reason for the lower bread volume obtained with the 7531 flour may originate in a too strong gluten (Table I).

ACKNOWLEDGMENTS

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