Predicting Baking Performance from Rheological and Adhesive Properties of Rye Meal Suspensions During Heating

A. Repeckiene,[1] A.-C. Eliasson,[2,3] G. Juodeikiene,[1] and E. Gunnarsson[4]

ABSTRACT

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Rheological methods were used to study the behavior of rye meal suspensions during a time-temperature treatment corresponding to the initial baking conditions (<70°C). Eight different rye cultivars were investigated, with four of the cultivars grown during two different years. Baking experiments included pan bread and hearth bread. Viscosity, falling number, and the amount of adhesive material present during heating were measured. The storage (G') and loss (G'') moduli increased during a temperature sweep from 45°C, reaching a maximum at 62.1–67.1°C. At the same time, the amount of adhesive material increased. A further increase in temperature caused a decrease in G' and G'', whereas the amount of adhesive material continued to increase. The mechanical spectra (G' or G'' vs. frequency) showed that the rye meal suspensions had gel-like behavior at 45°C which turned into behavior typical of a strong gel at 70°C. The rye meals performing the best in hearth bread baking gave intermediate values of G' and G'' and high values of the phase shift (δ) at 45°C. During the temperature sweep, the G' values of these rye meal suspensions increased slowly to a maximum of 62.1–67.1°C.

In the northern part of Europe (including Sweden and Lithuania), rye is used in breadmaking for sourdough bread, crisp bread, and mixed with wheat (Gunnarsson 1995; Weipert 1995). Baking procedure when using rye flour differs from baking with wheat flour; for example, rye bread is often baked from whole meal (Parkkonen et al 1994). The gas retention of rye flour dough is poor in comparison with wheat flour dough (He and Hoseney 1991), which may be due to the poor gas cell stabilization ability of the rye proteins (Autio et al 1996). Instead, other components present in the rye meal flour such as starch and the nonstarch polysaccharides are important for stabilization of gas cells and formation of structure.

Apart from α-amylase activity, the arabinoxylan content has been reported as the most important factor for rye flour baking performance (Vinkx and Delcour 1996). The chemical composition of rye flour is remarkable because of its high arabinoxylan content. During the last decade, the composition and properties of arabinoxylans and arabinogalactans have been investigated in considerable detail, and knowledge about their chemical structure and physicochemical properties has increased (Izydorczyk and Biliaderis 1992; Izydorczyk et al 1990, 1991a,b; Michniewicz et al 1990). It has, for example, been observed that arabinoxylans are surface active and that they contribute to viscosity.

Starch may be the major contributor to the structure of rye bread. Its role in the rye meal dough is affected by pH, dough composition and formulation, enzymatic activities, and extent of starch degradation (Pomeranz et al 1984). Rye starch gelatinizes at a lower temperature than wheat starch (Gudmundsson and Eliasson 1991), and also shows a lower retrogradation tendency (Fredriksson et al 1998).

Although both starch and arabinoxylans have important roles in the baking performance of rye meals, the proteins should not be neglected. They seem to be important at the dough mixing step, at least in certain cultivars (Parkkonen et al 1994). Although the rye proteins do not form gluten, they still have properties in common with wheat proteins. Rye proteins have some aggregation ability (Field et al 1983) and are surface active (Wannerberger et al 1995). However, the properties differ greatly from the gluten protein properties in wheat.

The baking procedure for rye meal often involves sourdough fermentation (Pomeranz et al 1984; Kühn and Grosch 1989; Autio et al 1996), but processes without sour dough are also used (Approved Method 10-70 [AACC 2000]). The use of whole rye meal for baking complicates the picture even more. Therefore, it is not surprising that few generally accepted methods exist for prediction of end-use quality of rye. Usually, falling number is the single measure; depending on the end product, rye flours with different values are preferred.

Although the importance of arabinoxylans and starch for the baking performance of rye has been indicated, the mechanisms for the function of these components are not completely understood. A method for evaluating rye flour quality needs to take all the rye meal dough components into consideration. In the present study, rheological methods were used, both fundamental and empirical, to evaluate the baking quality of a range of rye meal flours. A method developed for characterization of the degree of dispersion was further used to follow the behavior of a rye meal suspension during heating (Juodeikiene et al 1993). The falling number was included as a reference method and measurements were made both with and without an α-amylase inhibitor. The results obtained were correlated to results of baking experiments performed on pan bread as well as hearth breads.

MATERIALS AND METHODS

Materials

Eight different rye cultivars were collected from Lithuania (Rukai, Duoniai, Hy 345, and Hy 346) and Sweden (Motto, Amando, Olof, and SWHY 94031) (Table I). Lithuanian rye cultivars were harvested at the Lithuanian Institute of Agriculture, Dotnuva, in 1995, and Swedish rye cultivars were harvested at Svalöf Weibull AB, Landskrona, in 1995 and 1996. Distilled water was used in all experiments, except in the baking experiments, where tap water was used.

Rye Milling and Chemical Composition

Rye grains were milled using a laboratory mill (3100, Perten Instruments AB, Huddinge, Sweden). The resulting rye meals were analyzed for moisture content (Approved Method 44-19 [AACC 2000]), ash content (Approved Method 08-01), and crude protein (N × 5.7, analyzed by the Kjeldahl procedure). Pentosan content of Lithuanian cultivars (Englyst and Cummings 1984) and Swedish cultivars (Blakeney et al 1983 and Karlsson 1988) were also analyzed. All measurements were made in duplicate.

Falling Number

The falling number test (Approved Method 56-81B) was used to estimate the enzyme activity of the rye meal. Inclusion of $AgNO_3$

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[1] Department of Food Technology, Kaunas University of Technology, Radvilenu pl. 19, 3028 Kaunas, Lithuania.
[2] Department of Food Technology, Center for Chemistry and Chemical Engineering, University of Lund, P.O. Box 124, S-221 00 Lund, Sweden.
[3] Corresponding author. Phone: +46 46 222 9674. Fax: +46 46 222 9517. E-mail: Ann-Charlotte.Eliasson@livsteki.lth.se
[4] Svalöf Weibull AB, S-268 81 Svalöv, Sweden.

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TABLE I
Chemical Composition and Falling Number of Rye Meals

	Content (%, dm)[a]				
Cultivar	Protein	Ash	Pentosan	Falling No.	AgNO$_3$[b]
Lithuanian					
Rukai	10.5	1.92	8.2 (2.8)	278	378
Duoniai	10.0	1.92	7.3 (2.4)	218	328
Hybrid 345	10.8	2.04	8.8 (2.9)	271	365
Hybrid 346	12.3	1.77	8.3 (3.0)	229	301
Swedish, 1995					
Motto	8.96	1.8	9.8 (1.5)	345	376
Amando	9.07	1.69	10.9 (1.8)	358	402
Olof	8.88	1.72	9.9 (1.7)	353	397
SWHY 94031	9.12	1.62	12.2 (2.0)	380	396
Swedish, 1996					
Motto	8.88	nd[c]	9.3 (1.3)	312	340
Amando	9.02	nd	11.2 (2.0)	350	380
Olof	8.47	nd	9.7 (1.5)	328	365
SWHY 94031	8.37	nd	10.7 (1.8)	336	380
Lithuanian	10.9 ± 1.0a	1.91 ± 0.11	8.2 ± 0.5 (2.8 ± 0.2)	249 ± 30a	343 ± 35a
Swedish, 1995	9.01 ± 0.11b	1.71 ± 0.07	10.7 ± 1.0 (1.8 ± 0.2)	359 ± 15b	393 ± 11a
Swedish, 1996	8.69 ± 0.31b	…	10.2 ± 0.8 (1.7 ± 0.3)	332 ± 16c	366 ± 19a

[a] Values in parentheses show the amount of soluble pentosans. Values followed by the same letter in the same column are not significantly different ($P < 0.05$).
[b] Falling number in AgNO$_3$.
[c] Not determined.

TABLE II
Results of Test Baking[a]

	Pan Bread		Hearth Bread		
Rye Cultivar	Volume (mL)[b]	Spec. Vol. (mL/g)	Height (cm)	Diameter (cm)	Ratio (%)[c]
Lithuanian					
Rukai	270	1.53	2.9	10.5	28
Duoniai	300	1.70	2.9	11.1	27
Hy 345	301	1.72	2.9	10.9	27
Hy 346	279	1.59	2.6	12.4	21
Swedish, 1995					
Motto	252	1.41	3.6	9.2	39
Amando	278	1.57	4.2	8.3	51
Olof	270	1.54	3.7	8.8	43
SWHY 94031	264	1.50	3.6	8.9	41
Swedish, 1996					
Motto	251	1.44	3.2	9.6	33
Amando	280	1.61	4.0	8.4	48
Olof	262	1.49	3.0	10.0	30
SWHY 94031	263	1.52	3.2	10.2	31
Lithuanian	288 ± 15a	1.64 ± 0.09a	…	…	26 ± 3a
Swedish, 1995	266 ± 11a	1.51 ± 0.07a	…	…	44 ± 5b
Swedish, 1996	264 ± 12a	1.52 ± 0.07a	…	…	36 ± 8ab

[a] Values followed by the same letter in the same column are not significantly different ($P < 0.01$).
[b] Deviation from the mean value 3%.
[c] Form ratio = (height/diameter) × 100.

TABLE III
Viscosity Values for Three Groups of Rye Meals[a]

Cultivar	Initial (BU)[b]	Peak (°C)[c]	Peak (BU)	50°C (BU)
Lithuanian	93 ± 9a	80 ± 2a	368 ± 43a	293 ± 98a
Swedish, 1995	89 ± 41a	88 ± 2b	883 ± 156b	1,167 ± 306b
Swedish, 1996	150 ± 23b	85 ± 3ab	853 ± 92b	1,121 ± 313b

[a] Values followed by the same letter in the same column are not significantly different ($P < 0.05$ for pasting; $P < 0.01$ for peak temperature, peak viscosity, and viscosity at 50°C).
[b] Viscosity at initial pasting; at 60°C for all cultivars except Motto and Olof at 61°C.
[c] Temperature at peak viscosity.

TABLE IV
Average Values of Storage Modulus (G'), Loss Modulus (G''), and Phase Angle (δ) Measured for Rye Meal Suspensions[a]

Cultivar	G' (Pa)	G'' (Pa)	δ
Lithuanian	140.0 ± 19.5a	64.1 ± 9.4a	24.6 ± 0.8a
Swedish, 1995	198.2 ± 58.7a	101.6 ± 30.8b	27.1 ± 1.0b
Swedish, 1996	483.1 ± 131.4b	208.0 ± 61.2c	23.2 ± 0.5c

[a] Measured at $f = 1$ Hz and $\gamma = 0.00103$ in the frequency sweep at 45°C; Values followed by the same letter in the same column are not significantly different ($P < 0.01$ for G' and $P < 0.05$ for G'' and δ).

(at 100 mg/kg of total material, including water) was used to evaluate how the α-amylase activity contributed to the falling number (Kuracina et al 1987).

Viscosity

The viscosity of the rye meal suspensions was measured in a Brabender Viscograph (Brabender OHG Duisburg, Germany) with a 250-cmg measuring cartridge. The rye meal suspension (58 g of flour [dry matter] and 480 mL of water) was heated from 25 to 95°C with a temperature gradient of 1.5°C/min, kept at 95°C for 15 min, then cooled at the same rate to 50°C. The viscosity of initial pasting (the first inflection point where the curve begins to rise), peak viscosity, and viscosity at the end of the test at 50°C were recorded in Brabender units (BU).

Fundamental Rheological Measurements

The rheological measurements of rye meal suspensions were performed (Bohlin Rheometer VOR, Metric Analysis, Stockholm, Sweden) at 45–70°C. A concentric cylinder system with a volume of 13 mL of suspension was used. The rye meal suspension (41%, w/w) was preheated in a water bath at 28°C for 60 min, then transferred to the rheometer. Thermal equilibrium time at 45°C in the rheometer was 10 min. The sample was covered with a thin layer of silicon oil (low viscosity) to prevent the sample from drying.

The rheological measurements were performed in oscillation mode: 1) frequency sweep at 45°C, frequency range 0.01–10.0 Hz at a constant strain ($\gamma = 0.00103$); 2) strain sweep at 45°C, shear strain range 0.000206–0.206 at a constant frequency ($f = 1$ Hz); 3) temperature sweep, temperature range 45–70°C, temperature gradient 0.55°C/min, constant frequency ($f = 1$ Hz) and constant strain ($\gamma = 0.00103$) (when the temperature of the suspension reached 70°C, measurements were continued for 180 sec at this temperature); and 4) strain sweep at 70°C, with measurements performed similarly to the measurements at 45°C.

The strain sweep was used to establish the linear viscoelastic region for further measurements. A linear region up to a strain of 0.00103 was observed for G' when the frequency was 1 Hz. The

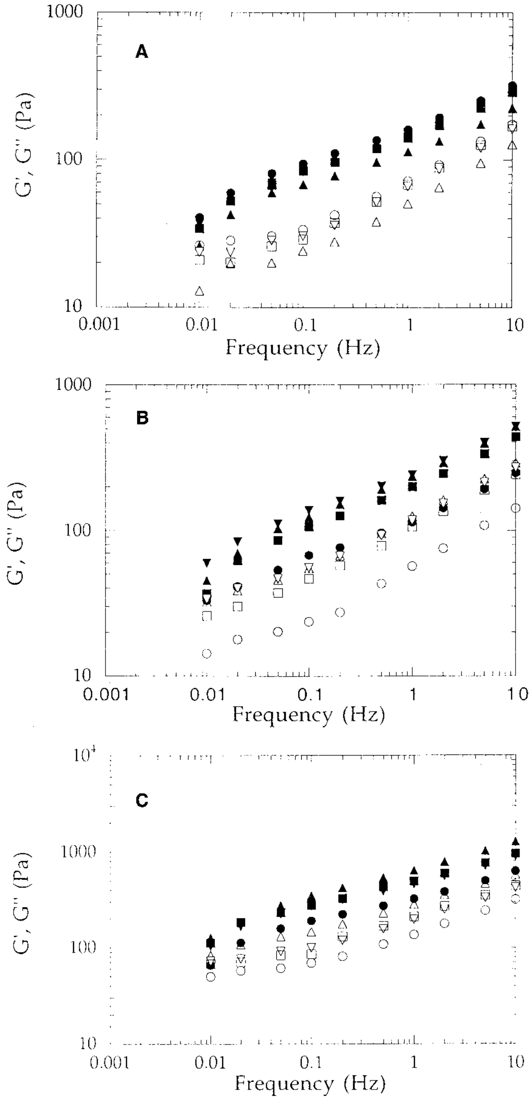

Fig. 1. Storage (G', filled symbols) and loss (G'', open symbols) moduli measured at 45°C for **A,** Lithuanian rye meal suspensions for Rukai (●, ○), Duoniai (▲, Δ), Hy 345 (▼, ∇), and Hy 346 (■, □); **B,** Swedish rye meal suspensions from 1995 for Motto (●, ○), Amando (▲, Δ), Olof (▼, ∇), and SWHY 94031 (■, □); and **C,** Swedish rye flour suspensions from 1996 for Motto (●, ○), Amando (▲, Δ), Olof (▼, ∇), and SWHY 94031 (■, □).

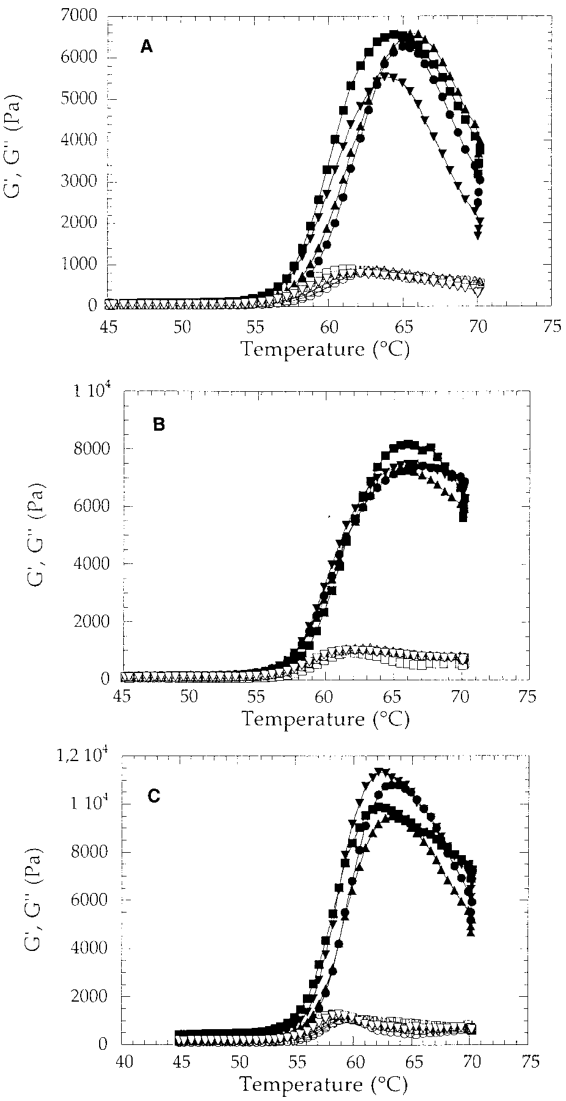

Fig. 2. Storage (G', filled symbols) and loss (G'', open symbols) moduli during a temperature sweep for cultivars from 1995: **A,** Rukai (■, □), Duoniai (●, ○), Hy 345 (▲, Δ), and Hy 346 (▼, ∇); **B,** Motto (■, □), Amando (●, ○), Olof (▲, Δ), and SWHY 94031 (▼, ∇); and **C,** cultivars from 1996: Motto (■, □), Amando (●, ○), Olof (▲, Δ), and SWHY 94031 (▼, ∇).

average of two replicates for each rye cultivar is presented and the deviation from the average value was typically within 7%.

Baking Test

The baking test dough consisted of rye meal (500 g, dry basis), compressed bakers' yeast (15 g), salt (7.5 g), and water (435–447 g). The dough was kneaded by hand for 3 min and fermentation was performed using a rotary test proving cabinet (Henry Simon, Stockport, Cheshire, England). After floor time (60 min at 28°C), the dough was divided into four 200-g pieces. The pieces were molded by hand. Two were panned (pan bottom area was 6 × 6 cm, height was 7 cm, and top area 8 × 8 cm), whereas the other two were free-standing pieces placed on a block. The molded dough pieces were then proofed for 50 min at 30°C. Loaves were baked at 186°C for 45 min in the rotary test baking oven (Henry Simon) and cooled at room temperature for 75 min before measuring weight, volume (rapeseed displacement), hearth bread height, and diameter.

Adhesion Measurements

This method is based on the fact that cohesive and adhesive forces of a dispersed system and a dipped plunger change significantly during a dispersion process. Thus, measuring the amount of the adhesive material can be used to follow the dispersion process (Juodeikiene et al 1993).

The measurements were performed on the material from the 1995 harvest using rye meal suspensions (12%, w/w) heated in a water bath from 30 to 91°C with a temperature gradient of 1°C/min. During heating, the suspension was stirred (Typ Stir 20, Roskilde, Denmark) at speed 6 (300 min^{-1}). An aluminum plate (3 × 11 × 0.1 cm, 8.03 g) was dipped 5 cm (dipped plate area 31 cm^2) into the rye meal suspension, kept in the suspension for 15 sec, removed, kept for 15 sec, then weighed. The amount of adhered material was estimated by the increase in weight of the plate.

Statistical Analysis

Regression analysis and the Student's *t* test (double-sided two sample test, assuming unequal variances) were made using standard Microsoft Excel software.

RESULTS

Chemical Composition

The rye cultivars used in the present study and the chemical composition are presented in Table I. Four of the cultivars (Rukai,

TABLE V
Rheological Parameters for Rye Meal Suspensions Evaluated During Temperature Sweep (45–70°C)[a]

Rye Cultivar	G'_{max} (Pa)	T at G'_{max} (°C)	δ at G'_{max}	ΔT (Pa/°C)	$G'_{max} - G_{70°C}$ (Pa)
Lithuanian	6241 ± 489a	64.7 ± 0.7a	7.0 ± 0.4a	841 ± 65 a	2,674 ± 498a
Swedish, 1995	7,586 ± 407b	66.4 ± 0.5b	4.1 ± 0.3b	785 ± 127a	911 ± 519b
Swedish, 1996	10,388 ± 840c	62.7 ± 0.6c	4.5 ± 1.3bc	1,463 ± 196b	3,744 ± 909a

[a] Storage modulus (G'), loss modulus (G''), and phase angle (δ). Maximum G' value during temperature sweep (G'_{max}). Temperature at G'_{max} (T). Rate of increase in G' (Δ). Decrease in G' between $G'_{max} - G'$ at 70°C.

[b] Values followed by the same letter in the same column are not significantly different ($P < 0.01$ for G'_{max} and $G'_{max} - G'_{70°C}$; $P < 0.05$ for T at G'_{max}, δ at G'_{max}, and Δ).

TABLE VI
Average Values of Storage Modulus (G'), Loss Modulus (G''), and Phase Angle (δ)[a]

Rye Cultivar	G' (Pa)	G'' (Pa)	δ
Lithuanian	2,701 ± 781a	420 ± 82a	9.1 ± 1.0a
Swedish, 1995	6,109 ± 539bc	635 ± 89bc	5.9 ± 0.8a
Swedish, 1996	6,289 ± 909c	690 ± 32c	6.3 ± 0.5a

[a] Measured at 70°C for rye meals (f = 1 Hz and γ = 0.00103). Values followed by the same letter in the same column are not significantly different ($P < 0.01$ and 0.05 for G' and G'', respectively).

Duoniai, and Hybrids 345 and 346) were grown in Lithuania during 1994–1995. Four other cultivars (Motto, Amando, Olof, and SWHY94031) were grown in Sweden during two subsequent years (1995 and 1996). Results are presented in three groups: Lithuanian samples, Swedish samples from 1995, and Swedish samples from 1996.

The protein content of the rye meals was 8.37–12.3%; Lithuanian rye meals had a higher protein content than the Swedish rye meals (Table I). The protein content of the Swedish cultivars did not vary between the two years. The ash content was higher for the Lithuanian cultivars (α = 0.05). The pentosan content is included only for information; the results are not analyzed because two different methods were used. The pentosan content did not differ very much between 1995 and 1996 for the Swedish cultivars, but Amando and SWHY 94031 both had a higher content for both years.

Falling Number

The falling number values were all high (Table I), even extremely high, for rye meals. They still differed among the cultivars, indicating differences in enzymatic activity between the rye meals. The Lithuanian flours had the lowest falling numbers (249 ± 30 sec, α = 0.01). The difference between 1995 and 1996 for the Swedish flours was small (α = 0.05). The effect of inclusion of $AgNO_3$, which was added to inhibit the α-amylase activity (Kuracina et. al 1987), was an increase in the falling number for all flours. The differences between the three groups of flours were not significant when $AgNO_3$ was added, indicating that when the flours were not affected by enzymatic hydrolysis their behavior was more similar. The observed increase in falling number in the presence of $AgNO_3$ was more pronounced for the Lithuanian samples than for the Swedish samples, with an increase from 249 ± 30 to 343 ± 35 sec for the Lithuanian samples. Falling number values without $AgNO_3$ showed a good correlation to falling numbers with $AgNO_3$ (R^2 = 0.71, $P < 0.001$).

In a study of pentosan and β-glucan content of Finnish winter rye cultivars and rye from six other countries, there was a negative correlation between pentosan content and falling number (Saastamoinen et al 1989). However, for the data in Table I, the pentosan content correlated positively with falling number content (R^2 = 0.84, $P < 0.001$). In the Finnish study (Saastamoinen et al 1989), the negative correlation was attributed to the poor weather conditions during the year of the study, causing a simultaneous decrease in falling number and increase in pentosan content. Most samples in that study had falling numbers <200; whereas, in the present study, all values were >200 (Table I).

Baking

The results of the baking tests, where breads were baked both as pan breads and as hearth breads, are presented in Table II. There was a tendency for the Lithuanian cultivars to give the largest volumes when the pan breads were compared, although the differences were not statistically significant. The results from the two different years were not significantly different for pan breads; whereas, for hearth breads, a significant difference was obtained between the Lithuanian and Swedish cultivar. A high value of the form factor is desirable (i.e., the bread should not be flat). When the form factors were compared, the lowest values were found for the Lithuanian cultivars and the highest values for the Swedish cultivars from 1995.

The correlation between falling number and bread volume/form factor was calculated; R^2 = 0.32 for pan bread and 0.67 for hearth bread ($P < 0.01$). Therefore, it seems that falling number correlates rather well to the characteristics of hearth breads but not to pan breads.

Viscograms

The rye meal viscosity results obtained from the viscograms are given in Table III. Standard deviation of the average values shows that the rye samples differed greatly in the measured parameters. All cultivars differed in the initial viscosity, although the initial pasting temperature was 60–61°C. The Swedish cultivars from 1996 gave higher values of initial viscosity than the corresponding cultivars from 1995 ($P < 0.05$) and the Lithuanian cultivars ($P < 0.01$). The temperature at the peak viscosity varied at 78–90°C, with peak viscosity at 334–1,030 BU. The Lithuanian cultivars had lower peak temperature ($P < 0.05$ in 1995, not significant in 1996) and lower peak viscosity ($P < 0.01$ in both years) compared with the Swedish cultivars. Viscosities at 50°C during cooling were considerably lower for the Lithuanian cultivars ($P < 0.05$, both years). This reflects the higher α-amylase activity for these meals, observed as low falling numbers and an increase in falling numbers in the presence of $AgNO_3$ (Table I). The Swedish cultivars harvested in 1996 had higher initial viscosity and temperature at peak viscosity than the samples from 1995. Other than that, there were no significant differences between the years.

The temperature at peak viscosity correlated well with falling number (R^2 = 0.88, $P < 0.001$). High falling number values corresponded to high viscosity values obtained from the viscograms, and the correlation between viscosity at peak temperature and falling number was also good (R^2 = 0.87, $P < 0.001$). The correlation between viscogram data and baking results were poor for pan bread but better for hearth bread. The best correlation was obtained for the temperature at peak viscosity and baking results for specific volume (R^2 = 0.11) for pan bread and for form factor (R^2 = 0.77) for hearth bread ($P < 0.001$).

Fundamental Rheological Measurements

Rheological measurements were performed after an incubation period (60 min) at 28°C, corresponding to the first fermentation stage in the breadmaking process. The results are presented as elastic modulus (G'), viscous modulus (G''), and phase angle (δ) versus frequency, strain, or temperature.

G' and G'' versus frequency are shown at a constant temperature of 45°C in Fig. 1A-C. Both moduli increased with frequency and G' was higher than G'', demonstrating that the system is elastic. The average values of G', G'', and the phase angle at the frequency $f = 1$ Hz are given in Table IV. G' and G'' values for Lithuanian samples were lower in comparison with G' and G'' for the Swedish cultivars (although the difference in G' was not significant when compared with the Swedish flours from 1995). The results in Table IV show that the values obtained at 45°C differed considerably between the years, although the chemical composition did not vary to that extent (Table I). For the flours from 1996, much higher G' ($P < 0.01$) and lower δ ($P < 0.01$) values were observed, indicating a stiffer and more elastic dough for these flours at 45°C compared with the other flours. Differences between the years also were observed for the viscosity at initial pasting in the viscogram (Table III). The viscograph values were collected at a somewhat higher temperature (60–61°C) but comparison of G' and G'' at this higher temperature (data not shown) also showed large differences between cultivars.

Rheological measurements next were done during a temperature sweep, in an attempt to mimic the initial part of a real breadbaking process. A change occurred in G' and G'' during the heating of rye meal suspensions for the Lithuanian cultivars (Fig. 2A), the Swedish cultivars from 1995 (Fig. 2B), and the Swedish cultivars from 1996 (Fig. 2C). The curves were characterized by increasing G' and G'' moduli with increasing temperature, and a peak in G' at ≈63.8–67.1°C, and in G'' at ≈58–63°C. In the viscosity measurements, the initial pasting temperature was 60–61°C. It is evident from Fig. 2 that at conditions more similar to baking (i.e., a higher meal concentration and without heavy shearing), the development of viscosity starts at a lower temperature. At 60–61°C, half the maximum value or more in G' and G'' was reached.

The maximum in G' (G'_{max}), the temperature at maximum in G' (T at G'_{max}), and the phase angle (δ) at maximum in G' are shown in Table V. It is evident that the highest G' values were obtained for the Swedish cultivars in 1996 ($P < 0.001$ in comparison with Lithuanian samples and $P < 0.01$ in comparison with Swedish samples from 1995), whereas the lowest values were obtained for the Lithuanian cultivars. The temperature at G'_{max} did not change much, but the temperature was lower for the Swedish cultivars in 1996 compared with 1995 ($P < 0.001$) and the Lithuanian cultivars. The phase angle was very low, with the highest values obtained for the Lithuanian cultivars. The phase angle at G'_{max} exhibited lower values compared with those at 45°C (25–28° at 45°C and 3.9–7.3° at G'_{max}), indicating a transformation into a much more elastic system during baking.

When the temperature sweep curves (Fig. 2A–C) are compared, it is evident that both the increase in G' and the decrease in G' after the peak differ between cultivars. To evaluate the importance of this result, the rate of increase in G' (Δ) was calculated as:

$$\Delta = (G'_{max} - 2000)/(T_{max} - T_{2000}) \qquad (1)$$

where G'_{max} denotes the maximum in G' (Table V), T_{max} is the temperature at G'_{max} (Table V), and T_{2000} is the temperature when G' has reached the value 2,000 Pa (evaluated from the temperature sweeps). At a G' value of 2,000 Pa, all curves had reached a phase of steady increase (Fig. 2A–C). The results are given in Table V. The Swedish cultivars from 1996 differed from the year 1995 and from the Lithuanian samples ($P < 0.05$ in both cases), whereas the Swedish and Lithuanian cultivars in 1995 were not significantly different. Thus, there was a much more rapid increase in G' for the cultivars from 1996 than for any other.

The decrease in G' from the temperature at G'_{max} to 70°C was calculated, and the results are shown in Table V. The values of G', G'', and δ obtained at 70°C are shown in Table VI. The lowest decrease in G' was observed for the Swedish cultivars in 1995 and the highest in 1996. However, the starting value was high for the samples from 1996. Therefore, the G' values at 70°C were rather similar for the two groups of Swedish cultivars, whereas the Lithuanian samples gave much lower values (Table VI). Although the G' values decreased considerably compared with the maximum value, the δ values changed only marginally. The average values for the two groups of Swedish samples were all very similar, whereas the Lithuanian cultivars had lower G' values and somewhat higher δ values. The strain sweep at 70°C showed that the linear region had increased, and G' was now linear up to $\gamma = 0.0185$.

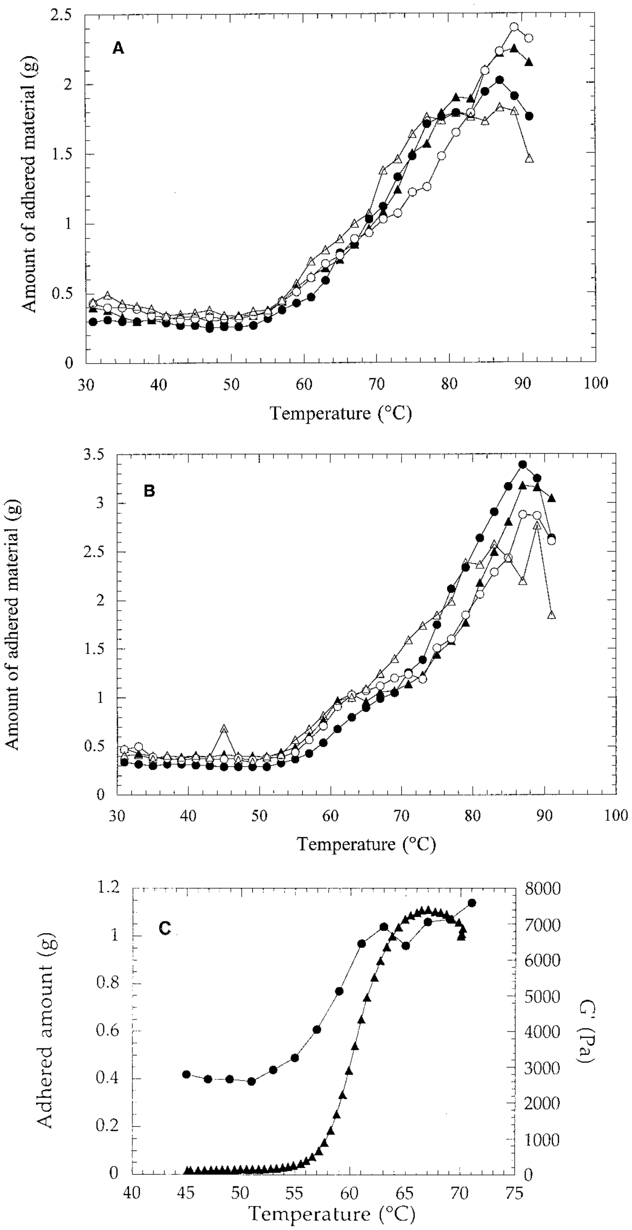

Fig. 3. Amount of adhesive material from rye meal suspensions as a function of temperature for **A,** Lithuanian flour Duoniai (●), Rukai (▲), Hy 345 (○), and Hy 346 (△); **B,** Swedish flour from 1995: Motto (●), Amando (▲), Olof (○), and SWHY 94031 (△); and **C,** change in adhesive material (●) and the change in G' (▲) vs. temperature for the rye meal suspension of Amando (from 1995).

Adhesion Measurements

The adhesion of the different flours in relation to temperature is shown in Fig. 3A–B. At temperatures <53°C, the amount of adhered material was very low, and the amount increased with increasing temperature. The maximum values were obtained at ≈87–89°C. The amount of adhered material was highest for the Swedish cultivars ($P < 0.05$). The behavior of Motto was interesting (Fig. 3B). This cultivar gave the lowest level of adhered material at temperatures <70°C, but at temperatures >80°C, it showed the most adhesive behavior. The curves in Fig. 3A and B show that the increase in the amount of adhered material occurred in two steps. There seemed to be a first maximum at ≈60–65°C (close to the maximum observed for G'). This is also when the gelatinization involving swelling of starch granules and leaking of amylose started for most rye starch granules (Gudmundsson and Eliasson 1991). The change in the amount of adhered material for this temperature is compared with the change in G' for Amando in Fig. 3C. The increase in adhesion seemed to start at about the same temperature as the increase in G'. After the first maximum, the amount of adhered material continued to increase, and the second maximum was observed at 87–89°C. The amount of adhered material was compared for the different groups of rye meals at the initial constant phase; at 71°C, corresponding to the end of rheological measurements; and for the maximum amount. The only significant difference ($P < 0.05$) was for the maximum amount.

DISCUSSION

The rye cultivars in this investigation can, from a chemical point of view, be characterized as belonging to two groups. The Lithuanian cultivars had a high protein content, whereas the Swedish cultivars were lower in protein (Table I). The falling number was lowest for the Lithuanian cultivars, although this may not bear any relation to the chemical composition, but strictly be a result of higher α-amylase activity. Inhibition of the α-amylase still resulted in the lowest falling numbers for the Lithuanian cultivars, but the differences were no longer statistically significant. The flour samples can be divided into three groups depending on the falling number values: Swedish flours from 1995 (highest values); Swedish flours from 1996; and the Lithuanian flours (lowest values) (Table I).

In the baking test, the Lithuanian flours gave the best result for pan breads, whereas the best hearth breads (best form factor) were obtained for the Swedish cultivars from 1995 (and from Amando from 1996). One possible interpretation is that, in the pan bread, the factors resulting in a more fluid dough (low falling number, low pentosan content) are not so crucial; whereas, for the hearth bread, a high fluidity is a disadvantage, so that cultivars with high falling number and high pentosan content perform best.

The baking tests show that the requirements for baking hearth and pan bread are different. The peak viscosity, temperature, and falling number correlated with the form factor for hearth breads, but very poorly, if at all, with the loaf volume of the pan breads. This seems to indicate that a high viscosity is extremely important for hearth breads. Also, the temperature at peak viscosity seems to be important, and the higher this temperature, the better. The falling number and viscosity parameters correlate quite well, which is not surprising because the falling number measurement, in fact, is a kind of viscosity measurement. The inclusion of $AgNO_3$ did not improve correlations, which was expected, because the baking tests and viscosity measurements were performed at the natural enzyme activity. However, the inclusion of $AgNO_3$ indicated that starch (or flour) structure contributed to the falling number as well as enzyme activity (because the falling number values differed also when enzyme activity was suppressed).

For the parameters obtained from the viscogram, it could be observed that the Swedish flours usually had the highest values and the Lithuanian the lowest, except for the initial viscosity. The values for the Lithuanian flours were either not significantly different from the Swedish (1995) or had low significance ($P < 0.05$). If the viscogram was recording mainly starch properties as influenced from other components, it could be expected that the Lithuanian and Swedish cultivars should behave quite similarly, because the nonstarch content, calculated from Table I, is rather similar for all the flours. The three flours performing best in the hearth bread baking (Amando 1995, Amando 1996, and Olof 1995) gave temperatures at peak viscosity among the four highest, viscosity at peak among the five highest, and viscosity at 50°C among the five highest. The highest values were obtained for SWHY 94031 1995, which gave the fourth best form factor. For the initial viscosity value, the top three cultivars ranked from third highest to second lowest. Duoniai gave the lowest viscogram values except for the initial viscosity, and it did not perform well in the hearth bread baking test. However, it was the best pan bread flour. The flours performing best in the hearth bread baking tests all had high falling numbers. Therefore, it seems that they could have been chosen based on the falling number, but Duoniai (which performed very well in the pan bread test) would probably not have been chosen.

Information is obtained about the structure of the dough in the fundamental rheological measurements,. The mechanical spectra at 45°C show a gel-like behavior for all rye meal suspensions; turning into the behavior typical of a strong gel at 70°C (Clark and Ross-Murphy 1987). The behavior at 45°C seems to be important for baking behavior, because δ correlated strongly to the form factor for hearth breads. However, the correlation was positive, meaning that a more viscous behavior at 45°C is beneficial. The best hearth bread baking flours (except Amando 1996) gave intermediate values of G' and G'' and high values of δ.

The maximum in G' occurred at a much lower temperature than the corresponding viscosity measurements (≈62–67°C compared with 78–90°C). Moreover, there was no initial decrease in G' and G'', as has been observed for wheat flour doughs (Bloksma 1980). This might be attributed to the high pentosan content and the swelling of these polysaccharides during heating. The peak in G'' seems to occur at a lower temperature than the peak in G'. At G'_{max}, the δ is very low, indicating almost complete elastic behavior. For the three best performing flours (hearth bread baking), the values of the rheological parameters (Table V) were intermediate for G'_{max}, high for T at G'_{max}, low for δ at G'_{max}, low for Δ, and low for the difference between G'_{max} and $G'_{70°C}$. If these results are related to baking, this could indicate that there should be a slow increase in G' up to the maximum value (which should not be too high), which should be obtained at as high a temperature as possible (late during the baking process). Then there should be only a small decrease in G' after the maximum. The value of δ at G'_{max} should be low. However, the differences in δ between the flours were small, and the values were all very low. This probably means that these values should be low enough, but that there is not an important difference between δ = 6.0 and δ = 4.5.

The amount of the adhered material of rye meal suspensions during the gelatinization process corresponded to the viscosity results determined by viscography. A gradual increase of the parameters analyzed by these two methods was observed until the maximum was reached. There was a positive correlation between the maximum values of the amount of the adhered material and the maximum viscosity of the suspensions ($R^2 = 0.61$, $P < 0.05$). Apart from that, the maximum of the amount of adhered material correlated ($R^2 = 0.78$, $P < 0.01$) with the falling number. The values of the adhered material and the viscosity started to decrease during further heating of the suspensions. The results indicated that the gelatinization process might be evaluated from the amount of adhered material.

Polymers with carboxyl and free hydroxyl groups (i.e., proteins and some carbohydrates) possess strong adhesive properties (Nikolaev 1976). Therefore, it is expected that proteins as well as pentosans contribute to the amount of adhered material. Some observations could be made while evaluating the initial gelatinization process by comparing the viscosity from viscogram and the adhered material. Heating of rye meal suspensions from 31 to 61°C indicated that the change of the adhered material depended on the rye chemical composition. These changes might not be observed by viscography. The analyzed temperature range is optimal for enzyme pentosanase activity. As described elsewhere, the amylograph is not very sensitive to small changes in relative viscosity (Hoseney 1986). Thus, the methods used in this study give us new opportunities for the assessment of rye for breadmaking and for animal feed.

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