Studies on Rye (*Secale cereale* L.) Lines Exhibiting a Range of Extract Viscosities. 2. Rheological and Baking Characteristics of Rye and Rye/Wheat Blends and Feeding Value for Chicks of Wholemeals and Breads

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Five rye lines exhibiting a wide range of extract viscosities were evaluated for the rheological and baking properties of their flours, individually and in blends with hard red spring wheat flour. Commercial cultivars of rye and triticale were included in the study as controls. Extract viscosities of rye flours were higher than those of corresponding wholemeals, indicating shifting of water-extractable arabinoxylan into flour during roller milling. Falling numbers of the rye flours correlated positively with their extract viscosities in the presence ($r = 0.73$, $p < 0.05$) or absence ($r = 0.65$, $p < 0.05$) of an enzyme inhibitor. Farinograms revealed the weakness of rye and triticale flours compared to wheat flour. Extract viscosities of rye flours were negatively correlated ($r = -0.65$, $p < 0.05$) with mixing tolerance index and positively correlated ($r = 0.64$, $p < 0.05$) with dough stability, suggesting a positive impact of extract viscosity on dough strength. Extract viscosity was negatively correlated ($r = -0.74$, $p < 0.05$) with loaf volume and specific volume ($r = -0.73$, $p < 0.05$) and positively correlated ($r = 0.73$, $p < 0.05$) with loaf weight of rye/wheat bread. Overall, the results indicated that 30% of flour from high or low extract viscosity rye could be incorporated into rye/wheat breads without seriously compromising bread quality. Inclusion of rye, particularly high extract viscosity rye, in chick diets seriously impeded growth performance and feed efficiency. Part of the arabinoxylan survived bread-making and exerted an effect on chicks, although substantially lower digesta viscosities were observed in chicks fed rye bread diets than in those fed rye wholemeals.

Keywords: *Rye; extract viscosity; water-extractable arabinoxylan; bread-making; digesta viscosity*

INTRODUCTION

High extract viscosity in rye has been shown to be associated with a high level of water-extractable arabinoxylan (WEAX), particularly the proportion of a high molecular weight fraction (*1*−*5*). The development of rye lines exhibiting a wide range of extract viscosities (*6*, *7*) has allowed the characterization of factors contributing to viscosity differences among the lines (*5*).

Recent evidence (*8*−*11*) has shown rye bran to be more effective than oat or barley fiber in lowering total plasma cholesterol and liver cholesterol in hamsters. In northern and eastern Europe, rye has traditionally been one of the most important dietary sources of carbohydrates for humans. It is usually consumed in various types of crisp or soft breads, produced in most cases from rye wholemeal. Although the consumption of rye breads has declined over the past several decades, the present level of intake in Denmark and Finland still makes rye bread the foremost source of dietary fiber in these countries. Rye was estimated to provide 28% of the dietary fiber intake (23 g/day) in Finland (*12*).

The dietary fiber content (measured as nonstarch polysaccharides) of the mature rye kernel is ∼17%, the major component of which is arabinoxylan (*4*). The total arabinoxylan content of rye grain has been reported to range from 6.5 to 12.2% (*13*−*15*). Bushuk (*16*) estimated the water uptake by arabinoxylan to be ∼15 g of water/g (moisture-free basis). This high water holding capacity affects water partitioning in rye-based doughs and, consequently, contributes structural elements to rye bread (*2*). Kühn and Grosch (*17*) reported that water-extractable arabinoxylan (WEAX) and unextractable arabinoxylan in rye flour affected dough consistency similarly, indicating that they had similar water binding capacities. However, the baking properties of rye flour were found to depend not only on total arabinoxylan content but also on the type of arabinoxylan present. WEAX, the major viscosity factor in rye grain, had an overall positive effect, whereas water-unextractable arabinoxylan was deleterious to the baking quality of rye flour.

Numerous studies on the baking quality of rye wholemeal have been reported (*17*−*20*). Observations relevant to the present study are that the loaf volumes of rye-based goods are approximately half those of wheat-based goods and that rye breads have a longer shelf life

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and a richer flavor and aroma than do wheat breads. Weipert et al. (*21*) reported that flours from rye cultivars exhibiting high total arabinoxylan content and a high proportion of WEAX yielded rye breads (using a sourdough formula) of good quality. Similarly, including WEAX from rye in a wheat bread formulation improved baking quality (*22*−*26*). On the basis of these studies, it could be concluded that the concentration of WEAX is an important factor determining the baking quality of rye and that higher levels of WEAX would be associated with superior baking quality.

In North America, rye is used principally as a flavoring agent and its usage level in bread does not generally exceed 30% of the rye/wheat flour blend. The baking performance of rye flours having different extract viscosities, in blends with wheat flour, has not been studied extensively. In this study, the rheological and baking properties of rye flours differing in their extract viscosities and in the contents and molecular structures of their WEAX were investigated. Also, the feeding quality of these ryes, as wholemeals and as breads, was studied with broiler chicks.

MATERIALS AND METHODS

Materials. Five rye (*Secale cereale* L.) lines exhibiting a range of extract viscosities (5−95 cP) were used in this study. Low (R5) and high (R95) extract viscosity spring ryes were grown at Saskatoon, SK, in 1997, and low (R10) and intermediate (R19 and R30) extract viscosity fall ryes were grown at Swift Current, SK, in 1996−1997. Each line was designated by the corresponding extract viscosity of the wholemeal (R = rye, number = extract viscosity in centipoise). Commercial samples of fall rye (cv. Prima), hard red spring wheat (*Triticum aestivum* L. cv. CDC Teal), and spring triticale (*Triticosecale* Wittmark cv. Banjo) were obtained locally. Grains were ground using a Cyclone sample mill (UDY Corp., Fort Collins, CO) to pass a 0.5 mm screen prior to analysis. Moisture content of wholemeals and flours was determined according to AACC Method 44-15A (*27*).

Milling Tests. The optimal tempering moisture level for the milling of rye grain was determined using 100 g samples of the commercial rye tempered to 10.5, 12.5, or 14.0% moisture for 8 h. Samples were milled in a Quadrumat Jr. flour mill (C. W. Brabender Instruments, Inc., South Hackensack, NJ) equipped with a 60 mesh (U.S.) reel sifter, yielding bran, shorts, and flour fractions. The tempering moisture (determined to be 12.5%) that resulted in the highest flour extraction rate without inducing a significant depression in loaf volume (as observed during preliminary baking experiments) was chosen for use in the milling of the experimental rye lines. Wheat and triticale were milled at 15.0 and 14.0% moisture, respectively. To improve flour yield, additional sifting (60 mesh U.S.) was applied to the shorts fractions from the experimental rye lines; a flour extraction rate of ∼77% was ultimately achieved for each.

Rheological Properties of Rye, Triticale, and Wheat Flours. *Extract Viscosity Measurement.* Rye, triticale, and wheat wholemeals and flours were extracted with deionized water (1:5 meal−flour/water, w/v) on a magnetic stirrer (6.5 rpm, 90 min, 25 °C) and then centrifuged (3000*g*, 10 min). The viscosities of the supernatants were determined at 25 °C using a Brookfield cone-plate viscometer (model LVTDCP-11, Brookfield Engineering Laboratories Inc., Stoughton, MA) equipped with spindle CP-40 (*3*).

Farinography. Water absorptions of flours and dough stabilities were determined using a farinograph (C. W. Brabender Instruments, Inc.) according to AACC Method 54-21 (50 g of flour, 14% moisture basis) (*27*). Values obtained from the farinograms were as follows: dough development time (DDT), the time interval (minutes) between the first addition of water and the point of maximum dough consistency; arrival time, the elapsed time (minutes) between the commencement of mixing and the point at which the top of the curve first intersected the 500 Brabender unit (BU) line; stability, the difference between departure time (leaving the 500 BU line) and arrival time; and, mixing tolerance index (MTI), the difference (in BU) between the top of the curve at the peak and the top of the curve measured 5 min after the peak.

Falling Number. Falling numbers for wheat, triticale, and rye flours in the presence and absence of enzyme inhibitor (0.2% mercuric acetate) were determined according to AACC Method 56-81B (*27*).

Bread-Making with Rye, Triticale, and Wheat Flours. AACC Method 10-10A (*28*) was used to determine the maximum replacement level of rye flour in rye/wheat blends that did not have a dramatic effect on loaf volume, using flour from low (R10) and high (R95) extract viscosity ryes at several levels (0−70% rye flour at 10% increments). The maximum acceptable replacement level (determined to be 30% w/w) was identified on the basis of loaf volume (measured by rapeseed displacement) and general loaf acceptability. Subsequently, all of the rye flours were used at this replacement level to determine the effect of rye extract viscosity on loaf characteristics. Triticale flour was also blended with wheat flour at a 30:70 (triticale/wheat, w/w) ratio.

Bread-Making with Wheat and Rye Whole Grain Flours for the Feeding Trial. Wheat, R5, and R95 were tempered and milled as described previously, and the resulting fractions (flour, shorts, and bran) were combined to obtain whole grain flour. Breads were prepared from the whole grain flours using the lean formula (whole grain flour plus yeast plus sugar plus water plus salt) procedure described in AACC Method 10-10 (*28*). Breads were dried at 40 °C in a forced-air oven and then ground (Laboratory Mill 811, Christy Norris Engineers Ltd., Chelmsford, U.K.). The ground breads were incorporated into chick diets (described below).

Chick Feeding Trial. Diets containing low (R5) and high (R95) extract viscosity rye and wheat wholemeals and breads were presented to male broiler chicks housed in a thermostatically controlled battery brooder (Animal Care Unit, Western College of Veterinary Medicine, University of Saskatchewan, Saskatoon, SK). Chicks were given a commercial starter for one day prior to distribution to treatment groups. Fourteen chicks were housed per pen, with five pens per dietary treatment. The experimental period was 14 days, terminating when the chicks were 15 days old. The chicks were weighed at the start and at the end of the experimental period, and weighed amounts of feed (as meals) were provided as required. The compositions of the experimental diets (percent) were as follows: ground grain or ground bread (rye or wheat), 60.0; soy meal, 33.0; tallow, 4.0; limestone, 1.20; dicalcium phosphate, 1.27; salt, 0.25; D,L-methionine, 0.20; choline chloride, 0.083; vitamin/trace mineral premix to meet requirements (*29*). Feeding of the chicks was staggered (45 min intervals) to allow digesta collection at a constant time after the initial feeding. Pooled digesta (collected from the duodenum/jejunum) from three chicks constituted a single replicate, with five replicates per dietary treatment. The digesta samples were placed on ice and taken to the laboratory immediately following collection and centrifuged (3000*g*, 10 min), and the viscosities of the supernatants were determined as described previously.

RESULTS AND DISCUSSION

Tempering and Milling. A preliminary milling experiment was conducted using the commercial rye cultivar to establish optimal tempering conditions for the experimental ryes, which were available in limited quantities. Tempering to 10.5% moisture resulted in a flour yield of 80.3% (Table 1) and a loaf volume in a preliminary baking experiment of 866 mL. At 12.5 and 14.0% moisture, extraction rates and loaf volumes were 72.3 and 67.1% and 896 and 910 mL, respectively. The low flour yield at 14.0% moisture may have been due to the hygroscopic arabinoxylan causing the flour to

Table 1. Yields and Extract Viscosities of Milling Fractions from a Commercial Rye Cultivar (Prima)[a] Generated at Various Tempering Moistures

milling fraction	tempering moisture (%)	particle size (μm)	yield (%)	viscosity[b] (cP)
flour	10.5	<250	80.3 ± 1.9[c]	28.8 ± 0.4
	12.5		72.3 ± 1.1	26.3 ± 0.1
	14.0		67.1 ± 0.9	25.6 ± 0.9
LSD[d]			3.1	2.7
shorts	10.5	250−425	7.1 ± 0.2	8.4 ± 0.1
	12.5		7.8 ± 0.1	9.2 ± 0.4
	14.0		7.1 ± 0.2	16.9 ± 0.2
LSD			0.5	2.1
bran	10.5	>425	12.6 ± 0.5	6.2 ± 0.1
	12.5		20.4 ± 0.2	5.6 ± 0.1
	14.0		25.8 ± 0.6	6.4 ± 0.3
LSD			1.1	0.4

[a] Extract viscosity of wholemeal was 12.5 cP. [b] Extract viscosities determined at a 1:5 (w/v) sample-to-water ratio. [c] Mean ± standard deviation ($n = 3$). [d] Least significant difference ($p < 0.05$).

agglomerate, which would interfere with sifting (*30*). Härkönen et al. (*31*) also observed a low yield of flour when rye was milled at 14.0% moisture. A tempering moisture of 12.5% was chosen for use in the milling of the experimental rye lines as this resulted in both a satisfactory flour extraction rate and an acceptable loaf volume.

The viscosities of water extracts of flours, shorts, and bran fractions from the commercial rye sample were determined as indicators of the distribution of WEAX in the milling fractions (Table 1). Tempering moisture had little effect on the extract viscosity of flour and bran fractions; the extract viscosity of the shorts fraction obtained at 14.0% moisture was substantially higher than those of shorts fractions obtained at 10.5 and 12.5% moisture. The extract viscosities of the flour fractions were 4−5 times those of corresponding bran fractions and 3−4 times those of corresponding shorts fractions, again with the exception of the shorts fraction generated at 14.0% moisture. The results indicated that WEAX was concentrated in flour, due to its occurrence in the cell walls of the starchy endosperm (*32*). This conclusion is supported by the results of Härkönen et al. (*31*). The relatively high extract viscosity of the shorts fraction obtained at 14.0% moisture presumably reflected the proportion of flour in this fraction.

Extract viscosities of flours from rye, triticale, and wheat reflected the extract viscosities of the corresponding wholemeals (Figure 1). The viscosities of the rye flour extracts ranged from 9 to 199 cP, compared to 5−95 cP for the wholemeals. A highly significant positive correlation ($r = 0.99$, $p < 0.05$) was observed between the extract viscosities of the rye wholemeals and those of their corresponding flours. Wheat and triticale flours exhibited very low extract viscosities (2−3 cP) compared to the rye flours.

Farinograph Characteristics of Flours from Rye, Triticale, and Wheat and Rye/Wheat Blends. Farinograms (Figure 2) showed triticale and rye flours to be very weak in comparison to wheat flour (*33*). The high water binding capacity of arabinoxylan (*1*) in the rye flours, as indicated by their high farinograph water absorptions (Table 2), resulted in sticky, weak doughs exhibiting short DDT (Table 2). Compared to wheat flour, rye flours also exhibited much shorter arrival times, much higher MTI, and much lower stabilities. Extract viscosity of rye flour was negatively correlated

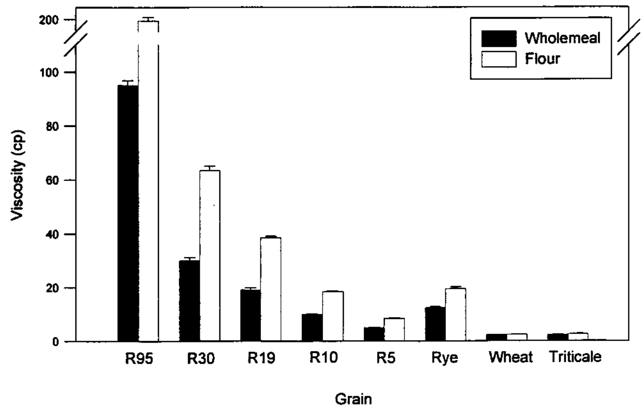

Figure 1. Extract viscosities of wholemeals and flours from experimental ryes and commercial cultivars of rye, wheat, and triticale. Each experimental rye line is designated R (rye) followed by the extract viscosity (in cP) of its wholemeal.

($r = -0.65$, $p < 0.05$) with MTI and positively correlated ($r = 0.64$, $p < 0.05$) with dough stability, reflecting a positive impact of extract viscosity of rye flour on dough strength. Among ryes, R30 and R95 doughs exhibited the highest stabilities, by far. No relationship was observed between extract viscosity and water absorption, arrival time, or DDT. Compared to the rye flours, triticale flour exhibited a low water absorption, a very short arrival time, a very short DDT, a similar MTI, and a higher stability.

The farinograph characteristics of all rye flours were much improved when blended with wheat flour (Figure 2; Table 2). A significant positive correlation ($r = 0.85$, $p < 0.05$) existed between the extract viscosities of the rye/wheat blends and their farinograph water absorptions. The arrival times of the blends were considerably longer than that of wheat flour and those of the individual rye flours, which indicated that the presence of rye flour in the system reduced its dough forming ability and increased the time required to form a consistent dough. DDT of the blends were similar to those of wheat. MTI of the rye/wheat blends were intermediate compared to those of wheat and rye.

Falling Number. There were significant differences in falling number (Table 3) among the rye flours when measured with and without enzyme inhibitor, although falling number was directly related to the extract viscosity of rye flour both in the presence ($r = 0.73$, $p < 0.05$) and absence ($r = 0.65$, $p < 0.05$) of the inhibitor. The significant increases in falling number observed for the commercial rye and triticale flours and the low extract viscosity rye flours in the presence of the inhibitor indicated a high level of α-amylase activity or arabinoxylanase activity, or both, in these flours, although none of the grain samples from which these flours were derived appeared to be weather damaged in any way. These results are in keeping with the hypothesis of Weipert (*20*) that arabinoxylans in rye reduce the amount of starch damage incurred during milling and, therefore, the susceptibility of starch in flour to degradation by α-amylase, as the largest increases in falling number resulting from the addition of enzyme inhibitor were associated with ryes having lower extract viscosities.

Determination of the Appropriate Level of Rye Flour in Rye/Wheat Blends. To determine the maxi-

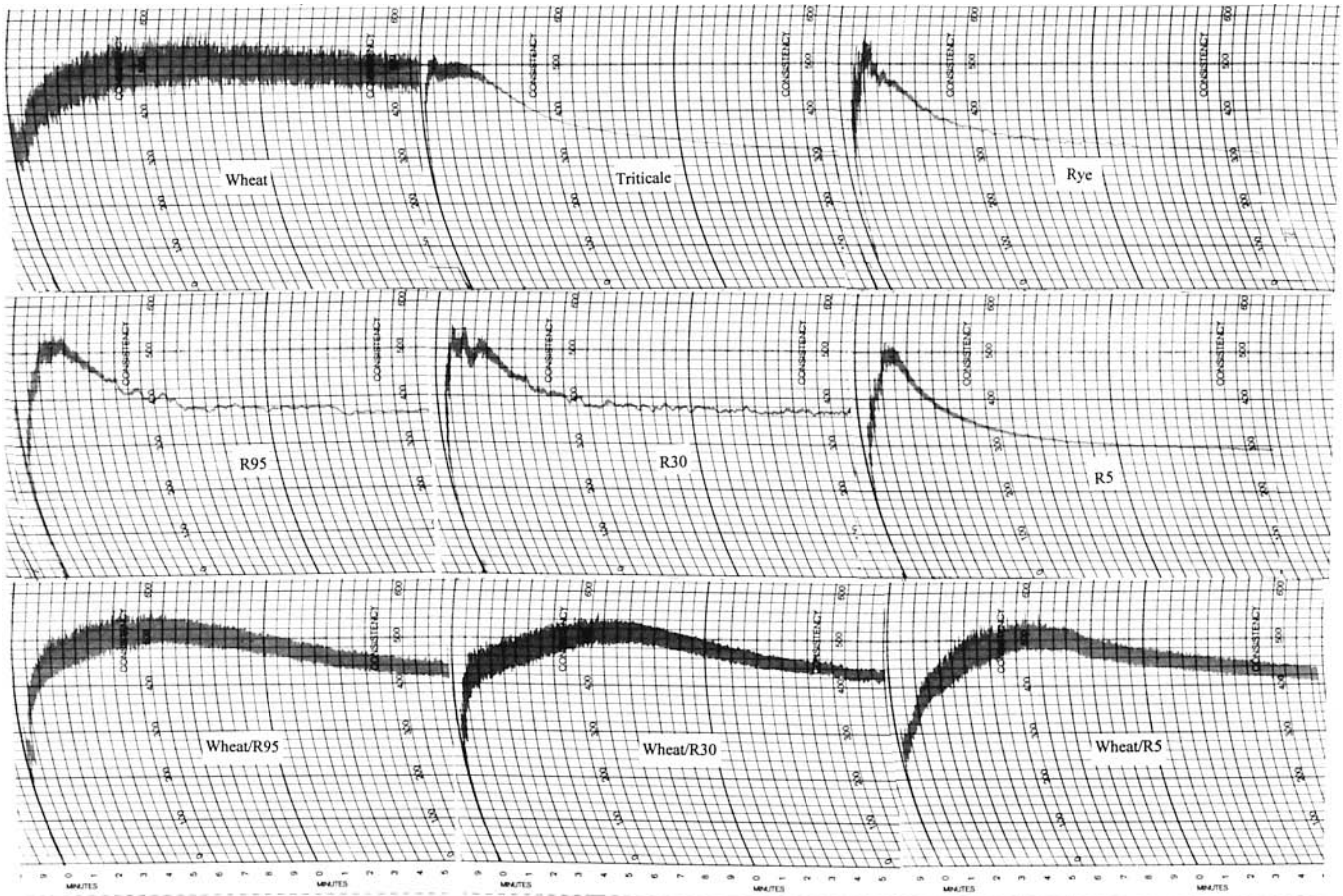

Figure 2. Farinograms of flours from commercial cultivars of wheat, triticale, and rye and from experimental rye lines (R95, R30, and R5), individually and in blends with wheat flour at a ratio of 30% rye/70% wheat (w/w). Each experimental rye line is designated R (rye) followed by the extract viscosity (in cP) of its wholemeal.

Table 2. Farinograph Characteristics of Experimental Rye Flours and Flours from Commercial Cultivars of Rye, Wheat, and Triticale, Individually and in Blends with Wheat Flour

	water absorption (%)	arrival time (s)	DDT (s)	MTI (BU)	dough stability (s)
		Experimental Ryes[a]			
R95	73.3 ± 0.1[b]	55.0 ± 2.5	92.5 ± 3.5	125.0 ± 7.1	97.5 ± 4.0
R30	68.1 ± 0.2	30.0 ± 0.1	52.5 ± 2.5	122.5 ± 3.5	117.5 ± 3.5
R19	72.8 ± 0.4	45.0 ± 0.1	87.5 ± 3.5	165.0 ± 7.1	60.0 ± 0.1
R10	66.3 ± 0.4	42.5 ± 1.5	63.5 ± 2.9	157.5 ± 3.5	47.5 ± 0.5
R5	72.3 ± 0.4	67.5 ± 3.0	80.0 ± 3.4	172.5 ± 3.5	47.5 ± 1.5
rye[c]	66.1 ± 0.2	57.5 ± 2.5	87.5 ± 3.5	127.5 ± 3.5	62.5 ± 2.5
LSD[d]	0.8	9.5	11.3	10.1	13.8
		Rye/Wheat Blends (30:70, w/w)			
R95	70.3 ± 1.1	157.5 ± 6.6	322.5 ± 10.6	20.0 ± 0.1	540.0 ± 22.4
R30	69.3 ± 0.4	127.5 ± 5.6	345.0 ± 15.2	47.5 ± 1.5	465.0 ± 21.2
R19	70.0 ± 0.1	180.0 ± 0.6	332.5 ± 3.5	37.5 ± 1.5	382.5 ± 10.6
R10	67.8 ± 0.4	157.5 ± 6.6	315.0 ± 21.2	22.5 ± 1.0	472.5 ± 10.6
R5	67.3 ± 0.4	175.0 ± 7.1	322.5 ± 10.6	52.5 ± 2.5	322.5 ± 10.6
rye	66.3 ± 1.1	127.5 ± 5.6	315.0 ± 0.1	20.0 ± 0.1	450.0 ± 20.4
LSD	2.3	13.4	23.9	6.8	51.1
wheat[c]	66.7 ± 0.4	115.0 ± 5.1	315.0 ± 14.2	5.0 ± 0.0	1155.0 ± 21.2
triticale[c]	59.8 ± 0.4	15.0 ± 0.1	37.5 ± 1.5	137.5 ± 3.5	130.0 ± 6.1
triticale/wheat[e]	64.3 ± 0.4	112.5 ± 5.3	285.0 ± 12.2	22.5 ± 1.0	585.0 ± 21.2

[a] Each line is designated R (rye) followed by its wholemeal extract viscosity (in cP). [b] Mean ± standard deviation ($n = 3$). [c] The wholemeal extract viscosities (in cP) of rye, wheat, and triticale were 12.2, 2.3, and 1.9, respectively. [d] Least significant difference ($p < 0.05$). [e] 30:70, w/w.

mum level of rye flour that could be incorporated into a rye/wheat blend without causing a marked decline in loaf quality, flours from two rye lines (R95 and R10) representing extremes in flour extract viscosity (199 and 20 cP, respectively, Figure 1) were substituted for wheat flour at levels of up to 70% rye flour (in 10% increments). Despite the differences in extract viscosity of the rye flours, loaf volume declined in a similar fashion as the level of each rye flour increased (Figures 3 and 4), although R95 had a somewhat greater depressing effect on loaf volume than did R10. The reductions in loaf volume were expected as a result of both dilution of the wheat gluten by the rye flour and the increase in the level of WEAX in the blend. Beyond 30% rye flour, loaf volume and other bread characteristics, including crust smoothness and crumb stickiness and density, became

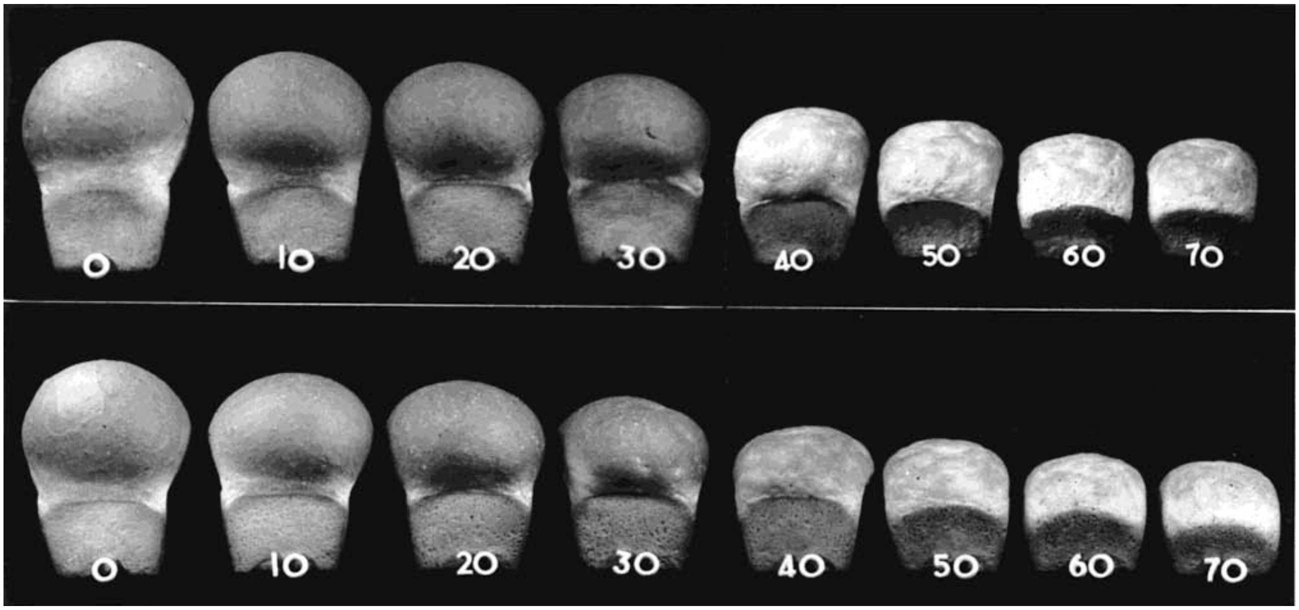

Figure 3. Appearance of bread baked from wheat flour replaced with 10−70% of R10 (top) or R95 (bottom) rye flour.

Table 3. Falling Numbers of Flours from Experimental Rye Lines and from Commercial Cultivars of Rye, Triticale, and Wheat, with and without the Addition of an Enzyme Inhibitor[a]

flour	falling number (s)	flour	falling number (s)
Without Enzyme Inhibitor			
R95[b]	295.5 ± 6.4[c]	rye[d]	82.5 ± 3.5
R30	287.5 ± 3.5	triticale[d]	112.0 ± 1.4
R19	274.0 ± 4.2	wheat[d]	422.0 ± 11.3
R10	263.0 ± 6.4	LSD[e]	10.3
R5	141.5 ± 2.1		
With Enzyme Inhibitor			
R95	402.0 ± 3.0	rye	314.0 ± 2.5
R30	377.0 ± 5.5	triticale	330.1 ± 11.3
R19	387.0 ± 4.5	wheat	450.0 ± 6.0
R10	313.0 ± 2.0	LSD	15.7
R5	297.0 ± 2.5		

[a] Mercuric acetate (0.2%, w/v). [b] Each line is designated R (rye) followed by its wholemeal extract viscosity (in cP). [c] Mean ± standard deviation ($n = 3$). [d] The wholemeal extract viscosities (in cP) of rye, wheat, and triticale were 12.2, 2.3, and 1.9, respectively. [e] Least significant difference ($p < 0.05$).

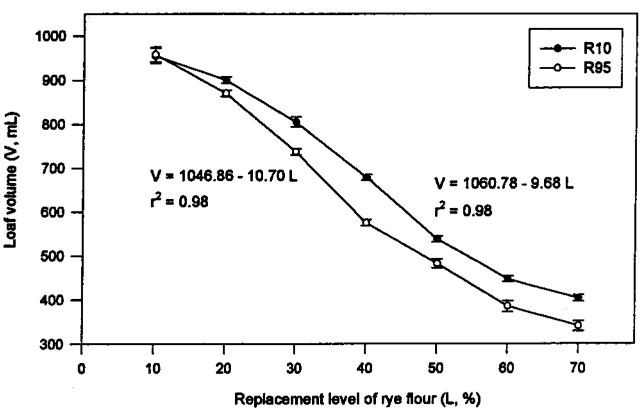

Figure 4. Effect of the level of replacement of wheat flour by R10 and R95 rye flour on loaf volume.

progressively less satisfactory as the proportion of rye flour in the blend increased. On the basis of these results, 30:70 rye/wheat blends were used in subsequent baking studies with the experimental rye lines. In light

Table 4. Extract Viscosity and Baking Quality of Rye/Wheat and Triticale/Wheat Blends (30:70, w/w) Compared to That of a Wheat Flour Control

	extract viscosity (cP)	loaf vol (mL)	loaf wt (g)	specific vol (mL/g)
blends[a]				
R95	10.3 ± 0.5[b]	793.3 ± 7.6	141.9 ± 1.2	5.6 ± 0.1
R30	8.8 ± 0.3	818.3 ± 7.6	141.9 ± 0.4	5.8 ± 0.0
R19	8.3 ± 0.1	841.7 ± 7.6	142.9 ± 0.9	5.9 ± 0.0
R10	5.2 ± 0.0	838.3 ± 2.9	140.1 ± 0.5	6.0 ± 0.1
R5	4.0 ± 0.0	815.0 ± 13.2	142.2 ± 0.6	5.7 ± 0.1
rye[c]	5.9 ± 0.0	896.7 ± 17.6	139.1 ± 0.6	6.4 ± 0.1
triticale[c]	2.3 ± 0.0	945.0 ± 13.2	139.7 ± 0.1	6.8 ± 0.1
wheat[c]	2.4 ± 0.1	971.7 ± 5.8	138.0 ± 0.4	7.0 ± 0.1
LSD[d]	0.7	17.7	1.2	0.1

[a] Each experimental rye line is designated R (rye) followed by its wholemeal extract viscosity (in cP). [b] Mean ± standard deviation ($n = 3$). [c] The wholemeal extract viscosities (in cP) of rye, wheat, and triticale were 12.2, 2.3, and 1.9, respectively. [d] Least significant difference ($p < 0.05$).

of the similarity in baking performance seen for R95 and R10 flours, it was concluded that extract viscosity would be a minor consideration in the selection of rye grain for its baking performance in rye/wheat blends.

The structural characterization of WEAX isolated from rye wholemeals (R95, R30, and R5) (*5*) may explain, in part, differences in the effects of rye flours varying in extract viscosity on dough characteristics and loaf volume. The molecular structure of WEAX from high extract viscosity rye (R95) was described as an extended, long-chain polymer with a large radius of gyration (R_g), a large hydrodynamic radius (R_h), and a high degree of unsubstituted xylopyranosyl (Xylp) residues. These structural features would facilitate hydrogen bonding (in the dough system) between gluten (from wheat flour) and the unsubstituted region of the WEAX. Hydrogen bonding would enhance the strength of the dough, as indicated by the relatively high farinograph stability of the R95/wheat blend (Table 2). The smaller loaf volume obtained with the R95/wheat blend (Table 4) suggests, however, that hydrogen bonding between arabinoxylan and gluten was disrupted during baking, which resulted in a loss of gas-retentive strength and, consequently, reduced loaf volume. More extensive

Table 5. Results Obtained from a Chick Feeding Experiment Using Diets Containing Wheat or R5 or R95 Rye Wholemeals or Breads Made from Whole Grain Flours

treatment	wt gain (g)	feed conversion (F/G)	viscosity (cP) extract	diet extract	digesta
wholemeals					
wheat	398.3 ± 14.0[a]	1.44 ± 0.05	2.4 ± 0.0	1.5 ± 0.0	5.9 ± 0.2
R5[b]	335.4 ± 10.0	1.61 ± 0.02	4.5 ± 0.0	3.4 ± 0.1	82.3 ± 3.2
R95	280.4 ± 19.8	1.71 ± 0.06	95.0 ± 1.1	9.3 ± 0.6	196.0 ± 5.0
LSD[c]	44.6	0.16	3.1	0.3	39.2
breads					
wheat	ND[d]	ND	2.1 ± 0.1	1.4 ± 0.1	2.9 ± 0.3
R5	ND	ND	3.7 ± 0.1	3.1 ± 0.1	13.2 ± 0.1
R95	ND	ND	28.2 ± 1.1	6.8 ± 0.1	57.6 ± 0.3
LSD			0.4	0.5	2.4

[a] Mean ± standard deviation ($n = 5$). [b] Each rye line is designated R (rye) followed by its wholemeal extract viscosity (in cP). [c] Least significant difference ($p < 0.05$). [d] Not determined.

dehydration of gluten by the higher concentration and higher molecular weight of arabinoxylan in R95 flour would also contribute to the inferior loaf volume obtained with the R95/wheat blend. Conversely, the lower concentration of WEAX in flour from low (e.g., R5) and intermediate (e.g., R30) extract viscosity ryes, along with its comparatively high degree of di- and monosubstitution of Xylp residues and its smaller molecular weight, R_g, and R_h, would hydrogen-bond less effectively with gluten in dough (reducing dough strength) and would compete, to a lesser extent, with gluten for moisture (which would enhance loaf volume). Udy (*34*) reported that gluten proteins in wheat interacted with pentosans through hydrogen bonding. The degree of interaction was found to depend on the molecular size (degree of polymerization), branching, and shape of the pentosans. These bonds appeared to contribute to the net strength of the dough.

Baking Quality of 30:70 Rye/Wheat and Triticale/Wheat Blends. The extract viscosities of the rye/wheat blends were positively correlated ($r = 0.81$, $p < 0.05$) with, but substantially lower than, those of the corresponding rye flours (Table 4). In all cases, the loaf volume obtained with the blend was lower than that obtained with the wheat flour control; the loaf volume of triticale/wheat bread was very similar to that of wheat bread. Extract viscosity of experimental rye/wheat flour blends was negatively correlated with loaf volume ($r = -0.74$, $p < 0.05$) and specific volume ($r = -0.73$, $p < 0.05$) and positively correlated ($r = 0.73$, $p < 0.05$) with loaf weight. The differences among the experimental rye lines in WEAX content and WEAX molecular weight (*5*) would account, at least in part, for the negative correlation obtained between extract viscosity and loaf volume of bread prepared from rye/wheat blends. Biliaderis et al. (*35*) demonstrated that the impact of WEAX (derived from wheat) on loaf volume was determined by both the concentration and the molecular weight of WEAX in the dough system; a linear increase in loaf volume was associated with an increase in WEAX concentration up to an optimum concentration, beyond which loaf volume again decreased due to viscosity buildup in the dough. The optimum concentrations of WEAX were determined to be 0.7 and 0.5% (w/w, WEAX/flour) for low (135000) and high (202000) molecular weight WEAX, respectively. Tao and Pomeranz (*36*) reported that WEAX in flours varied widely in their effects on bread-making quality.

Chick Feeding Experiment. The impact of WEAX on the nutritional value of rye was evident in the chick feeding experiment. The highest body weights (398 g) were associated with chicks fed the wholemeal wheat diet, followed by those of chicks fed the low extract viscosity rye (R5) diet (335 g) and those fed the high extract viscosity rye (R95) diet (280 g) (Table 5). Feed conversion (F/G) followed the same trend, with significant differences between wheat and both ryes but not between ryes. This confirms previous reports that high digesta viscosity in chicks fed diets containing rye seriously impeded growth and feed use efficiency (*37*–*41*). These results are consistent with the observation that viscosity reduction achieved through arabinoxylan depolymerization (xylanase supplementation) or water extraction improved the feeding value of rye grain (*39*).

Partial hydrolysis of WEAX during bread-making was evident, given the lower extract viscosities of the bread diets compared to the wholemeal diets (Table 5) and the significantly lower digesta viscosities of chicks consuming bread compared to those fed the corresponding wholemeals (Table 5). Digesta viscosities were reduced by approximately 50, 80, and 75% for wheat, R5, and R95, respectively, when the wholemeals were incorporated into diets as bread. This would indicate a reduction in the molecular weight of WEAX during bread-making. Cleemput et al. (*42*) reported changes in the molecular weight of WEAX during fermentation, which were attributed, in part, to enzymatic hydrolysis. Yeh et al. (*43*) reported the loss of a high molecular weight WEAX fraction after mixing of hard red wheat dough.

Conclusions. The availability of rye lines exhibiting a wide range of extract viscosities made it possible to investigate the relationships between extract viscosity and the baking quality and nutritional value (for chicks) of these ryes. Extract viscosity of rye flours was positively related to the strength of rye or rye/wheat doughs and negatively related to the loaf volume of rye/wheat (30:70, w/w) bread. The impact of extract viscosity on loaf volume was slight and, hence, would be a minor consideration in the selection of rye grain for its baking performance when blended with wheat. Extract viscosity was negatively related to the nutritional value of rye for chicks due to its impact on digesta viscosity. The relatively high digesta viscosities associated with the consumption of wholemeal rye bread indicated that a significant proportion of the arabinoxylan survived baking. This suggests that high extract viscosity rye could be incorporated into rye/wheat bread as a source of dietary fiber without seriously compromising bread quality.

ABBREVIATIONS USED

R5 and R10, low extract viscosity ryes; R19 and R30, intermediate extract viscosity ryes; R95, high extract viscosity rye; WEAX, water-extractable arabinoxylan; DDT, dough development time; BU, Brabender unit; MTI, mixing tolerance index; F/G, feed to gain; Xylp, xylopyranosyl residue; R_g, radius of gyration; R_h, hydrodynamic radius.

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