The Effect of Nonstarchy Polysaccharides from Yam, Sorghum, and Millet Flours on the Rheological Behavior of Wheat Doughs[1]

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ABSTRACT

Water-soluble and water-insoluble nonstarchy polysaccharides with accompanying protein were extracted from flours milled from two species of West African yam (*Dioscorea rotundata* Poir., *D. alata* L.), three different types of sorghum grain, and one type of millet grain (Souna II). They were tested for their effect on the farinographic characteristics and stress-strain behavior of wheat doughs prepared from CHRS wheat flour to which 1% of the tested isolated material was added (by replacing an equal amount of flour). Water-soluble and water-insoluble pentosans extracted from the same CHRS wheat flour were used for comparison. A great variability was found between the isolates of different plant origin with respect to both chemical composition and their effect on the rheological behavior of wheat dough. Isolated water-soluble material, with the exception of the isolates from Senegal sorghum, had a slight improving effect on the dough which became obvious not only from the rheological measurements, but also from the higher loaf volumes of loaves baked from flour to which the individual tested isolates were added (replacing 1% flour, at constant moisture content of the dough). On the other hand, water-insoluble fractions had a detrimental effect on the loaf volume; the greatest reduction was observed when water-insolubles from CHRS wheat flour were applied. Though grain and texture of the loaves were comparable with the control, the crumb color varied depending on the source of the isolates. The crumb color changes were positively correlated with the color of the lyophilized isolates.

In the past few decades, there has been an increased interest in the use of composite flours in bread baking. This has attracted the attention of many research workers to the functional properties of various components introduced into composite flour formulas by wheat flour substitutes.

It has been reported recently (1) that flours prepared from tubers of some species of yam (*Dioscorea*), when used in mixtures with strong wheat flour at concentrations not higher than 15%, may have a less deleterious effect on the rheological quality of the bread dough, and on the final loaf volume, than flours from some other starchy root or tuber crops. Since these results were obtained, in spite of rather unfavorable bread-baking characteristics of the starches extracted from the tested yam flours (high gelatinization temperature, very low amylolytic susceptibility, etc.), it could be concluded that some other components of these flours might play a more important role in the process of dough development and baking than the starch itself.

Since water extracts from the tubers of the above-mentioned species are very viscous and almost mucillagineous, it was expected that the flours might contain components similar in functional characteristics to those found in cereal flours and generally known as pentosans. Though there are still differences in opinion with respect to the functionality of these nonstarchy polysaccharides and associated glycoproteins in the process of dough development and baking, it is agreed that they may have a considerable effect on the baking potential of flour (2–9).

Therefore, both water soluble and insoluble nonstarchy polysaccharides were extracted from the tubers of the two most common West African species of yam

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(*Dioscorea*) and together with the same fractions of two other possible wheat flour substitutes, sorghum and millet flours, were compared with the pentosans of a strong flour milled from Canadian hard red spring wheats. In this part of the study, the main attention was paid to the effect of the isolated material on the rheological behavior of the wheat flour doughs.

MATERIALS AND METHODS

Samples

Both species of yam used in these investigations (*Dioscorea rotundata* Poir., cv. Puna, and *D. alata* L.) were grown in Ghana. The tubers were peeled and sliced into slices approximately 0.125 in. thick, sun-dried, then crushed and milled on an Allis-Chalmers mill to pass through a 70GG sieve. This procedure was preferred to any other technique of grinding or pulverizing since it allowed the best possible separation of fiber from other insoluble polysaccharides.

For the isolation of the nonstarchy polysaccharides from sorghum flours three different types of sorghum grains were used. Since complete botanical identification of these types was not available, the samples were identified by the country of origin: Senegal, Niger, Kansas. Millet grains (Souna II) were grown in Senegal and were supplied by H. Perten, L'Institute de Technologie Alimentaire, Dakar, Senegal. The grains were dry dehulled in the Palyi compact dehulling and milling system (10), and ground to pass through the same sieve as milled yam tubers. Then they were defatted with petroleum ether before starting the extraction.

Wheat pentosans used as standards for comparison were extracted from a commercial bread flour milled from Canadian hard red spring wheats supplied by Cherry Taylor Flour Mills Ltd., Preston, Ont. (14.1% protein, 0.56% ash, farinograph absorption 65.3%, all on 14% moisture basis).

Isolation of Nonstarchy Polysaccharides

The soluble nonstarchy polysaccharides were extracted from the tested materials by a procedure similar to that used by Lin and Pomeranz (11) for the extraction of water-soluble pentosans from wheat flour. For the extraction of water-insoluble fraction, the procedure by Jelaca and Hlynka (5) was applied. The extracted material was treated with fungal glucoamylase (grade II, Sigma Chemical Co., St. Louis, Mo.) to remove any remaining starch.

Chemical Analysis

Plant materials used for the preparation of flours as well as some of the milling products were tested for "total pentosans" using the bromine volumetric AACC standard method (12). Protein and fiber in the lyophilized extracted material were determined according to AOAC methods (13).

Paper Chromatography

Samples of lyophilized extracts were hydrolyzed (14) and chromatographed on Whatman No. 1 paper according to the procedure of Kuendig et al. (15). Xylose, arabinose, glucose, galactose, and mannose were located with silver nitrate solution (16). For quantitative determination, individual carbohydrates were eluted with water and determined in eluates by the phenol sulfuric method of Dubois et al. (17).

DEAE-Cellulose Chromatography

Fractionation of the water-soluble nonstarchy polysaccharides was performed with DEAE-cellulose chromatography (15). Carbohydrate content in the eluates was estimated by the phenol-sulfuric method of Dubois et al. (17). Protein content was determined by Lowry's method using the Folin-Ciocalteau phenol reagent (15).

Farinograph Measurements

To study the effect of the extracted material on the dough consistency and development time, the lyophilized samples were added to wheat flour at a level of 1%, replacing an equal amount of flour. Unless otherwise stated, the farinograph absorption was kept constant 65.3% (14% moisture basis). A farinograph (50-g. mixing bowl) with electronic strain-gauge recording system was used and therefore the results are reported in units of torque (kg. cm.) instead of Brabender units. Water nonsoluble material was mixed with flour in pulverized form; water-solubles were rehydrated and added in the form of a solution as suggested by Kulp (4).

Stress-Strain Measurements

Doughs for stress-strain measurements, using Instron Universal Testing Machine (Instron Engineering Corp., Canton, Mass.), were also prepared by mixing in the mixing bowl of a Brabender farinograph. Unless otherwise stated the doughs were prepared at a lower farinograph absorption of 64.4% (14% moisture basis) and after addition of 1.5% NaCl, the doughs were mixed to a

TABLE I. TOTAL "PENTOSANS" AS DETERMINED IN THE TESTED MATERIALS BY THE VOLUMETRIC BROMINE METHOD

Material Used for Pentosan Determination	Total "Pentosans" (d.b.) %
Wheat flour (CHRS)	2.9
Yam	
D. rotundata Poir.	
Peeled tubers	4.0
Coarse flour—70GG throughs 10xx tailings	4.3
Fine flour—10xx throughs	2.8
D. alata L.	
Peeled tubers	4.3
Coarse flour—70GG throughs 10xx tailings	4.5
Fine flour—10xx throughs	2.4
Sorghum (ground dehulled grains)	
Kansas	6.5
Niger	4.6
Senegal	2.6
Millet (ground dehulled grains)	
Souna II (Senegal)	3.6

maximum development. Further procedure of resting the dough, cutting it into rings of constant geometry, and stretching the rings in simple tensile mode was described in full detail earlier (18). All measurements were carried out at 25° C. and at four different crosshead speeds of 100, 50, 20, and 10 cm. min.$^{-1}$. The curves obtained on the recording chart of the Instron Universal Testing Machine were transformed into true stress (stress based on the actual cross-sectional area of the sample) - strain relationships, which were then analyzed in terms of time-independent strain function $\Gamma(\lambda)$, isochronal constant strain rate modulus $F(t^*)$ for $t^* = 0.1$ min., and time-dependent modulus $F(t)$. A procedure outlined by Tschoegl et al. (19) was used for this analytical treatment of stress-strain data.

Dough Extensibility

The extensibilities of the doughs were expressed in terms of "failure envelopes," constructed from the rupture data obtained by stretching the doughs at the above-mentioned four crosshead speeds until rupture occurred. The values of break stress, σ_b, were plotted against the values of corresponding break strain (λ_{b-1}) on logarithmic coordinates (20).

Baking Tests

Baking tests were done using a modified AACC straight-dough procedure (12) with 35 g. flour (14% moisture basis) and with 1% lyophilized extracted material added to replace an equal amount of flour. The soluble fraction was added to flour after being dissolved in water, whereas the water-insoluble one was added in powdered form. The baking formula included 3% yeast, 4% sugar, 1.5% salt, and 2% shortening. Doughs prepared at uniform absorption levels were mixed in Swanson mixograph to optimum consistency. A 2-hr. fermentation period and 55-min. proofing period were used. The setting on the sheeting rolls (National Manufacturing, Lincoln, Nebr.) for punching (after 65 min. and additional 35 min.) was 3/16 in., for molding, first 3/16, second 5/32 in. The doughs were molded with the National Manufacturing molder with the stops on the rolls removed. Loaves were baked at 230° C. for 20 min., and the loaf volumes were measured by rapeseed displacement 1 hr. after baking. Baking tests were done in triplicate and the average value of the specific loaf volume was reported. Color and textural characteristics were evaluated after 24 hr. of storage in polyethylene bags. Crumb color was scored on a basis of 1 to 5, number 1 representing very good and number 5, poor.

RESULTS AND DISCUSSION

Analytical Data

The results obtained by the bromine volumetric method with materials used for the extraction of the nonstarchy polysaccharides indicated a pentosan content in all samples, even in the finest milling fractions, comparable to that of CHRS wheat flour used in the control tests (Table I).

However, chemical analysis and paper chromatography of the isolated material showed that most of it contained considerable quantities of protein (water-insoluble fractions contained also fiber) and that sugars other than pentosans were also present in larger amounts (Table II). It was therefore found more appropriate to consider the isolates as nonstarchy polysaccharides with

TABLE II. CHEMICAL COMPOSITION OF FRACTIONS USED IN THIS STUDY, ISOLATED BY PROCEDURE USED FOR THE ISOLATION OF WHEAT FLOUR PENTOSANS (2,11)

Flour Used for Isolation	Fraction[1]	Yield (flour basis)	Chemical Composition (d.b.)							Ratio L-arabinose: D-xylose
			Protein %	Fiber %	Glucose %	Galactose %	Mannose %	L-arabinose %	D-xylose %	
CHRS Wheat	WS	0.83	8.0	...	3.9	5.6	0.8	27.9	50.0	0.56
	WIS	2.50	7.5	7.3	1.2	trace	0	30.3	53.5	0.57
Yam										
D. rotundata	WS	0.31	1.7	...	5.0	9.9	4.7	10.6	66.5	0.16
	WIS	1.73	6.3	9.7	77.1	0.6	trace	1.6	4.7	0.32
D. alata	WS	0.30	3.7	...	25.6	3.1	3.2	17.9	41.8	0.43
	WIS	1.50	7.5	11.0	64.8	2.0	2.6	5.1	5.1	0.50
Sorghum										
Kansas	WS	1.25	1.6	...	86.1	4.4	0	4.5	2.7	1.7
	WIS	4.60	23.8	7.4	57.3	trace	trace	5.7	3.9	1.46
Niger	WS	0.20	2.5	...	48.7	9.8	0	29.4	9.6	3.06
	WIS	1.30	18.2	9.6	25.5	8.4	0	25.5	12.7	2.00
Senegal	WS	0.27	2.0	...	46.6	9.3	0	28.0	14.0	2.00
	WIS	0.80	14.0	10.1	33.7	trace	0	25.6	17.1	1.51
Millet										
Souna II	WS	0.65	1.9	...	54.9	3.9	7.8	23.5	7.8	3.00
	WIS	1.08	16.6	5.5	25.9	0	0	25.9	25.9	1.00

[1] WS = water-soluble; WIS = water-insoluble.

TABLE III. DISTRIBUTION OF PROTEIN[1] IN FRACTIONS OF WATER-SOLUBLE ISOLATES ELUTED FROM DEAE-CELLULOSE COLUMN USING PROCEDURE ACCORDING TO KUENDIG et al. (15)

Source of Water-Soluble Isolates	Fraction No.				
	I %	II %	III %	IV %	V %
Wheat (CHRS)	0	0.8	19.4	17.7	62.1
Yam					
D. rotundata Poir.	0	0.6	3.6	29.9	65.7
D. alata L.	0	0.5	3.8	40.1	55.5
Sorghum					
Kansas	0	1.0	21.6	24.6	52.8
Niger	3.0	6.0	22.6	5.9	62.5
Senegal	0	1.0	52.7	13.6	32.7
Millet					
Souna II	4.4	1.3	39.3	19.5	35.4

[1] As percentage of total protein in the isolate.

TABLE IV. FARINOGRAPH DATA FOR MIXTURES OF CHRS WHEAT FLOUR WITH POLYSACCHARIDE FRACTIONS USED IN THIS STUDY[1]

Dough[2]	Development Time min.	Consistency (maximum) kg. cm.
Control	5.5	16.25
With 1% WS fraction from		
CHRS Wheat	7.0	16.72
Yam		
D. rotundata	8.5	17.39
D. alata	8.5	16.72
Sorghum		
Kansas	7.0	15.70
Niger	6.5	16.15
Senegal	7.0	15.10
Millet, Souna II	7.5	15.96
With 1% WIS fraction from		
CHRS Wheat	8.0	17.25
Yam		
D. rotundata	7.0	20.80
D. alata	6.5	17.48
Sorghum		
Kansas	8.0	17.40
Niger	6.0	16.34
Senegal	8.0	15.96
Millet, Souna II	6.5	16.36

[1] Study employed 50-g. mixing bowl, constant-flour method, constant farinograph absorption 65.3% on 14% m.b.

[2] WS = water-soluble; WIS = water-insoluble.

TABLE V. FARINOGRAPH DATA FOR MIXTURES OF CHRS WHEAT FLOUR WITH POLYSACCHARIDE FRACTIONS USED IN THIS STUDY[1]

Dough[2]	Absorption (14% m.b.) %	Water-Binding Capacity (14% m.b.) g. H_2O/g. added fraction	DDT min.	Stability min.
Control	65.3	...	5.5	6
With 1% WS fraction from				
CHRS Wheat	67.7	2.4	5.5	7.5
Yam (*D. rotundata*)	71.1	5.8	6.0	7.0
With 1% WIS fraction from				
CHRS Wheat	68.4	3.1	5.5	...
Yam (*D. rotundata*)	68.5	3.2	5.5	...

[1] Study employed 50-g. mixing bowl, constant-flour method, at optimum consistency of 16.25 kg. cm.
[2] WS = water-soluble; WIS = water-insoluble.

some accompanying protein, instead of using the term water-soluble or water-insoluble pentosans. The distribution of protein in individual fractions of water-soluble isolates, as obtained by DEAE-cellulose chromatography, is shown in Table III. It has not been established whether this protein was present in the individual fractions in a free form or bound to the carbohydrates in the glycoprotein form. This is now the subject of further study.

The isolates were used in this crude form to examine their total effect on the studied rheological characteristics of wheat dough.

Effect of Isolated Nonstarchy Polysaccharides on Farinograph Measurements

Table IV summarizes the effect of the isolated nonstarchy polysaccharides, both soluble and insoluble, on the farinograph consistency and development time when added to a strong (CHRS) wheat flour at a level of 1% (by replacing the same amount of flour). The results, obtained on a constant farinograph absorption basis, show the differences between tested isolates of different plant origin. As expected, water-soluble pentosans from CHRS wheat flour increased the farinograph consistency. The greatest increase, however, was observed when water-soluble isolates from *D. rotundata* Poir. were added, whereas water-solubles of *D. alata* L. origin exhibited practically the same effect as those extracted from CHRS wheat flour. On the other hand, a decrease in consistency was recorded when water-soluble polysaccharides from sorghum and millet were used. The most severe reduction in consistency resulted from the incorporation of soluble isolates from Senegal sorghum.

When these results were compared with the L-arabinose:D-xylose ratios of individual water-soluble, nonstarchy polysaccharides (Table II), an apparent relation between these ratios and the changes in farinograph consistency was noticed. Water-soluble nonstarchy polysaccharides which increased the dough consistency under the given test conditions were all found to have the L-arabinose:D-xylose ratio less than unity. On the other hand, in those which exhibited an opposite effect, L-arabinose was the predominant pentose. Though this relation was quite evident, more experimental data are needed for drawing any general conclusions. No such relation was found when water-insoluble

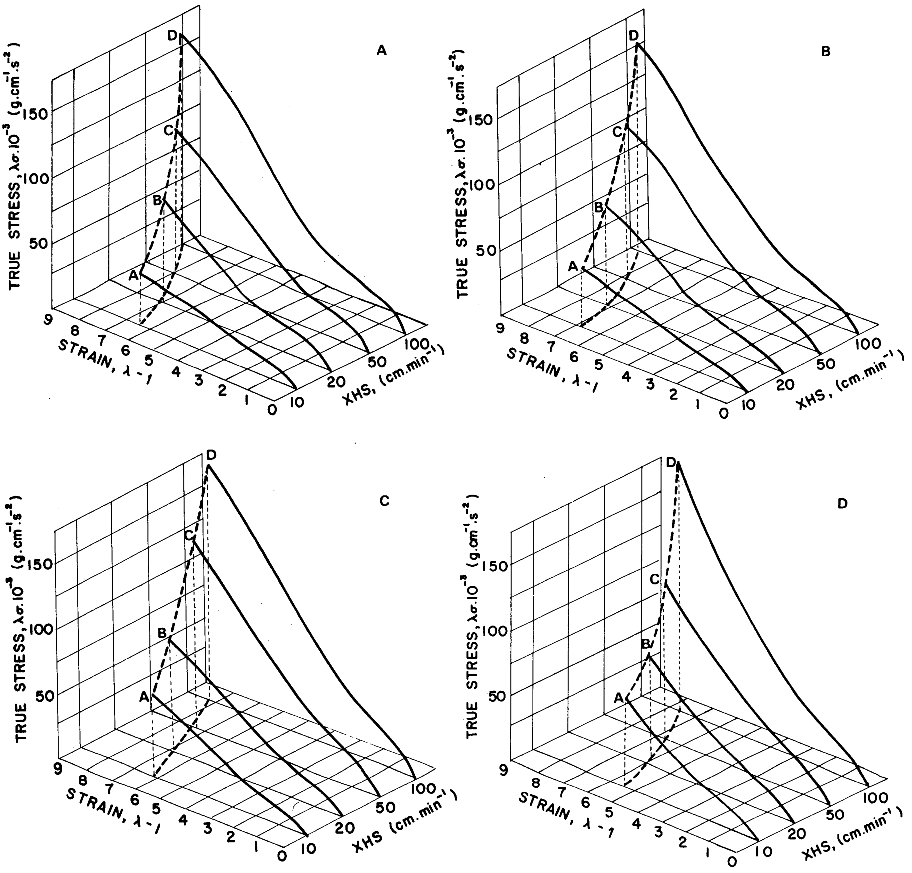

Fig. 1. True stress-strain curves for wheat doughs as obtained with Universal Testing Machine (Instron) at constant farinograph absorption 64.4% (on 14% m.b.) and 25°C. A, control; B, 1% CHRS wheat flour water-soluble pentosans; C, 1% nonstarchy polysaccharides from *D. rotundata* Poir. flour; and D, 1% CHRS wheat flour water-insoluble pentosans.

isolates were applied, in spite of the similarity of the L-arabinose: D-xylose ratios for both soluble and insoluble fractions of the same plant origin. Obviously, the presence of other components in the water-insoluble fractions had a more pronounced effect than the ratio between the present pentoses.

Water-insoluble isolates had generally a more uniform effect on the dough consistency. They all increased the consistency of the dough with the exception of insolubles from Senegal sorghum, which, like the soluble fraction of the same origin, considerably reduced the dough consistency.

Both soluble and insoluble isolates prolonged the time required to reach the maximum farinograph consistency under the conditions of uniform farinograph absorption.

Data in Table V show the results of farinograph tests with some of the

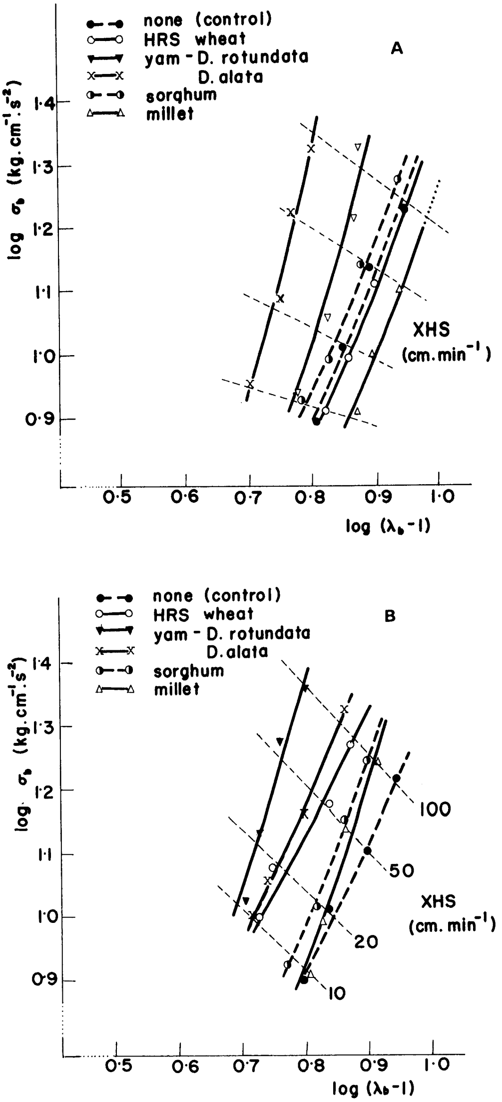

Fig. 2. "Failure envelopes" for doughs from mixtures prepared by replacing 1% CHRS wheat flour with equal amount of nonstarchy polysaccharides. A, doughs with water-soluble isolates; B, doughs with water-insoluble isolates.

tested materials on the basis of constant farinograph consistency. Under these conditions, no significant changes in dough development time were recorded, but the stability of the doughs increased slightly. The values of the calculated water-binding capacity are much lower than those reported by Kulp (4) and Jelaca and Hlynka (5) for the constant-flour farinograph method. Nevertheless, they show a

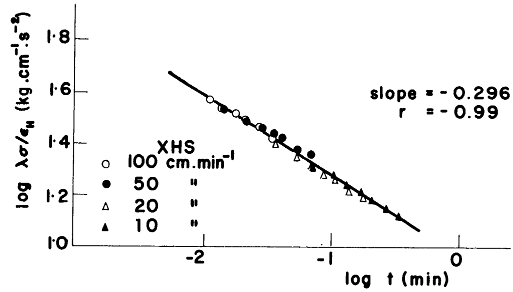

Fig. 3. Graphical determination of the exponent n from the plot of log $\lambda\sigma/\epsilon_H$ vs. log t. (Dough prepared from flour with 1% water-soluble pentosans from *D. rotundata* Poir., 64.4% moisture content.)

significantly higher water binding capacity of water-soluble nonstarchy polysaccharides from *D. rotundata* flour than those from CHRS wheat flour.

The Evaluation of Dough Extensibility from Stress-Strain Curves

For each tested dough four stress-strain curves were obtained (Fig. 1). The extensibilities of the doughs, as obtained from these curves, are graphically presented in Fig. 2 in the form of "failure envelopes." Since it is generally known that materials with the same break strength, as measured at one extension rate, will not necessarily have the same break strength at a different rate of extension, "failure envelopes" offer a better picture of the ultimate properties of the tested material than just a "one-point" measurement. In our case, the "failure envelopes" of all tested doughs were more or less parallel over the applied range of extension rates and the extensibilities of the individual doughs were given by the relative position of the "envelopes" on the break stress-break strain logarithmic coordinates.

Among the soluble nonstarchy polysaccharides, those extracted from yam flours, both of *D. rotundata* and *D. alata* origin, had a negative effect on dough extensibility. Soluble material extracted from sorghum and wheat had a less pronounced effect, the former reducing the dough extensibility, the latter changing it slightly in the positive direction. The only significant increase in the extensibility was recorded with the dough prepared from flour mixed with water-soluble nonstarchy polysaccharides from millet.

When water-insoluble isolates were applied, the extensibilities of all doughs were reduced, the degree of reduction depending upon the origin of the material used. The highest reduction was again recorded with the water insolubles from yam flours which were followed by those extracted from CHRS wheat flour.

Nonstarchy water insolubles from sorghum and millet exhibited a milder effect, the latter changing the ultimate properties of the dough to the least extent.

Since there was no significant difference found between the extensibilities of the doughs prepared from wheat flour with added sorghum isolates of different origin, either soluble or insoluble, for the sake of clarity only one representative of sorghum samples (Niger) was included in the diagrams in Fig. 2.

TABLE VI. THE EVALUATION OF STRESS-STRAIN DATA IN TERMS OF 0.1-MIN. ISOCHRONAL MODULUS, F(0.1), AND EXPONENT n FOR DOUGHS USED IN THIS STUDY[1]

Dough	Water-Soluble Fraction			Water-Insoluble Fraction		
	F(0.1) kg. cm.$^{-1}$•s^{-2}	Exponent *n*	Correlation Coefficient	F(0.1) kg. cm.$^{-1}$•s^{-2}	Exponent *n*	Correlation Coefficient
Control	19.75	-0.331	-0.98	19.75	-0.331	-0.98
With 1% addition of isolated material from						
CHRS Wheat	17.49	-0.282	-0.98	24.82	-0.333	-0.99
Yam						
D. rotundata	21.61	-0.296	-0.99	28.90	-0.299	-0.99
D. alata	19.95	-0.310	-0.99	22.92	-0.351	-0.99
Sorghum						
Kansas	18.37	-0.324	-0.97	19.72	-0.309	-0.99
Niger	19.71	-0.293	-0.99	20.63	-0.315	-0.99
Senegal	15.30	-0.279	-0.97	19.26	-0.349	-0.99
Millet, Souna II	18.00	-0.305	-0.98	19.49	-0.347	-0.99

[1] Doughs prepared at constant moisture absorption 64.4% on 14% m.b. with 1.5% NaCl and 1% replacement of wheat flour with tested polysaccharide fraction.

The Evaluation of Isochronal Modulus and Time-Dependent Modulus

Following the procedure outlined in a great detail by Tschoegl et al. (19) the stress-strain curves were analyzed in terms of 0.1 min. isochronal modulus, F(0.1), and exponent n, indicating the time dependency of the time dependent modulus, F(t). This time dependency is expressed by the following equation:

$$F(t) = Ft^{*}) \cdot (t/t^{*})^{n} \qquad (1)$$

where F(t*) is the isochronal modulus for the fixed time of extension, t*. The value of the exponent n is 0 for a material with a purely elastic response; a value of −1 signifies a steady viscous flow. Any value of n within these limits indicates that the rheological behavior of the material is both elastic and viscous.

The first step in the treatment of the stress-strain data was the establishment of the range of extensions for which the method was applicable for the tested material. For all tested doughs, the range of applicability was found between the

TABLE VII. RELATION BETWEEN FARINOGRAPH CONSISTENCY AND ISOCHRONAL MODULUS F(0.1)

Dough	Farinograph Absorption (14% m.b.) %	Farinograph Consistency (maximum) kg. cm.	Isochronal Modulus F(0.1) kg. $cm.^{-1} \bullet s^{-2}$
Control	65.3	16.25	19.66
With 1% insoluble fraction from CHRS wheat	65.3	17.25	24.01
With 1% insoluble fraction from CHRS wheat	68.4	16.25	25.2
With 1% insoluble fraction from *D. rotundata*	65.3	20.80	28.01
With 1% insoluble fraction from *D. rotundata*	68.5	16.27	19.76

TABLE VIII. THE EFFECT OF CHEMICAL FLOUR IMPROVERS ON THE VALUES OF EXPONENT n CHARACTERIZING THE VISCOELASTIC BEHAVIOR OF DOUGH[1]

Flour Treated with $KBrO_3$		Flour Treated with ADA	
Concentration of Improver p.p.m.	Exponent n	Concentration of Improver p.p.m.	Exponent n
0	-0.33	0	-0.33
30	-0.28	7	-0.28
60	-0.21	14	-0.25
90	-0.16	20	-0.18
120	-0.14		

[1] Doughs prepared at constant farinograph absorption and rested 2 hr. at 30°C.

TABLE IX. EFFECT OF STUDIED WATER-SOLUBLE AND INSOLUBLE NONSTARCHY POLYSACCHARIDES ON WHEAT FLOUR LOAVES

Dough	Water-Soluble Fraction		Water-Insoluble Fraction	
	Specific loaf volume ml./g.	Crumb color	Specific loaf volume ml./g.	Crumb color
Control	3.68	1	3.68	1
After 1% replacement of wheat flour with isolated material from				
CHRS Wheat	3.78	3	2.83	3
Yam				
D. rotundata	3.89	2	3.45	2
D. alata	3.88	2	3.07	2
Sorghum				
Kansas	3.94	1	3.51	4
Niger	3.84	2	3.42	3
Senegal	3.50	2	3.59	4
Millet, Souna II	3.78	4	3.87	5

elongations of 10 to 200%; any extrapolation to lower or higher values of elongation would lead to grossly erroneous results.

Next, the time-independent strain function, Γ (λ), required for the evaluation of both isochronal and time-dependent moduli, was established. It was found that for the tested material and for the above-mentioned range of elongations, the Hencky strain, ϵ_H, was the most appropriate strain function. (Hencky strain is defined as $\epsilon_H = \ln \lambda$, where λ is the ratio of the length of the deformed to underformed sample.) The isochronal modulus was then evaluated as the proportionality constant between the true stress for 0.1-min. interval of extension and the corresponding Hencky strain (19). The exponent n from equation 1 was calculated as the slope of the straight line resulting from the plot of log true stress/strain vs. log time of extension using linear regression program (Fig. 3).

The values of isochronal moduli and exponent n, obtained with doughs of constant moisture content and 1.5% added NaCl, are summarized in Table VI. Though Jelaca and Hlynka (5) reported that no significant changes in the rheological properties of salted doughs with added pentosans could be expected, the "Instron" method was found sufficiently sensitive to detect the effect of the added isolates even under these conditions.

The results show that, at constant moisture content in the dough, the water-soluble material extracted from yam flours was the only one among the water-solubles which increased the 0.1-min. modulus of the dough. A considerable increase was observed with dough containing water-soluble fraction from *D. rotundata* flour. On the other hand, water-soluble fractions from all other flours reduced the isochronal modulus; the greatest reduction resulted from 1% substitution of wheat flour with water-soluble fraction from Senegal sorghum.

Most of the water-insoluble materials increased the isochronal modulus, with the exception of water-insolubles extracted from Senegal sorghum and millet. Like the water-soluble fraction from Senegal sorghum, the water-insoluble one had also the strongest reducing effect on the 0.1-min. modulus. The comparison of these results with those obtained with Brabender farinograph may lead to an impression that there is a close relation between the isochronal modulus and farinograph consistency. Both farinograph consistency and isochronal modulus of the dough were strongly reduced by the addition of isolates from Senegal sorghum, both water-soluble and water-insoluble. On the other hand, the highest increase in dough consistency as well as isochronal modulus was observed after adding material isolated from *D. rotundata* flours. However, data in Table VII give sufficient evidence that this relation is ambiguous. Keeping the farinograph consistency constant by adjusting moisture content in the dough did not result in the same effect on the isochronal modulus. This was demonstrated on doughs, in which 1% of wheat flour was replaced by equal amounts of water-insolubles from CHRS wheat flour and *D. rotundata* flour, respectively. After adjusting the consistency of the dough containing the water-insolubles from *D. rotundata* flour to that of the control dough, the isochronal moduli of these two doughs were more or less identical. However, dough containing water-insolubles from CHRS wheat flour still had a much higher isochronal modulus than the control even after adjusting its consistency. The reason for this effect requires further detailed study of the effects of the individual components of the tested materials on the evaluated rheological characteristics.

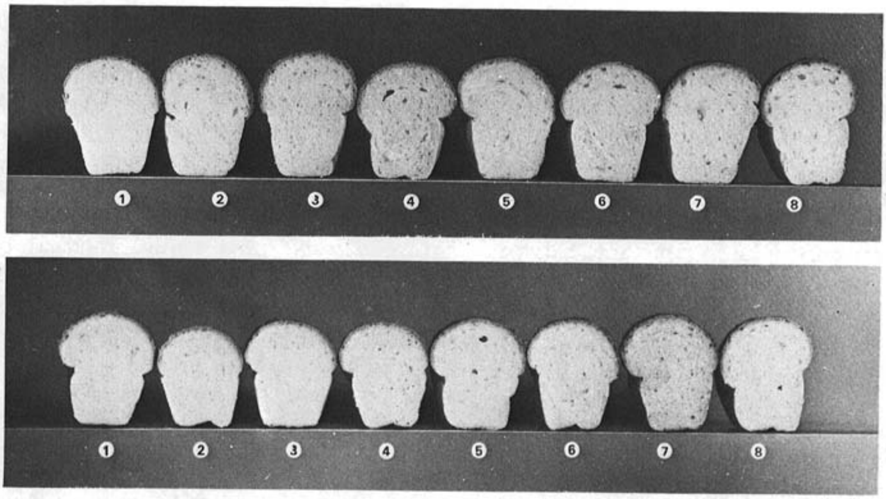

Fig. 4. Test loaves from flours (35 g.) with added nonstarchy polysaccharides (1%) at uniform moisture content. A, water-solubles from: 1. none (control), 2. CHRS wheat, 3. *D. rotundata* Poir., 4. *D. alata* L., 5. sorghum Kansas, 6. sorghum Niger, 7. sorghum Senegal, 8. millet Senegal. B, water-insolubles from: 1. none (control), 2. CHRS wheat, 3. *D. rotundata* Poir., 4. *D. alata* L., 5. sorghum Kansas, 6. sorghum Niger, 7. sorghum Senegal, 8. millet Senegal.

As far as the effect of the isolated material on the exponent n is concerned, a marked difference was found between the water-soluble and water-insoluble fractions. While water-soluble fractions exhibited, in most cases, a certain "strengthening" effect demonstrated by lower positive values of the exponent n (indicating an increase in elastic response), the water-insoluble fractions behaved more or less as an inert material. In this case, with the exception of water-insoluble fraction from *D. rotundata* flour, the changes in the values of exponent n were within the method error.

To get a better picture about the practical significance of reported changes in exponent n, values of this exponent which were obtained in earlier experiments (18) on doughs treated with some common chemical improvers (potassium bromate and azodicarbonamide) are presented in Table VIII. The data show that the "strengthening" effect of most of the water-soluble isolates, applied under the above described conditions, equaled that obtained at the lowest improver concentrations (30 p.p.m. $KBrO_3$, 7 p.p.m. azodicarbonamide) when these were applied to doughs mixed in nitrogen and rested for 2 hr. at 30° C.

Baking Tests

As expected, replacing of 1% wheat flour with an equal amount of tested water-soluble nonstarchy polysaccharides increased slightly the loaf volume of the test loaves. Smaller loaf volume resulted only from the incorporation of water-solubles from Senegal sorghum. On the other hand, water-insoluble fractions had an adverse effect with the exception only of water-insolubles from millet (Souna II). The same fraction from CHRS wheat flour had the most detrimental effect (Table IX).

Though no significant changes in the textural characteristics of the crumb were noticed, some of the breads had noticeably darker color of both the crumb and crust. This was most evident with loaves containing water-soluble or water-insoluble material from millet (Souna II) flour, followed by loaves containing water-insolubles from Kansas and Senegal sorghum. The color of the baked loaves was positively correlated with the color of the lyophilized isolates.

CONCLUSIONS

Present results indicate a considerable variability in the effect of the nonstarchy polysaccharides and accompanying protein from the tested wheat flour substitutes on the rheological characteristics of wheat flour dough. Most of the water-soluble fractions, especially those extracted from tested yam (*Dioscorea*) flours, exhibited a distinct strengthening effect. This was obvious not only from an increased farinograph consistency and stability of the dough, but also its more pronounced elastic response evaluated from the stress-strain curves. Water-insoluble fractions increased the farinograph consistency at constant absorption but, with the exception of isolates from *D. rotundata* flour, had no significant effect on the balance between the elastic behavior and steady viscous flow of the dough. The explanation of this variability in the functional characteristics of the tested materials calls for further research on their chemical structure and the functionality of their individual components.

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Literature Cited

1. RASPER, V., RASPER, J., and MABEY, G. L. Functional properties of non-wheat flour substitutes in composite flours. I. The effect of non-wheat starches in composite doughs. Can. Inst. Food Technol. J. 7: 86 (1974).
2. KULP, K., and BECHTEL, W. G. Effect of water-insoluble pentosan fraction of wheat endosperm on the quality of white bread. Cereal Chem. 40: 493 (1963).
3. TAO, R. P., and POMERANZ, Y. Water-soluble pentosans in flour varying widely in bread making potential. J. Food Sci. 32: 162 (1967).
4. KULP, K. Pentosans of wheat endosperm. Cereal Sci. Today 13: 414 (1968).
5. JELACA, S. L., and HLYNKA, I. Water-binding capacity of wheat flour crude pentosans and their relation to mixing characteristics of dough. Cereal Chem. 48: 489 (1972).
6. JELACA, S. L., and HLYNKA, I. Effect of wheat-flour pentosans in dough, gluten, and bread. Cereal Chem. 49: 489 (1972).
7. JELACA, S. Pentozani psenicnog brasna i njihov uticaj na reoloske osobine testa (Wheat flour pentosans and their effect on the rheological characteristics of dough). Hrana Ishrana 12: 384 (1971).
8. D'APPOLONIA, B. L., GILLES, K. A., and MEDCALF, D. G. Effect of water-soluble pentosans on gluten-starch loaves. Cereal Chem. 47: 194 (1970).

9. D'APPOLONIA, B. L. Role of pentosans in bread and dough. Baker's Dig. 45: 20 (1971).
10. DeMAN, J. M., BANIGO, E. O. I., RASPER, V., GADE, H., and SLINGER, S. J. Dehulling of sorghum and millet with the Palyi compact milling system. Can. Inst. Food Technol. J. 6: 188 (1973).
11. LIN, F. M., and POMERANZ, Y. Characterization of water-soluble wheat flour pentosans. J. Food Sci. 33: 599 (1968).
12. AMERICAN ASSOCIATION OF CEREAL CHEMISTS. Approved methods of the AACC. The Association: St. Paul, Minn. (1969).
13. ASSOCIATION OF OFFICIAL ANALYTICAL CHEMISTS. Methods of analysis. The Association: Washington, D.C. (1970).
14. KARM, A., and ROONEY, W. Characterization of pentosans in sorghum grain. J. Food Sci. 37: 369 (1972).
15. KUENDIG, W., NEUKOM, H., and DEUEL, H. Untersuchungen über Getreideschleimstoffe. I. Chromatographische Fraktionierung von wasserloeslichen Weizenmehl Pentosanen an Diaethylaminoaethyl-cellulose. Helv. Chim. Acta 44: 823 (1961).
16. TREVELYAN, W. E., PROCTER, D. P., and HARRISON, J. S. Detection of sugars on paper chromatograms. Nature 166: 444 (1950).
17. DUBOIS, M., GILLES, K. A., HAMILTON, J. H., REBERS, P. A., and SMITH, F. A colorimetric method for the determination of sugars and related substances. Anal. Chem. 28: 350 (1956).
18. RASPER, V., RASPER, J., and DeMAN, J. M. Stress-strain relationships of chemically improved unfermented doughs. I. The evaluation of data obtained at large deformations in simple tensile mode. J. Text. Studies 5: 414 (1973).
19. TSCHOEGL, N. W., RINDE, J. A., and SMITH, T. L. Rheological properties of wheat flour doughs. II. Dependence of large deformation and rupture properties in simple tension on time, temperature, and water absorption. Rheol. Acta 9: 223 (1970).
20. SMITH, T. L. Ultimate tensile properties of elastomers. I. Characterization by a time and temperature independent failure envelope. J. Polymer Sci. A I: 3597 (1963).

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