

## Factors Affecting Viscosity of Slurries of Oat Groat Flours

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### ABSTRACT

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Oat grain is routinely kilned and steamed before milling to develop flavor and to inactivate lipid-degrading enzymes. Heat treatments can significantly affect viscous properties, which have functional and nutritional importance. Oat flour slurries (23%, w/w, solids dry basis) made from steamed (for 20 min) or autoclaved (at 121°C, 15 psi, for 10 min) grain developed high viscosities, whereas flour slurries made from raw or kilned (105°C for 90 min) oats did not. Flour slurries made from raw groats, surface-sterilized by 1% hypochlorite, were more viscous than untreated raw groat flour slurries, suggesting that  $\beta$ -glucan hydrolases on the surface of the groat caused the viscosity losses observed in raw or kil-

ned groats. However, because viscosities developed by surface-sterilized groats were not as great as in steamed oat-flour slurries and because some roasting treatments also inactivated enzymes without enhancing viscosity, it appears steaming might also affect the  $\beta$ -glucan polymer, resulting in its greater hydration in solution. Smaller particle size and higher incubation temperature also resulted in increased flour slurry viscosity, presumably because of increased hydration of the  $\beta$ -glucan. Removal of lipids from steamed oat flour significantly increased the oat flour slurry viscosity, apparently by increasing the  $\beta$ -glucan concentration in the flour.

Oat (*Avena L.*) has long been considered a wholesome and healthful food. The water-soluble dietary fiber (1 $\rightarrow$ 3), (1 $\rightarrow$ 4)- $\beta$ -D-glucan ( $\beta$ -glucan) of oat flour or bran is of particular importance to human nutrition because of its capacity to lower blood cholesterol when incorporated into the diet (Anderson and Bridges 1993). The proposed mechanism for the hypocholesterolemic effects of soluble oat fiber seems to be related to the high viscosity imparted by the high-molecular-weight  $\beta$ -glucans (Shinnick and Marlet 1993). On the other hand, when oat was used as chicken feed, the increased gut viscosity caused by the oat  $\beta$ -glucan inhibited chicken weight gain and decreased the feed efficiency (Fadel et al 1987, Cave et al 1990). Therefore, the high viscosity imparted by  $\beta$ -glucans may be favorable when used as a human food but undesirable when used as an animal feed.

Autio et al (1987) stated that "from the point of view of application in the food industry, one of the most important physical characteristics of cereal  $\beta$ -glucans is their viscosity." The rheological properties of oat  $\beta$ -glucan extracts have been the subject of several studies (Autio et al 1987, Autio et al 1992, Westerglund et al 1993, Wilkstrom et al 1994, Doublier and Wood 1995), but the flow properties of whole oat flour slurries have not been extensively investigated. Oat is used primarily as whole-grain flour or as flakes, and the rheological properties of aqueous slurries of whole-grain oat flour may be important for both food and non-food applications of oat.

Doehler et al (1997a) reported that oat flour slurry viscosity can be used as an indirect means of estimating flour  $\beta$ -glucan concentration. The viscosity of enzyme-inactivated (steam-treated) whole-groat oat flour slurries, as measured with a rotational spindle-type viscometer, were linearly correlated with  $\beta$ -glucan concentration in the flour. The same research group (Doehler et al

1997b) also reported that heat treatments of oat grain had significant effects on the viscosity of oat flour slurries. Steamed oat produced highly viscous flour slurries, the viscosity of which increased hyperbolically with time. However, the viscosity of flour slurries from raw and roasted oats (104°C for 120 min) was much lower and degraded rapidly with extended time. Effects of steaming were partly reversed by roasting treatment and vice versa. The heat treatment used in the above experiments was chosen to represent industrial oat processing conditions (Deane and Commers 1986, Ganssmann and Vorwerck 1995).

The objective of this research was to further investigate factors such as oat flour particle size, oat flour slurry incubation temperature, and the length of heat treatments on oat flour slurry viscosity.

### MATERIALS AND METHODS

#### Oat Grain

Oat (*Avena sativa L.*) cultivars Marion and Robert were chosen for this study because Marion is a high  $\beta$ -glucan cultivar containing 5.6%  $\beta$ -glucan, and Robert is a low  $\beta$ -glucan cultivar, containing 3.9%  $\beta$ -glucan (Doehler et al 1997b). Grain was grown at Fargo, ND, during the 1995 growing season and was obtained from Michael McMullen (Department of Plant Sciences, North Dakota State University, Fargo). Samples were dehulled with a Codema laboratory oat huller (Eden Prairie, MN) and were hand picked to obtain hull-free groats. Oat groats were milled in a Retsch ZM-1 centrifugal mill (Brinkmann Instruments, Westbury, NY), fitted with a 0.5-mm collar screen unless otherwise specified. Screen sizes 1.0 and 0.2 mm were used to generate oat flours of coarse and fine particle size, respectively.

#### Heat Treatments of Oat Grain

Heat treatments were applied to grain prior to dehulling and milling. Grain was steamed in a vegetable steamer (260  $\times$  170 mm), fitted with a lid, by placing the grain in a metal basket positioned over boiling water. Grain was steamed for 20 min, unless specified otherwise. Oats were steamed in batches of 250 g at a time, which formed a layer no deeper than 1 cm in the steamer basket. Roasting consisted of placing 200 g of grain in a glass dish (190  $\times$  100 mm) and roasting the grain in a convection oven for 2 hr at 105°C, unless specified otherwise. Autoclaving was performed at 121°C and 15 psi for 10 min, in open (uncovered) containers, unless otherwise noted. After heat treatments, grain was exposed to the atmosphere, at room temperature, for 24 hr to allow moisture equilibration.

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A qualitative peroxidase activity test was conducted on oat flours by following the procedure reported by Borenstein et al (1990). Moisture content of all flour preparations were determined from weight loss from 2-g samples after incubation in a convection oven for 2 hr at 130°C.

### Viscosity Measurement

Flour slurry viscosity was measured with a Brookfield spindle-type rotational viscometer, model DV-II+, with an RV-6 spindle (Brookfield Engineering Laboratories Inc., Stoughton, MA). Oat flour (6.5 g dry basis) and distilled water to a total weight of 28.0 g (23.2%, w/w, solids dry basis) were added to a 50-ml polypropylene centrifuge tube. The flour-water mixture was stirred manually with a spatula to form a uniform suspension and then allowed to incubate in a controlled temperature water bath until viscosity measurements were made. The viscosity was measured at 50 rpm, and the accuracy of the instrument was confirmed with standard viscosity fluids (obtained from Brookfield Engineering Laboratories).

### Surface Sterilization of Oat Groats

Dehulled raw oat groats were surface sterilized with a 1% sodium hypochlorite solution for 10 min under a transfer hood and then rinsed five times with sterilized water. The surface-sterilized grain was then left under the transfer hood for 24 hr with occasional stirring to evaporate the surface moisture.

Microbial population of oat groats was quantified by the most probable number method (Alexander 1982). Two hundred groat kernels were soaked in 50 ml of double autoclaved 0.1M phosphate buffer (pH 7.2) at 4°C for 15 min with gentle shaking to suspend the microbes. The original microbial buffer suspensions were diluted in a series of 10-fold dilutions (up to 10<sup>5</sup> fold). Ali-

quots (0.1 ml) of the dilutions were spread on plates of potato-dextrose agar medium poured one day before spreading. Three plates were prepared for each dilution. Colonies were counted 48 hr after incubation at 25°C. The estimation of most probable microbial number was calculated based on the method described by Cochran (1950).

### Fat Extraction from Oat Flour

Fat extractions from oat flours were performed by using a Soxhlet fat extraction apparatus with hexane as the extraction solvent. The procedure was as described by AOCS Official Method Aa4-38 (AOCS 1993), except a 500-ml Soxhlet flask was used, 25 g of ground oat was extracted, and the extraction time was 12 hr. For reconstitution of oat lipid with defatted oat flour, oat lipid in hexane of mass equal to that extracted from the defatted flour was added back to the defatted flour. The hexane was then allowed to evaporate.

### Statistical Analyses

Experiments were conducted in triplicate. Results were analyzed by using a Statistical Analysis System (SAS) computer program (SAS Institute, Cary, NC). Analysis of variance (ANOVA) was performed by following the General Linear Model (GLM) procedure of SAS. Duncan's new multiple range test ( $\alpha = 0.05$ ) was used to differentiate treatment means determined to be significantly different. Error bars on figures represent standard deviation of means. Where error bars are not visible, standard deviation was smaller than the line symbol.

## RESULTS AND DISCUSSION

### Oat Flour Particle Size

Steamed oat flours with three different particle sizes were compared for their viscosity development at 30°C (Fig. 1). Viscosities of all slurries increased hyperbolically with time. Oat flours with fine particle size (from a 0.2-mm grinding screen) generated much greater viscosity than medium (from a 0.5-mm grinding screen) and coarse (from a 1.0-mm grinding screen) particle size oat flours (Fig. 1). The maximum viscosities ( $\eta_{max}$ ) were calculated from an extrapolation of the hyperbolic function to their asymptotes as described by Doehlert et al (1997a). All three particle sizes differed significantly ( $P < 0.05$ ) in the  $\eta_{max}$  of their slurries for both cultivars (data not shown). This finding is consistent with a previous report that more finely ground oat flour will yield more  $\beta$ -glucan during the  $\beta$ -glucan extraction process (Wood et al 1978). At the same oat flour concentration, fine particle size oat flour has greater surface area for faster hydration than does larger particle size oat flour.

### Temperature Effects on Viscosity

Temperature effects on viscosity of steamed oat flour slurries were tested at 20, 30, and 40°C. Slurries from both Robert and Marion cultivars at 40°C generated much greater viscosity than

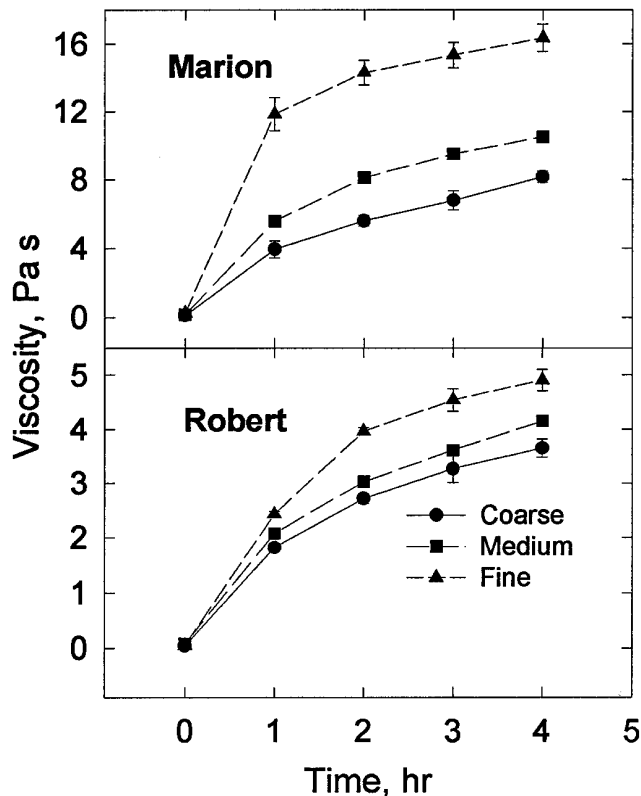


Fig. 1. Effect of oat flour particle size on viscosity development of steamed oat flour slurries (23.2%, w/w, solids dry basis). Coarse, medium, and fine oat flours were generated with 1.0, 0.5, and 0.2 mm screens, respectively. Apparent viscosity was measured with a Brookfield viscometer (RV-6 spindle, 50 rpm) at 30°C ( $n = 3$ ).

TABLE I  
Effect of Incubation Temperature on Maximum Viscosity<sup>a</sup> ( $\eta_{max}$ )  
Development of Steamed Oat Flour Slurries  
from Marion and Robert Oats

Incubation Temperature (°C)	Viscosity, (Pa·sec)	
	Marion	Robert
20	15.13 c <sup>b</sup>	4.72 b
30	18.72 b	5.23 b
40	22.67 a	7.95 a

<sup>a</sup> Maximum viscosity was calculated by the method described by Doehlert et al (1997a).

<sup>b</sup> Values within a column labeled with same letter are not significantly different ( $\alpha = 0.05$ ).

oat flour slurries at 20 or 30°C over a 4-hr incubation period (data not shown). Higher incubation temperatures for both cultivars generated significantly greater ( $P < 0.05$ )  $\eta_{\max}$  values (Table I). Temperature is an important consideration for any rheological measurement (Willett et al 1995). The viscosity of polymer solutions generally decreases with increased temperature because of increased free energy at higher temperature (Owen et al 1992). However, the oat flour slurry is a suspension, not a true solution. Higher temperatures may have increased the extent of  $\beta$ -glucan hydration, thereby increasing the viscosity of the oat flour slurries.

### Surface Sterilization of Groats

In an earlier study (Doehle et al 1997b), the time-dependent degradation of raw and roasted oat flour slurry viscosity was attributed to the enzymatic depolymerization of oat  $\beta$ -glucan. Wood et al (1978) reported that (1 $\rightarrow$ 3), (1 $\rightarrow$ 4)- $\beta$ -D-glucanase activity exists in sound oat kernels. Surface sterilization of oat groats with 1% sodium hypochlorite had significant effects on oat flour slurry viscosity (Fig. 2). Untreated (raw) Marion and Robert oat flour slurry viscosity increased initially, then decreased very

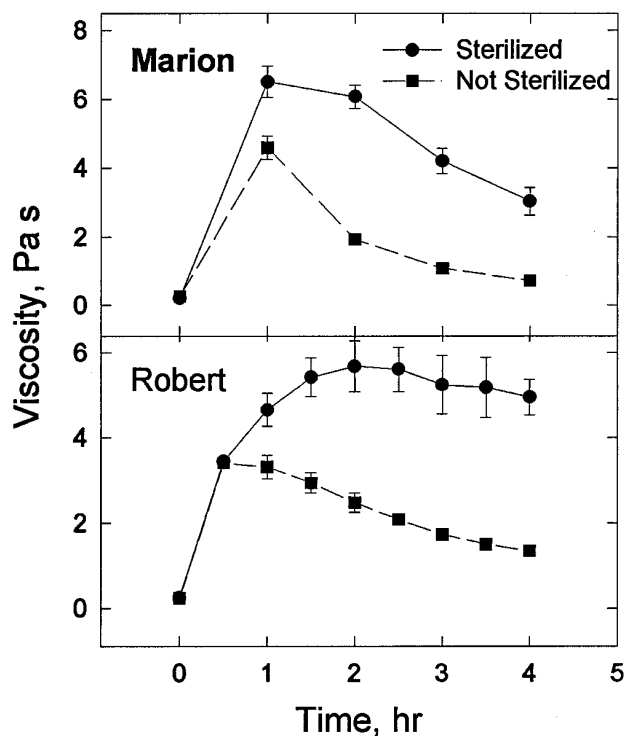


Fig. 2. Effect of oat groat surface sterilization on the viscosity development of raw oat groat flour slurries (23.2%, w/w, solids dry basis). Apparent viscosity was measured with a Brookfield viscometer (RV-6 spindle, 50 rpm) at 30°C ( $n = 3$ ).

rapidly with time. The viscosity of surface-sterilized Robert oat flour slurry viscosity increased with time and remained stable for up to 4 hr. Surface-sterilized Marion oat did not maintain a stable viscosity, but the viscosity was significantly higher than that of untreated Marion oat flour slurry. The results suggested that either surface microorganisms or endogenous oat enzymes on the groat surface are responsible for at least some of the raw oat flour slurry viscosity degradation. Results of microbial quantification indicate that untreated (raw) oat groat had between 22 and 1,300 microbes per seed and the surface sterilization process eliminated almost all of the surface microorganisms. Surface sterilization can also inactivate the oat groat surface enzymes, which may contribute to the changes in oat flour slurry viscosity. Based on microbial quantification data, it is difficult to conclude that microbial population in raw oats contain sufficient mass to affect slurry viscosity. It is likely that much of the  $\beta$ -glucanase activity in oat is located on the surface of the groats. The viscosity degradation of surface-sterilized Marion oat flour slurry may be caused by either the incomplete surface sterilization or endogenous  $\beta$ -glucanase activities inside the oat kernel.

### Heat Treatment of Oat Grain

The effect of roasting oat grain for 2 hr at different temperatures on oat flour slurry viscosity is summarized in Table II. Raw oat grain without heat treatment was used as a control. The roasting treatment followed by 24 hr at room temperature resulted in decreased moisture content of the grain of both cultivars (Table II). Higher roasting temperatures resulted in lower grain moistures (Table II). Roasting grain at 95°C resulted in slightly increased mean viscosity of oat flour slurries, but the increase was not significant ( $P > 0.05$ ). With the increased roasting temperature, the resulting oat flour slurry viscosities were decreased in both Marion and Robert oats. After roasting at 155°C for 2 hr, the viscous properties of both Marion and Robert oat flour were greatly reduced. A qualitative peroxidase activity test indicated that enzyme activity existed in all roasting treatments except those roasted at 155°C. The results suggested that roasting of oat grain affected  $\beta$ -glucan polymer properties and the effect was independent of oat enzymes.

Steaming of oat grain followed by a 24-hr period of drying at room temperature also resulted in lower moisture levels from the untreated controls (Table III). Steaming of oat grain significantly ( $P < 0.05$ ) increased oat flour slurry viscosity (Table III). Steaming of oat grain for only 5 min resulted in the highest slurry viscosity among all the treatments. Increased steaming time slightly, but significantly ( $P < 0.05$ ), decreased the oat flour slurry viscosity. Results of qualitative peroxidase activity assays indicated that all steaming treatments of oat grain inactivated this enzyme. Autoclaving (121°C, 15 psi) of oat grain also significantly ( $P < 0.05$ ) increased oat flour slurry viscosity, and the viscosity increased with the extended autoclaving times (Table IV).

It was reported earlier that steaming of oat grain for 20 min did not gelatinize the starch, and the differences in viscosity between

TABLE II  
Effect of Oat Grain Roasting Temperature on Grain Moisture After Roasting and the Viscosity of Oat Flour Slurries of cv. Marion and Robert

Roasting Temperature (°C)	Peroxidase Activity <sup>c</sup>	Grain Moisture (%) <sup>a</sup>		Apparent Viscosity <sup>b</sup> (Pa·sec)	
		Marion	Robert	Marion	Robert
Control	Positive	9.7a	10.9a	3.57a	0.44a
95	Positive	6.0b	6.0b	3.81a	0.48a
105	Positive	5.2c	4.8c	3.14b	0.43a
130	Positive	3.3d	3.4d	2.91b	0.34b
155	Negative	1.8e	2.4e	0.17c	0.18c

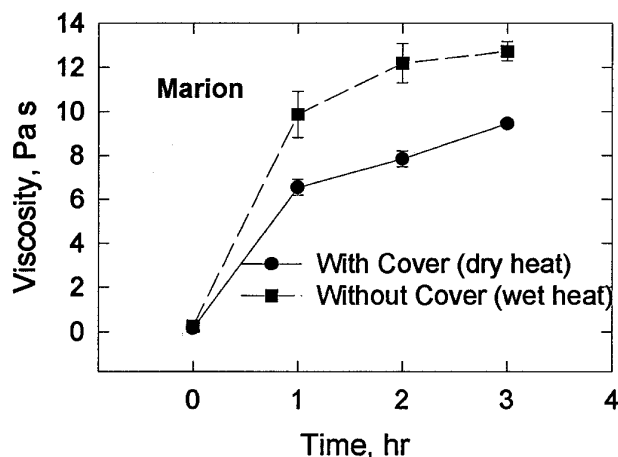
<sup>a</sup> Measured 24 hr after the grain heat treatment.

<sup>b</sup> Apparent viscosities of 23.2%, w/w, solids dry basis oat flour slurries were measured with a Brookfield viscometer with an RV-6 spindle at 50 rpm after 1 hr holding time at 30°C ( $n = 3$ ). Values within a column with the same letter are not significantly different ( $\alpha = 0.05$ ).

<sup>c</sup> Using the method of Borenstein et al (1990).

the roasted oat flour slurries and the steamed oat flour slurries were attributed to changes in the endosperm cell wall component of  $\beta$ -glucan (Doehlert et al 1997b). Because steaming and autoclaving both involve steam penetration of oat grain, we hypothesized that the steam penetration process may have a significant effect on functional properties of oat  $\beta$ -glucan. This hypothesis was tested by autoclaving the oat grain with (dry heat) and without (moist heat) a protective cover on the grain. After autoclaving, the grain autoclaved with a cover contained 7.7% moisture, which was significantly lower ( $P < 0.05$ ) than the samples autoclaved without a cover, which had 8.2% moisture. Samples autoclaved without a cover, where steam could freely penetrate the oat grain generated significantly greater ( $P < 0.05$ ) viscosity in 23.2%, w/w, solids dry basis slurries than did the samples autoclaved with a cover (Fig. 3) at all three data points.

The mechanism by which dry heat (roasting) and moist heat



**Fig. 3.** Effect of covering the container during autoclaving on the viscosity development of the subsequent oat flour slurries (23.2%, w/w, solids dry basis). Apparent viscosity was measured with a Brookfield viscometer (RV-6 spindle, 50 rpm) at 30°C ( $n = 3$ ).

(steaming) affected oat grain was not clear. Because most of the viscosity associated with oat flour slurries can be attributed to  $\beta$ -glucan (Doehlert et al 1997a), these two types of heat treatment must affect oat  $\beta$ -glucan differently, possibly by affecting polymer hydration and chain interaction. The effect of steaming and roasting of oat grain on oat  $\beta$ -glucan rheological properties is currently under further investigation.

### Fat Extraction from Oat Flour

Oat contains the highest lipid concentration among all the cereals, and the lipids are distributed throughout the oat kernel (Youngs 1978). Removal of lipids from oat flours increased their slurry viscosity, but the effect was significant ( $P < 0.05$ ) only for the steamed oat flour (Table V). When the lipids were added back to the defatted oat flours, the viscosity was not significantly ( $P > 0.05$ ) different from the untreated controls (Table V). Removal of oat flour lipids increased the relative  $\beta$ -glucan concentration of oat. The defatting process removed 5.36% (dry basis) of the mass from the steamed oat flour sample. Based on the relative increase in  $\beta$ -glucan concentration after defatting and the natural log relationship between viscosity and  $\beta$ -glucan concentration (Doehlert et al 1997a), we predicted that if the change in viscosity of the defatted oat slurry viscosity was entirely due to the increase in its  $\beta$ -glucan concentration, then the mean viscosity of its slurries would be 3,844 mPa-sec (or  $e^{(\ln 2470)/0.946}$ ), which was not signifi-

**TABLE V**  
Effect of Soxhlet Fat Extraction and Fat Reconstitution on Apparent Viscosity<sup>a</sup> (mPa-sec) of Oat Flour Slurries Derived from Raw, Roasted, and Steamed Robert Oats

Sample	Raw	Roasted	Steamed
Control oat flour	436a	740a	2,470b
Defatted oat flour	646a	836a	3,796a
Reconstituted oat flour	593a	803a	2,653b

<sup>a</sup> Apparent viscosity of 23.2%, w/w, dry basis oat flour slurries were measured with a Brookfield viscometer with RV-6 spindle at 50 rpm after 1 hr holding time at 30°C ( $n = 3$ ). Values within a column labeled with same letter are not significantly different ( $\alpha = 0.05$ ).

**TABLE III**  
Effect of Oat Grain Steaming Time on Grain Moisture After Steaming and Apparent Viscosity of Oat Flour Slurries of cv. Marion and Robert

Steaming Time (min)	Peroxidase Activity <sup>c</sup>	Grain Moisture <sup>a</sup> (%)		Apparent Viscosity <sup>b</sup> (Pa-sec)	
		Marion	Robert	Marion	Robert
0	Positive	9.7a	10.9a	3.51c	0.44d
5	Negative	7.7bc	7.9bc	6.39a	2.81a
10	Negative	7.5c	7.9bc	5.55b	2.70ab
20	Negative	7.6c	7.7c	4.97b	2.60bc
40	Negative	7.3c	7.5c	4.99b	2.59bc
60	Negative	8.2b	8.3b	5.08b	2.47c

<sup>a</sup> Measured 24 hr after the grain heat treatment.

<sup>b</sup> Apparent viscosities of 23.2%, w/w, dry basis solids oat flour slurries were measured with a Brookfield viscometer with an RV-6 spindle at 50 rpm after 1 hr holding time at 30°C ( $n = 3$ ). Values within a column with the same letter are not significantly different ( $\alpha = 0.05$ ).

<sup>c</sup> Using the method of Borenstein et al (1990).

**TABLE IV**  
Effect of Oat Grain Autoclaving Time on Grain Moisture<sup>a</sup> After Autoclaving and on Apparent Viscosity of Oat Flour Slurries of cv. Marion and Robert

Autoclaving Time (min)	Grain Moisture (%)		Apparent Viscosity <sup>b</sup> (Pa-sec)	
	Marion	Robert	Marion	Robert
0	9.7a	10.9a	3.51c	0.44d
5	8.0c	8.5c	8.86b	5.75c
10	8.4b	8.5c	11.09ab	6.49bc
20	8.4b	8.7bc	12.49a	6.98b
40	8.5b	9.0b	13.03a	9.49a

<sup>a</sup> Measured 24 hr after the heat treatment.

<sup>b</sup> Apparent viscosities of 23.2% w/w solids dry basis oat flour slurries were measured with a Brookfield viscometer with an RV-6 spindle at 50 rpm after 1 hr holding time at 30°C ( $n=3$ ). Values within a column with the same letter are not significantly different ( $\alpha=0.05$ ).

cantly different ( $P < 0.01$ ) from the observed mean viscosity of 3,796 mPa·sec for the steamed defatted oat flour (Table V). Therefore, slurry viscosity increase after defatting appears to be due to the increase in relative  $\beta$ -glucan concentration. The results suggest that the viscous properties of oat  $\beta$ -glucan were not affected by the fat extraction process.

## CONCLUSIONS

Oat  $\beta$ -glucan concentration,  $\beta$ -glucanase activity,  $\beta$ -glucan polymer hydration, and heat treatments of oat grain affected oat flour slurry viscosity. Marion oat, which has a greater  $\beta$ -glucan concentration than Robert oat, had consistently greater viscosity in its flour slurries than Robert. Defatting increased slurry viscosity to an extent consistent with that predicted by the relative increase in  $\beta$ -glucan concentration. Surface sterilization stabilized raw oat flour slurry viscosity (Fig. 2) by eliminating hydrolytic enzymes on the surface of oat groat.

The hyperbolic increase in slurry viscosity with time (Figs. 1 and 3) presumably occurs from the increasing hydration of the  $\beta$ -glucan polymer with time. Higher slurry incubation temperature (Table I) and smaller particle size (Fig. 1) may stimulate the rate and extent of polymer hydration, thereby resulting in higher viscosities. Although steaming and autoclaving of oat grain inactivated enzymes, viscosities resulting from these slurries were much greater than slurries from surface-sterilized groats, suggesting that these hydrothermal treatments may increase the  $\beta$ -glucan polymer hydration capacity. Roasting of oat grain at 155°C also eliminated enzyme activities but had a negative effect on slurry viscosity (Table II), possibly because the dry heat reduced polymer hydration. The influence of moisture penetration of oat grain during autoclaving on slurry viscosity (Fig. 3) is also consistent with hypothesized role of polymer hydration on slurry viscosity. Possible roles of protein and starch in influencing viscosity after various heat treatments were considered in our earlier study (Doehlert et al 1997b) and concluded to be negligible.

Studies have suggested that viscosity mediates the physiological effects of oat soluble fiber (Gallaher et al 1993, Wood 1993). Our studies have indicated that the potential viscosity resulting from an oat slurry can be affected by various heat treatments applied to the grain, many of which are commonly used in oat processing. It may become desirable to modify some aspects of oat processing in order to optimize functional properties of  $\beta$ -glucan for specific applications.

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