Rheological Characterization of a New Oat Hydrocolloid and Its Application in Cake Baking

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ABSTRACT

A new oat hydrocolloid containing 20% β-glucan, called C-trim20, was obtained from oat bran concentrate through steam jet-cooking and fractionations. The rheological characterization of the C-trim20 was conducted using steady and dynamic shear measurements. The C-trim20 suspension exhibited a shear-thinning behavior that was more pronounced at high shear rates and high concentrations. Its dynamic viscoelastic moduli increased with increasing concentration while the frequency at which *G'* and *G"* crossover decreased. The C-trim20 suspension at various concentrations followed the Cox-Merz rule. C-trim20 was also evaluated for potential use in baked products, specifically cakes. The baking performance of C-trim20 was tested by incorporating it into cake formulations. The inclusion of this hydrocolloid gave increased elastic properties to cake batters and produced cakes containing 1 g of β-glucan per serving with volume and textural properties similar to those of the control cake.

Public health concerns related to the role of diet in development of heart disease and other chronic diseases have created opportunities for functional ingredients that beneficially modify risk factors. The known nutritional benefits of oat β-glucan make oats an excellent source for developing ingredients for health benefits (Wood 1984; Wood et al 1989). Although the milled oat products, oatmeal, flakes, and flour are widely used and are the primary commercial materials, other functional compositions have been produced. An early ingredient from oats was Oatrim, which became a manufactured functional ingredient in 1991 (Inglett and Grisamore 1991). Oatrim was a fat replacer prepared by α-amylase conversion of oat flour starch to a specific level of maltodextrin without destroying its β-glucan content (Inglett 1993). It appeared at a time when lowering intake of dietary fat was a popular marketing concept. FDA approval of Oatrim for a heart healthy label claim was allowed recently (FDA 2003). During this period, another product, Nutrim, was developed as a functional oat ingredient for heart-healthy foods. This was a hydrocolloid that was prepared from oat bran without amylolytic action and was suitable for the FDA health claim on food labels (FDA 1997). Many other fat replacers found their way into foods. One such functional ingredient, called Z-Trim, was successfully developed using oat hulls. This was useful in expanding the market into reducing both fat and calories in foods (Warner and Inglett 1997). All three patented technologies (Oatrim, Nutrim, and Z-Trim) were licensed to industrial users who are now selling these functional oat ingredients (Inglett 1991, 1998, 2000). A new oat hydrocolloidal ingredient, called C-Trim, has recently been developed from oat bran concentrate for applications in foods. The physical and rheological characterization of this new hydrocolloid and its application in cakes are described in this study.

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MATERIALS AND METHODS

Preparation of C-trim20 Oat β-Glucan Hydrocolloid

Oat bran concentrate (10.5% β-glucan, 18.6% protein, 7.4% total lipid, and 3.9% ash, db) was obtained from Quaker Oats Company (Chicago, IL, Lot No. 18608408, Item No. 26629). Oat bran (100 g) was mixed with 1,900 mL of water in a 3L plastic container. The slurry was adjusted to pH 6.55 after it was mixed with a spatula to suspend and then vigorously mixed at 4,000 rpm for 60 min using a colloid mill (Polythron PT6000 with Aggregat PT-DA-6060/2WEC, Brinkmann Instruments, Westbury, NY). By passing the slurry through a 400-mesh sieve, the wet solids were separated and saved. The sieve liquid was centrifuged at 1,590 × *g* for 15 min to separate out the dense starch particles, and the supernatant was mixed with the saved wet solids. The reconstituted slurry was subjected to jet cooking (65 psi, 285°F, 1.2 L/min flow rate), followed by filtering the jet-cooked slurry using a 200-mesh sieve. The separated liquid was drum-dried and its composition (20.9% β-glucan, 27.0% protein, 7.2% total lipid, 4.0% ash, and 39.0% starch, db) was analyzed (AACC International 2000; AOAC International 2003).

Cake Preparations

Ingredients for making cakes were purchased from commercial sources and the formulation for the control cake was 270 g of all-purpose flour (General Mills, Minneapolis, MN); 200 g of granulated sugar (Domino Foods, Yonkers, NY); 125 g of skim milk (Kroger Co., Cincinnati, OH); 125 g of water; 85 g of vegetable oil (Hunt-Wesson, Fullerton, CA); 68 g of dry cocoa (Hershey Foods Co., Hershey, PA); 52 g of whole egg (Kroger Co., Cincinnati, OH); 11 g of vanilla extract (Virginia Dare, Brooklyn, NY); 6.5 g of baking powder (Kraft Foods, Rye Brook, NY); 6.5 g of baking soda (Arm & Hammer, Princeton, NJ); and 6.5 g of salt (Morton Salt, Chicago, IL).

Milk, egg, vanilla, and oil were mixed in a mixer (KitchenAid, St. Joseph, MI) on speed 4 setting for 5 min to stir well together. On speed 2, the sifted dry ingredients were slowly added and mixed well on speed 4 for 2 min. The water, heated to 100°C was slowly added on speed 2 and continued to mix for an additional 2 min. The batter was poured into a round cake pan 20 cm in diameter and baked at 170°C for 32 min. For C-trim20 cakes, C-trim20 was added at 60 g for 1 g of β-glucan per serving and 120 g for 2 g of β-glucan per serving in the formulation by replacing equal amounts of the flour.

Rheological Measurements

C-trim20 was suspended in distilled water, heated at 80°C for 20 min, and then cooled down to room temperature. Rheological properties were evaluated in a stress-controlled rheometer (AR2000, TA Instruments, New Castle, DE) operated at 25°C using a 60-mm parallel plate. The shear viscosity was investigated as a function of shear rates at 0.01–10/sec or 0.01–100/sec, depending on the sample concentrations. The dynamic viscoelastic properties of the C-trim20 suspensions were measured at a frequency range of 0.01–10 Hz and a strain of 0.1%. For the rheological measurements of cake batters, the frequency sweep (0.01–10 Hz) was conducted at a strain of 0.5%. The selected strains were within the linear viscoelastic limits of each sample. A thin layer of mineral oil was applied to the exposed sample surface to avoid dehydration problems during measurement. The reported curves are the average values of at least two measurements.

Volume, Color, and Texture Profile Analysis of Cakes

The volume of baked cakes was measured using a layer cake measuring template according to Approved Method 10-91 (AACC International 2000). A spectrocolorimeter (Labscan XE, Hunter Associates Laboratory, Reston, VA) was used to measure the color of cake crumb, which was expressed in terms of L^* (lightness/darkness), a^* (redness/greenness), and b^* (yellowness/blueness). Instrumental texture evaluation of cakes was conducted using a texture analyzer (Texture Technologies Co., Scarsdale, NY). A cylindrical probe with 2.5 cm diameter was used at a speed of 5 mm/sec to compress cylindrical cake crumb (2.5 cm height × 4 cm diameter) twice to 50% of the original height. From the deformation curve obtained, the hardness, cohesiveness, adhesiveness, springiness, and chewiness were calculated. All measurements were made in triplicate and significance of difference among samples was examined from analysis of variance (ANOVA) for a randomized block design. Duncan's multiple range test was then applied for mean comparisons.

RESULTS AND DISCUSSION

Steady shear viscosities of C-trim20 suspensions at three different concentrations (5, 8, 11%) were investigated over shear rates (0.01–100/sec) (Fig. 1). The apparent viscosity increased with increasing concentrations. Also, the C-trim20 suspension exhibited relatively constant viscosity at low shear rates and then a rapid fall in viscosity at high shear rates, showing a typical shear-thinning behavior. The effect was more pronounced at higher concentrations. This type of shear thinning behavior is related to the disruption of entangled network structure in a system by the applied shear deformation (Morris 1990; Vaikousi et al 2004). Sufficient time at low shear rates allows the formation of new entanglements to supply the disruption of existent entanglements by shear deformation. It leads to no net changes in the extent of entanglements, resulting in constant values of viscosity because molecular entanglement is responsible for the increased resistance to the solvent flow. At higher shear rates, the progressive decrease in viscosity with increasing shear rates takes place because the formation rate of new entanglements is slower than the disruption rate of entanglements.

The effect of C-trim20 concentration on the viscoelastic properties was presented in Fig. 2. Both parameters (*G'* and *G"*) increased with an increase in concentration. At low frequencies, the *G"* of the C-trim20 suspension dominated over *G'* (more viscous properties). As frequency increased, *G'* crossed *G"* due to more dependence of the *G'* on frequency. At a concentration of 5%, the crossover of *G'* and *G"* did not occur within the experimental frequency ranges because it probably takes place at higher frequencies. *G'* was greater than *G"* (more elastic properties) beyond this crossover frequency, which shifted to lower frequencies as C-trim20 concentration increased. In agreement with the results of the steady shear viscosity, Fig. 2 shows the typical behavior of entanglement network systems that are formed by the simple topological interaction of polymer chains rather than by cross-linking (Doublier et al 1993; Lazaridou et al 2003). At low frequencies, viscous or liquid-like behavior predominates because there is sufficient time for entangled chains to relax. On the contrary, deformation at high frequencies does not allow the entanglements to unravel within the short period of oscillation. Hence, the entanglement sites behave like temporary cross-linking junction zone (Lazaridou et al 2003), contributing to *G'* more than *G"*.

The relationship between the steady shear and dynamic properties of C-trim20 suspensions was experimentally investigated to evaluate the applicability of the Cox-Merz rule.

$$\eta^* (\omega) = \eta(\dot{\gamma}) |_{\omega=\dot{\gamma}}$$

According to the Cox-Merz rule (Cox and Merz 1958), the complex viscosity (η^*) is closely superimposed on the steady shear viscosity (η) at equal values of angular frequency (ω) and shear rate ($\dot{\gamma}$) and this empirical correlation has been confirmed for various random coil polymers such as galactomannans and oat β-glucans (Morris et al 1981; Andrade et al 1999; Lazaridou et al 2003, 2004). In contrast, ordered polymers with a weak gel structure deviate from the Cox-Merz rule with dynamic viscosity higher than steady shear viscosity (Bot et al 2001; Skendi et al 2003).

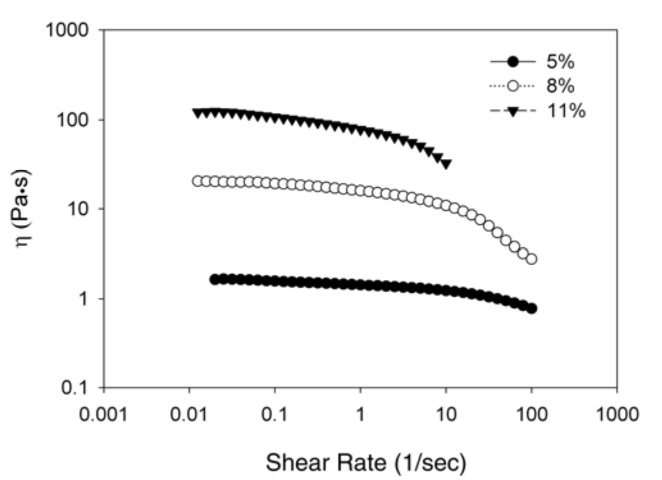

Fig. 1. Apparent viscosity as a function of shear rates of C-trim20 hydrocolloidal suspensions at a concentration of 5, 8, and 11%.

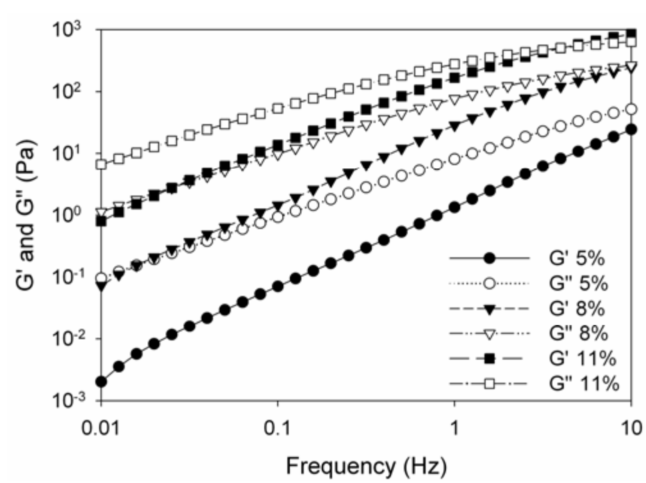

Fig. 2. Plot of dynamic viscoelastic properties of 5, 8, and 11% C-trim20 suspensions.

In Fig. 3, the complex and apparent viscosities of the C-trim20 suspensions were plotted against frequency and shear rate. The Cox-Merz correlation was favorably applied with the complex and steady shear viscosities superimposed. However, it is interesting to note that the steady shear viscosity of 8% C-trim20 suspension decreased more rapidly than the complex viscosity at high shear rates. That is, it showed the departure from the Cox-Merz rule, which is caused by the decay of structure due to the degree of the applied strain deformation (Chamberlain and Rao 1999). The large and nonlinear deformation (destructive) in the steady shear flow can break entanglements or molecular associations in a system, compared to the deformation in oscillatory shear flow (nondestructive).

Figure 4 shows the dynamic rheological properties of the cake batters containing 1 g and 2 g of β-glucan per serving, which were compared with those of the control cake batter. In Fig. 4A, *G'* and *G"* of the cake batters increased with increasing frequencies, showing frequency dependence. However, they became less frequency dependent when more C-trim20 hydrocolloids were included. *G'* was higher than *G"* throughout the tested frequency range, implying an elastic weak gel-like network. Also, both moduli increased with increasing levels of C-trim20 with a greater increase in *G'* being observed. Hence, the results show that the cake batters with more C-trim20 had greater elastic characteristics, which was also observed from the changes in tanδ in Fig. 4B, which represents the relative elastic and viscous properties of a material. The cake batter containing 2 g of β-glucan had the lowest value of tanδ while the control had the highest. Thus, more inclusion of the hydrocolloid caused the decrease in tanδ, indicating greater elastic properties.

The volume of the cakes containing C-trim20 was compared with that of the control (Fig. 5). The cake containing 1 g of β-glucan per serving had a slightly higher volume than the control but increased level of C-trim20 caused a decrease in the volume of cakes. As shown in Fig. 4, the cake batter became more solid-like (more elastic properties) as the level of the hydrocolloid within the flour increased. Hence, the decreased expansion of the 2 g of β-glucan cake may be related to the increased elastic properties, giving rise to a tight and dense cell structure.

The effect of C-trim20 addition on the crumb colors of baked cakes was investigated also (Table I). The values of L^* increased significantly ($P < 0.01$) with increasing levels of the hydrocolloids, indicating a lighter color, while there was no change in the values of a^* among the samples. The addition of C-trim20 which has an intrinsic yellowish color, gave higher yellowness values (b^*).

The parameters of texture profile analysis of the cakes containing C-trim20 were examined and compared with those of the control cake (Table II). Hardness represents the maximum force required to accomplish a given deformation during the first compression. No significant difference ($P < 0.01$) in the hardness was observed between the control and the cake containing 1 g of β-glucan per serving. Also, there were no significant changes in other texture parameters between two cakes except cohesiveness ($P < 0.01$). However, in the cake with 2 g of β-glucan per serving, the hardness of its crumb increased by more than two times (relative to control) and more energy for mastication would be required during chewing (increased chewiness) (Szczesniak 1963). The distinct changes in the rheological characteristics of the cake containing 2 g of β-glucan per serving presumably relate to the lower volume and dense crumb structure. The incorporation of C-trim20 was thus shown to make cakes containing 1 g of β-glucan per serving without textural quality loss. These cakes could carry the FDA-recognized health claim on food labels (FDA 1997).

CONCLUSIONS

A new oat β-glucan-rich hydrocolloid, C-trim20 was produced from oat bran concentrate. The rheological properties of this hydrocolloid suspension exhibited a shear-thinning behavior which was more pronounced at high strain rates and high concentrations. It demonstrated also a typical viscoelastic response of macromolecular solutions with topological entanglement. The Cox-Merz rule was also applicable to the results of its steady and dynamic shear viscosities at a concentration <8%.

In addition, the application of C-trim20 in baking produced cakes containing 1 g of β-glucan per serving with comparable

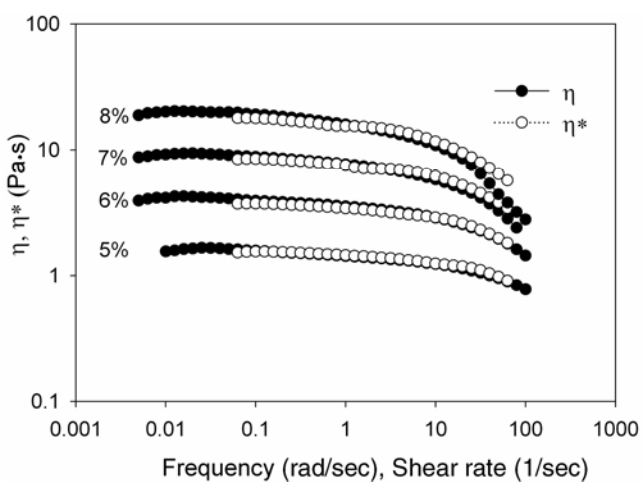

Fig. 3. Cox-Merz plots of C-trim20 suspensions with different concentrations.

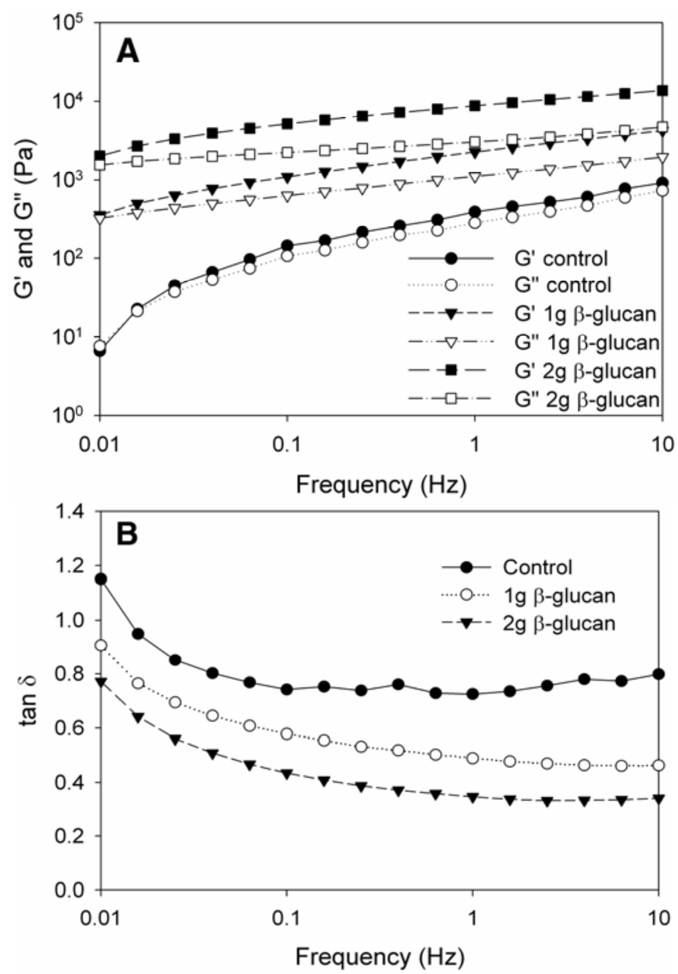

Fig. 4. Effect of C-trim20 on viscoelastic moduli of cake batters: *G'* and *G"* (**A**) and tanδ (**B**).

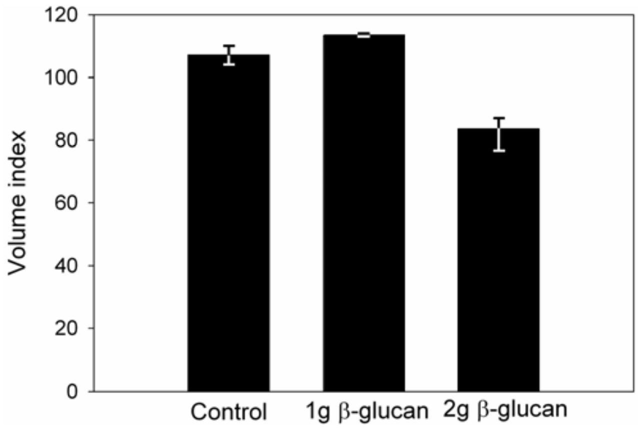

Fig. 5. Volume comparisons between the control and C-trim20 cakes.

quality attributes to the control. This new oat hydrocolloid can be formulated into various foods to control their rheology and texture and also to add health benefits by increasing the levels of β-glucan soluble fiber.

TABLE I
Effect of C-trim20 on Color of Cake Crumb[a]

	Control	1 g β-Glucan (per serving)	2 g β-Glucan (per serving)
*L**	14.6c	17.7b	18.8a
*a**	6.8a	6.8a	6.5a
*b**	5.9c	8.2b	9.6a

[a] Means with the same letter in the same row are not significantly different at the 1% level.

TABLE II
Textural Comparisons Between Cakes Containing C-trim20 and the Control[a]

	Control	1 g β-Glucan (per serving)	2 g β-Glucan (per serving)
Hardness (N)	11.6b	12.0b	25.9a
Cohesiveness	0.59b	0.65a	0.67a
Adhesiveness	0.02a	0.03a	0.02a
Springiness	0.89a	0.85a	0.89a
Chewiness	6.08b	6.50b	15.27a

[a] Means with the same letter in the same row are not significantly different at the 1% level.

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