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Rheology of Fiber-Enriched Steamed Bread: Stress Relaxation and Texture Profile Analysis

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ABSTRACT

Wheat bran is one of the major dietary fiber sources widely used in the food industry in order to produce fiber-enriched foods. The effects of wheat bran substitution (0 - 30%), water absorption (46 - 62%) and electric power (4 - 12 kW) of steamer on stress relaxation and textural parameters of steamed breads were evaluated by the Texture Analyzer. The results showed that mechanical stress relaxation data of steamed breads were fitted well by both the Peleg-Normand and three-element Maxwell models. At 10 - 40% strains tested, common and bran-enriched steamed breads were more elastic measured at low strain. It was suitable to perform the stress relaxation test of steamed bread at 10 - 30% strains. Generally, increasing the substitution of flour by bran resulted in less elasticity and higher hardness of steamed bread. Results of sensory evaluation indicated no significant difference in textural and overall acceptability among various steamed breads with 0, 10 and 20% of wheat bran. Medium and high water absorptions (54 - 62%) produced fiber-enriched steamed bread with better elasticity and texture. The elasticity of the steamed bread was the lowest at 4 kW electric power of steamer. Significant correlations were found between textural characteristics and stress relaxation parameters. This study suggests that 20% bran-enriched steamed bread, with better elasticity and sensory acceptability, can be produced at 54% of water absorption and 12 kW of electric power of the steamer.

Key words: steamed bread, rheology, stress relaxation, Peleg-Normand model, Maxwell model, fiber

INTRODUCTION

Steamed bread is an important staple food in East Asian countries. Wheat flours of medium protein content (10 - 12%) and medium dough strength are the most suitable for steamed bread[(1)]. Generally, the procedures for producing steamed bread are mixing, fermenting, sheeting, rolling, dividing, proofing and steaming[(2)]. Both the quantity and constitution of flour protein are important factors determining steamed bread quality. Rubenthaler *et al.*[(3)] reported that flours which contained 10 - 11% of protein and had medium to low strength were best suited for steamed bread. Huang *et al.*[(4)] indicated that the optimal conditions for producing southern-style steamed bread were as follows: water addition, 80% of farinograph water absorption; fermentation time, 150 min; fermentation temperature, 32°C; proof time, 35 min; steaming rate, 155 g per m^3 per min of steam; and steam time, 20 min. Chen[(5)] reported that steam generation rate significantly affected the quality of steamed breads produced by various protein contents of wheat flours.

Dietary fiber (DF) is the edible plant material not hydrolyzed by the endogenous enzymes in the human small intestine. Individuals with high intakes of DF appear to be at significantly lower risk of developing coronary heart diseases, diabetes and certain gastrointestinal diseases[(6-8)]. Although the addition of some soluble dietary fibers strengthened the structure of dough and improved the quality of bread[(9)], excess amounts of insoluble dietary fibers had a negative effect on the formation of gluten network[(10)] and bread quality[(11-13)] due to gluten dilution effect. The addition of insoluble wheat fiber increased dough consistency, probably through a filler-like effect in the dough matrix[(14)]. Dry potato fiber and two derived enzymatically-treated fiber powders containing a high level of insoluble DF led to the increase in hardness, deformation modulus and gumminess of bread[(13)]. The addition of 10% hydrated hazelnut testa decreased the quality of bread crumb by sensory evaluation[(12)]. However, white pan bread with bran addition up to 20% possessed

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a lower compression force than control bread[15]. He *et al.*[16] indicated that steamed bread enriched with 5% bran had optimum sensory quality. Increasing DF intake may be achieved by consuming fiber-enriched steamed bread.

Rheology concerns the flow and deformation of a material. Stress relaxation has traditionally been employed as one of the principal means for measuring the viscoelastic behavior of foods. Generally, experimental force decay curves have been presented in the form of discrete Maxwell model[17] containing 2 to 4 elements. Peleg and Normand[18] suggested that stress relaxation data can be recalculated to a normalized stress (or force) and next fitted with time. The Peleg-Normand model has fewer constants than the Maxwell model, thus the former is a simple, quick and effective method to handle stress relaxation data. Singh *et al.*[19] reported that the k_2 value in the Peleg-Normand model was suitable for differentiating various food products. Hatcher *et al.*[20] reported that uniaxial stress relaxation provided a complementary discriminating method for texture measurement of yellow alkali noodle. Sozer *et al.*[21] found the stress relaxation data of spaghetti enriched with fiber were fitted well by both the three-element Maxwell and Peleg-Normand models. Huang *et al.*[22] found that stress relaxation was significantly and negatively correlated with the overall eating quality of steamed bread. Study on the stress relaxation of steamed bread is very rare so far.

The aim of this study was to investigate the stress relaxation and textural parameters of fiber-enriched steamed breads prepared with different wheat bran substitutions and water absorptions, as well as steamed at various electric power of steamer. The correlation between fundamentally mechanical stress relaxation parameters and empirical textural characteristics of the steamed breads was also investigated.

MATERIALS AND METHODS

I. *Materials*

Wheat bran and wheat flour with medium strength were gifts from Chia-Fha Enterprise Co. Ltd. (Taichung, Taiwan). The total, insoluble and soluble dietary fibers of wheat bran, analyzed by the AOAC methods[23], were 55.34, 53.95 and 1.39%, respectively. The proximate compositions of wheat flour on wet basis, analyzed by the AACC methods[24], were 12.1% moisture, 11.0% crude protein, 0.6% crude fat and 0.4% ash contents. Commercial instant dried yeast and sodium stearoyl 2-lactylate (SSL) were obtained from S. I. Lesaffre Co. (France) and Danisco Ingredients (Malaysia), respectively. Food-grade sucrose and shortening were purchased from Taiwan Sugar Co. (Taiwan).

II. *Preparation of Dough*

Unless stated otherwise, basic fiber-enriched dough constituents were: wheat flour (80%), bran (20%), water (54%), yeast (1.5%), sucrose (8%), shortening (5%) and SSL (0.5%). Yeast (6 g) and sucrose (32 g) were individually dissolved in 60 and 156 mL of distilled water, respectively. The solutions were mixed with wheat flour (320 g), bran (80 g) and SSL (2 g) in a mixer (Model TS-108, Tian Shuai Food Machine Co., Taichung, Taiwan) using slow and medium speeds for 2 then 1 min, respectively. Then shortening (20 g) was added and remixed at slow then medium speeds for 4 and 1 min, respectively, to form dough.

III. *Preparation of Steamed Bread*

Steamed bread was prepared according to the method of Chen[5] with some modifications. The dough was fermented for 20 min at 32°C and 95% R.H. in a bread proofer (Model CM-4P, Chanmag Bakery Machine Co., New Taipei, Taiwan), and then sheeted by passing the fermented dough between two stainless steel rollers of a dough sheeter (Model CM-450B, Chanmag Bakery Machine Co., New Taipei, Taiwan). The dough sheet was gradually reduced to a final thickness of 5 mm by consecutively passing through roller gaps of 15, 10 and 5 mm. The resulting sheet was rolled up, divided into small pieces (about 100 g per piece) with a knife, and placed on a steam tray for proofing in the bread proofer. Proofing at 32°C and 95% R.H. was terminated after the swell ratio of the rolled dough in a graduated cylinder was equal to 150% (v/v). Finally, the proofed doughs (about 600 g) were steamed for 10 min in a steamer (Internal dimension: 60 × 60 × 90 cm; Model KS-60, Yuan Jaan Stainless Steel Industrial Co., Taoyuan, Taiwan) heated at 12 kW of electric power, unless otherwise stated. The steamed breads were cooled for 60 min at ambient temperature (about 28°C), and the rheological test was performed as soon as possible.

IV. *Stress Relaxation of Steamed Bread*

Stress relaxation of steamed bread was measured according to the method proposed by Sozer *et al.*[21] with some modifications. The cooled bread was sliced horizontally to remove the top and then a 3 × 3 × 4 cm rectangular sample was taken through the center of the bread by cutting. The stress relaxation test was executed by using a Textural Analyzer (TA-XT2i, Stable Micro Systems, Surrey, UK) equipped with a cylindrical probe of P20 (20 mm diameter). The sample was deformed in penetration to a constant strain of 20% with test speed of 0.5 mm/s. The data acquisition rate was 10 points per second. The residual force was continuously recorded as a function of time for 480 s.

The stress relaxation data were analyzed by using a Peleg-Normand model as well as a Maxwell model. Equation 1 is a model proposed by Peleg and Normand[18].

$$\frac{F_0 t}{F_0 - F(t)} = k_1 + k_2 t \tag{1}$$

where F_0 is initial force, $F(t)$ is the momentary force at time t, and k_1 and k_2 are constants. The k_1 and k_2 values are the intercept and slope of regressive straight line plotted by normalized force and time, respectively. Moreover, percentage stress relaxation (% SR)[20] was calculated from the following equation:

$$\%SR = \frac{F_0 - F_{t=20}}{F_0} \times 100 \quad (2)$$

where F_0 is initial force, and $F_{t=20}$ is the force at 20 s after the initial strain was achieved.

Equation 3 is a Maxwell model with three elements:

$$F(t) = F_1 \exp(-t/\lambda_1) + F_2 \exp(-t/\lambda_2) + F_3 \exp(-t/\lambda_3) \quad (3)$$

where F(t) is the actual force as a function of time in a stress relaxation test, λ_1, λ_2, and λ_3 are the relaxation times, and F_1, F_2, and F_3 are the decay forces. The experimental data were modeled by using non-linear regression in Sigma-Plot 8.0 software (Systat Software Inc., San Jose, CA, USA) based on a least square algorithm.

V. *Texture of Steamed Bread*

Texture profile analysis (TPA) of the rectangular bread sample (3 × 3 × 4 cm) was measured by the Textural Analyzer equipped with a P20 adapter moving at a rate of 2 mm/s, and the penetration depth into bread sample was 20 mm. Hardness (N) and springiness were calculated using the TPA curve[25]. The hardness of the bread sample was recorded from the maximum force on the first penetration graph curve. The ratio of distance from zero force to the maximum force of the second and first penetration curves was defined as springiness.

VI. *Sensory Assessment*

Fresh steamed breads with 0 - 30% wheat bran substitutions were refrigerated for less than two days at 4°C. The reheated and cooled steamed breads were served at room temperature (26 ± 2°C) under normal lighting conditions. Consumers' sensory evaluation of steamed bread was performed by 30 panelists consisting of students, employees and visitors in Tajen University. Color, odor, texture and overall preference of steamed bread samples were evaluated by a 7-point hedonic scale; which was 1: very unacceptable, 2: unacceptable, 3: mildly unacceptable, 4: neither unacceptable nor acceptable, 5: mildly acceptable, 6: acceptable, and 7: very acceptable.

VII. *Statistical Analysis*

The data in triplicate, unless stated otherwise, for different treatments were analyzed by one-way ANOVA and Duncan's new multiple range tests to determine the statistical significance of differences among the values, using the SAS system (SAS Institute, Cary, NC, USA). Pearson's simple correlation analysis was also conducted for observing the relations between stress relaxation parameters and textural characteristics.

RESULTS AND DISCUSSION

I. *Effect of Strain*

Fundamental viscoelastic properties of foods have frequently been measured by stress relaxation. The stress relaxation data of steamed bread in this study were analyzed by Peleg-Normand model and Maxwell model, and % SR. Figure 1A shows the relaxation curves of steamed bread at 10 - 40% strains. As for most viscoelastic materials, after application of a constant strain, a decrease in force values necessary for maintaining the deformation was observed. Relative residual force values of the steamed breads during the stress relaxation test decreased with increasing strain. This indicated that the steamed bread had more solid-like behavior at lower strain. The Peleg-Normand model is easy to perform and to analyze the data. In Figure 1B, the normalized force values determined during stress relaxation were well fitted ($R^2 > 0.998$) to the Peleg-Normand model (Equation 1). Thus we could have the k_1 and k_2 parameters by regression.

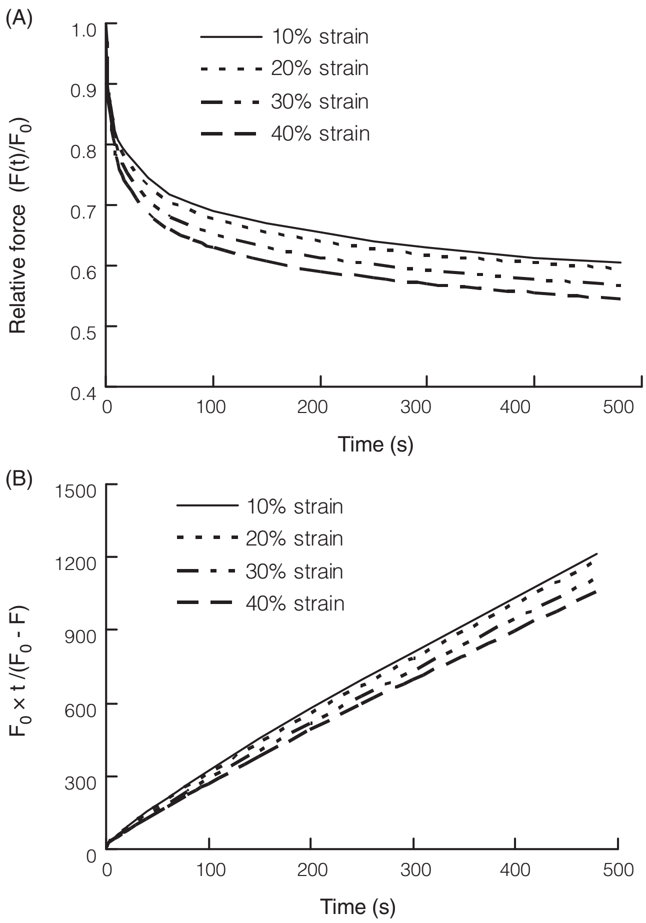

Figure 1. Relaxation curves of steamed bread at different strains.

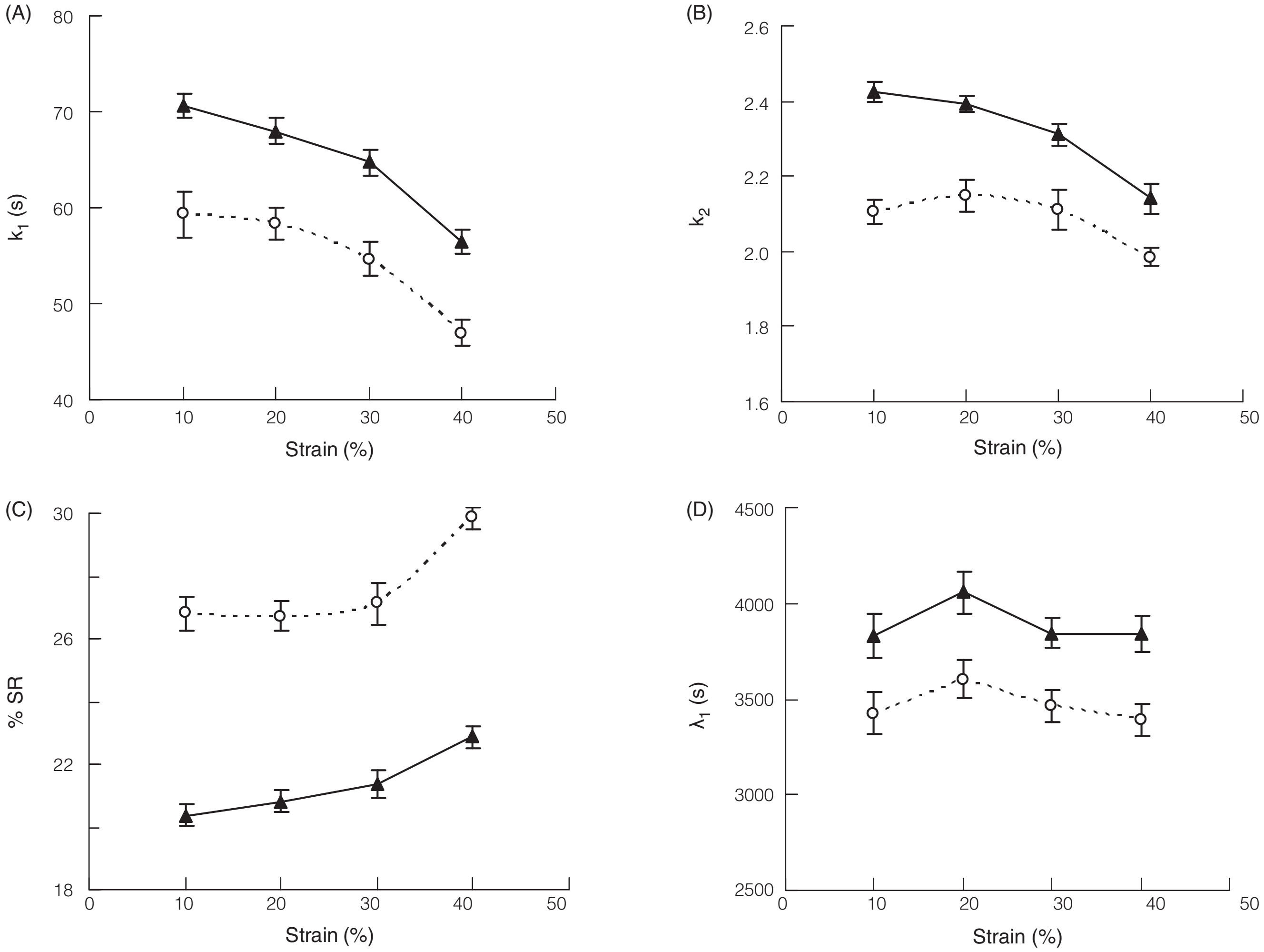

Figure 2. Effect of strain on the stress relaxation parameters of common (▲) and 20% bran-substituted (O) steamed breads. The water absorption and electric power were 54% and 12 kW, respectively.

Figure 2 shows the effect of strain on the stress relaxation parameters of common and fiber-enriched (20% bran) steamed breads. Generally, both k_1 and k_2 values (Figure 2A and B) of the steamed breads decreased with increasing strain. The reciprocal of the k_1 value in the Peleg-Normand model represents the initial decay rate. A high k_1 value was associated with a low decay rate, indicating a pronounced elastic behavior. The k_2 value is the representative of the degree of solidity and it varies between 1, for a material that is truly a liquid, to infinity, for an ideal elastic solid where the stress does not relax at all[18]. Singh *et al.*[19] indicated k_2 was a better representative of elastic nature for food materials. Therefore the steamed breads in this study are more elastic measured at low strain. Nussinovitch *et al.*[26] indicated that the percent recoverable work (or elasticity) of bread decreased exponentially by increasing strain from 20 to 80%.

Percentage stress relaxation (% SR) is a convenient and informative parameter to understand viscoelastic properties of food products, and is obtained directly from the stress relaxation versus time plot at an arbitrary time[19]. For the ideal elastic solid, % SR is equal to 0, while for the ideal liquid, % SR is 100[27]. Results showed that % SR of steamed bread tested ranged from 20.4 to 29.8 (Figure 2C), and thus the bread was classified as a viscoelastic solid. The % SR values of common and fiber-enriched steamed breads at 10 - 30% strains were significantly lower than that at 40% strain (Figure 2C). Therefore, the stress relaxation test of the common and fiber-enriched steamed breads should be performed at 10 - 30% strains. Safari-Ardi and Phan-Thien[28] observed the sufficient resolution of the stress relaxation responses of wheat doughs at a strain level of 20%.

The elastic component of the Maxwell element can be represented by the decay force (F_1, F_2 or F_3), which indirectly measures the rigidity of the material being tested. Relaxation time (λ_1, λ_2 or λ_3) was defined as the time taken for a macromolecule to be stretched out when deformed[29]. Although all decay forces (F_1, F_2 and F_3) (data not shown) of the steamed breads obviously increased with increasing strain, λ_1 (Figure 2D), λ_2 and λ_3 (data not shown) values were not significantly different at various strain levels tested. This result showed that relaxation times in the Maxwell model were not sensitive to strain variable. From the results in Figures 1 and 2, we suggest that the stress relaxation test of steamed bread should be performed at 10 - 30% strains.

II. *Effect of the Substitution with Wheat Bran*

Gluten protein was the main contributor to the strength of steamed bread[30]. Because insoluble dietary fiber is the major dietary fiber in wheat bran, wheat bran incorporated into the dough may interfere with gluten network. The Peleg-Normand model is a good alternative to the Maxwell model because it is easy to execute for analyzing the stress relaxation data of spaghetti[21]. Table 1 lists the fitting parameters of the Peleg-Normand model for steamed breads with various ratio of substitutions of flour by wheat bran. The results showed that the stress relaxation data of steamed breads were fitted well by the Peleg-Normand model ($R^2 >$ 0.998). The F_0 (initial force) parameter of steamed bread increased with increasing substitution. However, both k_1 and k_2 parameters of steamed bread significantly decreased with increasing substitution with wheat bran (Figure 3A). Hence 20 - 30% bran fiber-enriched steamed breads were more rigid and less elastic than breads with low (0 - 10%) wheat bran. Li *et al.*[31] indicated that the relaxation properties of dough depended on its gluten protein and that relaxation spectra of glutens were similar to those for the corresponding doughs. Zhang *et al.*[32] found moderate correlation coefficient (r = 0.55 - 0.61) between stress relaxation of steamed bread and glutenin fraction of wheat cultivar.

Since stress relaxation data of steamed bread has not been analyzed by Maxwell model, we tried to use different Maxwell model equations for fitting the experimental data. The number of Maxwell elements required to represent the viscoelasticity of the bread sample was determined by the R^2 value. For one-element, two-element and three-element Maxwell models, the R^2 values were approximately 0.75, 0.98 and 0.999, respectively. For one Maxwell element parallel with a spring, the R^2 value was 0.94. Hence the three-element Maxwell model fitted to the data better than the other Maxwell models. Table 2 lists the fitting parameters of the three-element Maxwell model of steamed bread with various substitutions of wheat bran. The results showed that all stress relaxation data of steamed breads were fitted very well by the Maxwell model with three elements ($R^2 = 0.999$). A three-element Maxwell model was found adequate for demonstrating the stress relaxation data of spaghetti[21], and a generalized Maxwell model satisfactorily fitted the stress relaxation data of various bulky and sponge foods[33,34].

Both λ_1 and λ_3 parameters of steamed bread significantly decreased with increasing substitution of wheat bran (Table 2). All decay forces (F_1, F_2 and F_3) of 20 - 30% bran fiber-enriched steamed breads were significantly higher than those of the breads enriched with 0 - 10% wheat bran. Higher decay force and shorter relaxation time of steamed bread with high wheat bran content indicated that the bread had a more rigid and less elastic behavior, corresponding to the results from the Peleg-Normand model in Table 1. Moreover, % SR of steamed bread obviously increased with increasing substitution of wheat bran (Figure 3B). This is the first study of using different mathematical models to describe the viscoelastic properties of steamed bread to our knowledge. Dough from strong wheat cultivar exhibited slower rates of stress relaxation and higher storage modulus as compared to moderate, weak, and very weak cultivars[35]. The relaxation time of bran-enriched spaghetti was affected

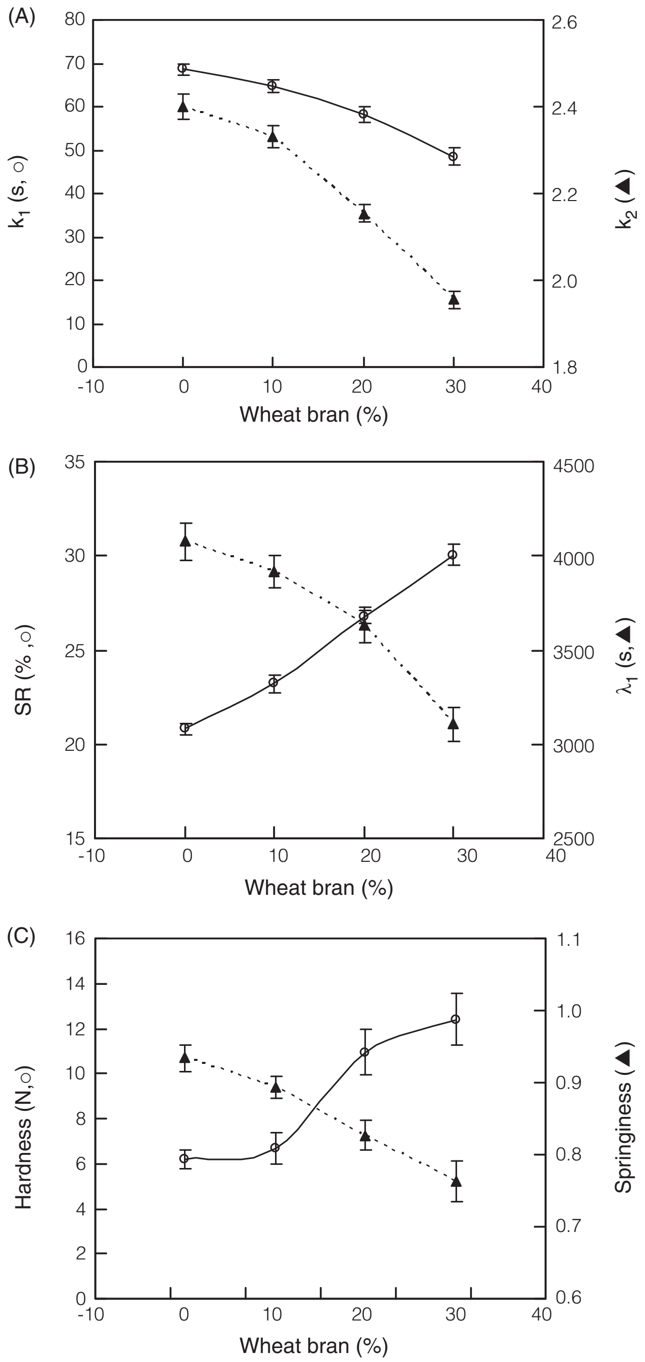

Figure 3. Effect of substitution of flour by wheat bran on the stress relaxation parameters (A and B) and textural characteristics (C) of steamed bread. The water absorption and electric power were 54% and 12 kW, respectively.

by cooking time[21].

Figure 3C shows the effect of substitution on the hardness and springiness of steamed bread. 20 - 30% bran fiber-enriched steamed breads had higher hardness than those with 0 - 10% wheat bran. The springiness of steamed bread obviously decreased with increasing substitution (0 - 30% wheat bran). The increasing and decreasing patterns of steamed breads in hardness and springiness, respectively, were consistent with F_0 and k_1 (or k_2) in the Peleg-Normand model (Table 1) as well as F_1 and λ_1 in the Maxwell model (Table 2). The increase in hardness and F_0 of steamed bread enriched with wheat bran maybe related to the decrease of free water in the bread or the rigid nature of wheat bran. Sangnark and Noomhorm[36] found that bread with 5% fiber from rice straw had higher firmness and lower springiness than control bread. Kaack *et al.*[13] found that the hardness of bread increased with the quantity (0 - 12%) of potato fiber with high insoluble dietary fiber content. The addition of 15% sugar-beet fiber[37] and 10% hydrated hazelnut testa[12] decreased the quality of bread crumb. However, white pan bread with bran addition up to 20% possessed a lower compression force than control bread[15].

Different wheat bran substitutions significantly affected the rheological properties of steamed bread measured instrumentally (Table 1, 2 and Figure 2). Generally, objective instrumental measurement had higher sensitivity than subjective sensory evaluation. The results of consumers' sensory assessment of steamed breads with various substitutions of wheat bran are shown in Table 3. The bran-enriched steamed bread with the highest substitution (30%) had the lower sensory scores in color, odor, texture and overall acceptability. Compared to the control bread, these consumers' sensory scores of steamed bread with 10 and 20% wheat bran were not significantly different. Therefore we suggest that fiber-enriched steamed bread should be prepared with 20% wheat bran in order to increase the intake of dietary fiber.

III. *Effect of Water Absorption*

The amount of water present in wheat flour dough is known to significantly affect both the rheological properties of the dough and the quality of the finished product[38]. Figure 4 shows the effect of water absorption on the stress relaxation parameters (Figure 4A and B) and textural characteristics (Figure 4C) of fiber-enriched steamed bread. The results showed that k_1 and k_2 in the Peleg-Normand model (Figure 4A) and λ_1 in the Maxwell model (Figure 4B) roughly increased with the water absorption from 46 to 62%. % SR roughly decreased with increasing water absorption. Although the springiness of fiber-enriched steamed bread was not affected by water absorption, the hardness significantly ($p < 0.05$) decreased with increasing water absorption, R^2 = 0.80 (Figure 4C). Therefore fiber-enriched steamed bread with better elasticity and texture can be produced at medium and high water absorptions (54 - 62%).

Lai *et al.*[11] reported that the combination of increasing water absorption, addition of shortening and sodium stearoyl lactylate could overcome the detrimental effect of

Table 1. Fitted parameters of the Peleg and Normand model using stress relaxation data of steamed breads with various substitutions of flour by wheat bran

Bran (%)	F_0 (mN)	k_1(s)	k_2	R^2
0	1869 ± 80^b	68.60 ± 1.22^a	2.40 ± 0.03^a	0.998
10	1765 ± 108^b	64.65 ± 1.45^b	2.33 ± 0.03^a	0.998
20	2717 ± 73^a	58.33 ± 1.81^c	2.15 ± 0.02^b	0.998
30	2758 ± 177^a	48.48 ± 1.88^d	1.95 ± 0.02^c	0.999

*: Means with different letter within the same column are significantly different at $p < 0.05$ level.

Table 2. Fitted parameters of the three-term Maxwell model using stress relaxation data of steamed breads with various ratio of substitutions of flour by wheat bran

Bran (%)	F_1 (mN)	F_2 (mN)	F_3 (mN)	λ_1 (s)	λ_2 (s)	λ_3 (s)	R^2
0	1287 ± 60^b	256 ± 9^b	262 ± 7^b	4077 ± 97^a	58.8 ± 1.5^a	5.91 ± 0.36^a	0.999
10	1168 ± 81^b	246 ± 19^b	285 ± 10^b	3915 ± 87^a	61.6 ± 3.3^a	5.90 ± 0.39^a	0.999
20	1705 ± 129^a	400 ± 21^a	494 ± 36^a	3633 ± 95^b	59.7 ± 2.5^a	5.30 ± 0.26^b	0.999
30	1619 ± 155^a	434 ± 58^a	559 ± 73^a	3107 ± 89^c	57.0 ± 1.5^a	4.77 ± 0.19^c	0.999

*: Means with different letter within the same column are significantly different at $p < 0.05$ level.

Table 3. Consumers' sensory evaluation of steamed breads with various substitutions of flour by wheat bran

Bran (%)	Color	Odor	Texture	Overall
0	5.40 ± 1.13^a	4.90 ± 1.03^a	5.43 ± 1.01^a	5.00 ± 1.11^a
10	5.30 ± 1.12^a	4.73 ± 1.20^a	5.43 ± 1.22^a	5.00 ± 1.26^a
20	4.93 ± 1.26^{ab}	4.57 ± 1.36^a	4.97 ± 1.19^a	4.73 ± 1.26^a
30	4.33 ± 1.37^b	3.83 ± 1.34^b	4.33 ± 1.32^b	3.83 ± 1.12^b

*: Means with different letter within the same column are significantly different at $p < 0.05$ level.

adding wheat bran to white pan bread dough. Rubenthaler *et al.*[39] found that the hardness of steamed bread with 45.5% water absorption was obviously higher than that with 47.5 - 53.5% water absorption. Yue and Rayas-Duarte[2] reported that a higher absorption improved the volume and texture of steamed bread. Huang *et al.*[4] reported that water addition (75 - 85% of farinograph water absorption) had a negative effect on the total score of steamed bread made from strong flour. However, the total score of steamed bread made from medium flour was mildly and positively affected by water addition.

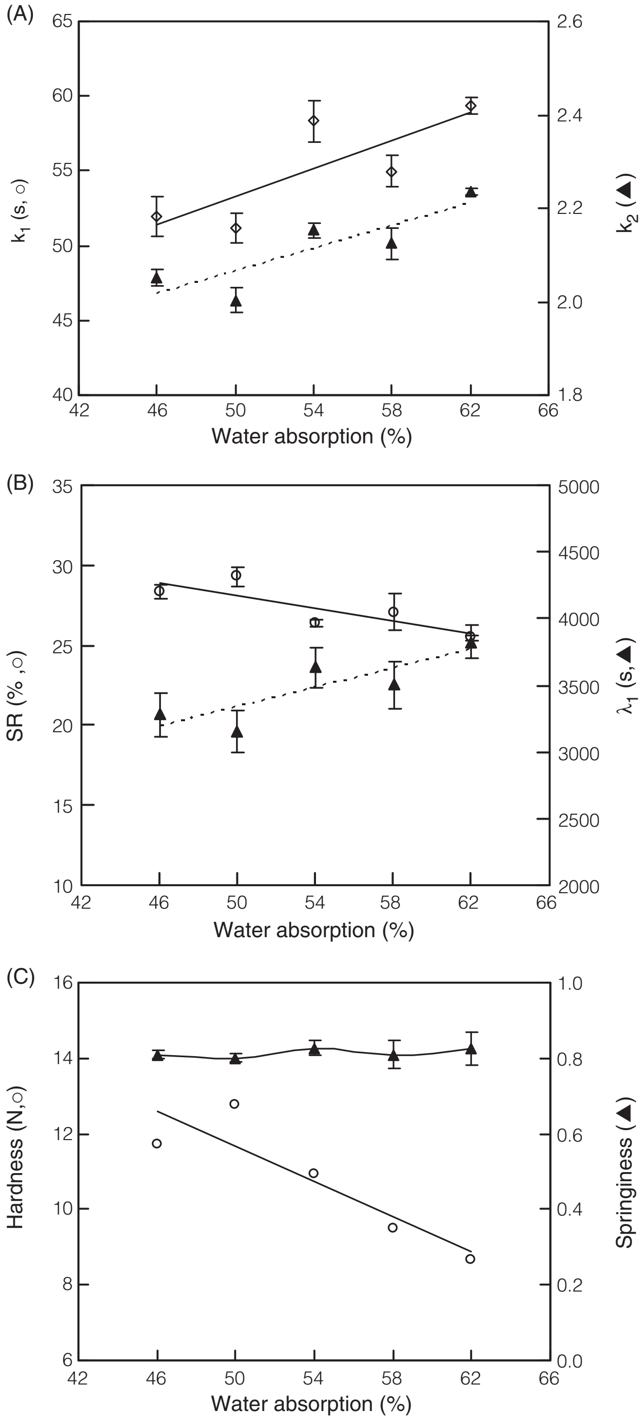

Figure 4. Effect of water absorption on the stress relaxation parameters (A and B) and textural characteristics (C) of bran-substituted steamed bread. The substitution of flour by wheat bran and electric power were 20% and 12 kW, respectively.

VI. *Effect of Electric Power*

Electric power affects water vapor production in the steamer. The steam generation rates at 4 - 12 kW in this study are 102, 490 and 796 g per m^3 per min, respectively. Since steam generation rate relates to protein denaturation, starch gelatinization, gas expansion and yeast inactivation, the quality of steamed bread is affected by the steam rate. Figure 5 shows the effect of electric power on the stress relaxation parameters and textural characteristics of fiber-enriched steamed bread. The results showed that both k_1 and k_2 values (Figure 5A) of the steamed bread were the lowest at low power (4 kW) and furthermore % SR (Figure 5B) was the highest. However, λ_1 of the bread steamed at high power (12 kW) was significantly higher than those at low and medium power (Figure 5B). The springiness of the steamed bread was the lowest at 4 kW (Figure 5C), while the hardness increased with the electric power of steamer from 4 to 12 kW. The results are in line with the report that the hardness and springiness of steamed breads prepared from wheat flours with low, medium and high protein contents increased with the steam rate[5]. Huang *et al.*[4] reported that steam rate had a negative effect on the total score of steamed bread made from strong flour but had a positive effect on the total score of steamed bread made from both weak and medium flours. From the results in Figure 5, we suggest that 20% bran-enriched steamed bread should be steamed by using medium or high steam rate.

V. *Correlations Between Stress Relaxation and Textural Parameters of Steamed Breads*

Table 4 lists the correlation coefficients of rheological and textural parameters of steamed breads. The hardness of steamed bread was found to be positively correlated to the fitting parameters (F_0, F_1, F_2 and F_3) in both Peleg-Normand and Maxwell models ($p < 0.01$). Moreover, the springiness of steamed bread was found to be positively correlated to k_1 and k_2 in the Peleg-Normand model and λ_1, λ_2 and λ_3 in Maxwell models ($p < 0.05$), and negatively correlated to % SR ($p < 0.01$). This demonstrates that empirical textural characteristics (hardness and springiness) were consistent with fundamental mechanical properties (F_0, λ_1, k_1, etc.) of steamed bread. Huang *et al.*[23] found that stress relaxation (SR) was negatively correlated with the sensory structure score of steamed bread. Hatcher *et al.*[20] reported that significant correlations were found among textural characteristics (maximum cutting stress, resistance to compression, and recovery) and stress relaxation parameters (% SR, k_1 and k_2) of cooked yellow alkali noodles. Among the fitting parameters of stress relaxation, both k_1 and k_2 in the Peleg-Normand model had positive correlation with λ_1 and λ_3 in the Maxwell model ($p < 0.01$) (Table 4), while k_1, k_2, λ_1, λ_2 and λ_3 were negatively correlated to % SR ($p < 0.05$). Thus, it is adequate to use the Peleg-Normand model, three-element Maxwell model and % SR for studying the stress relaxation behavior of fiber-enriched steamed bread.

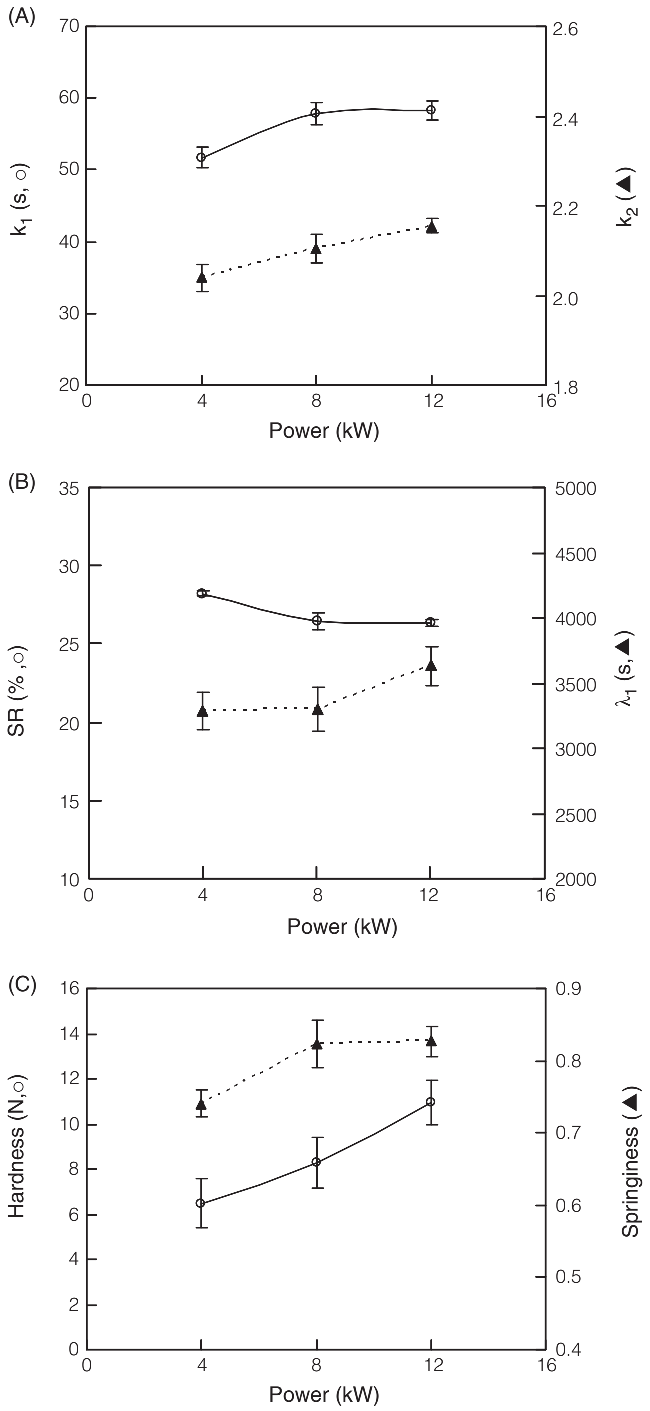

Figure 5. Effect of electric power of steamer on the stress relaxation parameters (A and B) and textural characteristics (C) of bran-substituted steamed bread. The substitution of flour by wheat bran and water absorption were 20% and 54%, respectively.

Table 4. Correlation coefficients between stress relaxation parameters and textural properties of steamed breads

	F_0	k_1	k_2	% SR	F_1	F_2	F_3	λ_1	λ_2	λ_3	Hardness	Springiness
F_0	1.000											
k_1	-0.447	1.000										
k_2	-0.441	0.964**	1.000									
% SR	0.485	-0.989**	-0.987**	1.000								
F_1	0.988**	-0.311	-0.301	0.348	1.000							
F_2	0.991**	-0.539	-0.548	0.582	0.960**	1.000						
F_3	0.971**	-0.637*	-0.632*	0.674*	0.923**	0.990**	1.000					
λ_1	-0.386	0.913**	0.981**	-0.946**	-0.246	-0.498	-0.577	1.000				
λ_2	-0.299	0.650	0.751**	-0.679*	-0.200	-0.389	-0.432	0.787**	1.000			
λ_3	-0.570	0.933**	0.925**	-0.938**	-0.449	-0.652*	-0.728*	0.864**	0.673*	1.000		
Hardness	0.860**	-0.424	-0.386	0.436	0.856**	0.845**	0.817**	-0.301	-0.075	-0.518	1.000	
Springiness	-0.224	0.941**	0.900**	-0.912**	-0.088	-0.322	-0.420	0.833**	0.615*	0.851**	-0.290	1.000

*: Significant at $p < 0.05$; **: significant at $p < 0.01$.

CONCLUSIONS

The results showed that the stress relaxation test of steamed bread should be performed at 10 - 30% strains. Mechanical stress relaxation data of steamed breads were fitted well by both three-element Maxwell and Peleg-Normand models. Increasing substitution of flour with wheat bran in the range of 0 to 30% decreased the k_1 and k_2 in the Peleg-Normand model, the λ_1 in the Maxwell model, and the springiness of steamed bread. On the contrary, increasing substitution of flour with wheat bran increased the % SR and hardness of steamed bread. The fiber-enriched steamed bread (20% bran) with proper elasticity and sensory acceptability can be prepared at 54% water absorption and high steam generation rate. Empirical textural characteristics (hardness and springiness) were significantly correlated with fundamental mechanical properties (F_0, λ_1, k_1, etc.) of steamed breads.

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