Textural Optimization of Shelf-Stable Bread: Effects of Glycerol Content and Dough-Forming Technique

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ABSTRACT

Cereal Chem. 77(2):169–176

The effects of glycerol content and dough-forming method on the physical, textural, and sensory characteristics of shelf-stable bread were determined. Bread dough was produced with 0, 2, 4, and 6% nominal glycerol content, and formed into rolls by either dough-dividing or extrusion-forming methodologies. Baked products were evaluated by uniaxial compression and fitting of stress-strain data to a three-parameter mathematical model. A trained sensory panel quantified textural attributes using magnitude estimation methodology. Selected characteristics were also judged by an untrained consumer panel. Sensory-instrumental relationships were determined. Products were tested instrumentally after different storage intervals to determine effects of glycerol level and dough-forming process on degree of firming. Results showed that extrusion-forming produced, on average, relatively more dense and less deformable products than did the dough-dividing method; extrusion-formed samples also had greater sensory firmness and were less similar to an ideal sensory texture. However, high glycerol concentrations in extrusion-formed products gave sensory profiles that were substantially closer to the ideal. Sensory firmness and chewiness were closely correlated with parameters of power law functions that described compression behavior. Glycerol reduced ultimate firmness after storage.

Shelf-stable bread is a military product developed for the purpose of producing more “freshlike”, less processed rations that can also be stored for prolonged periods of time. Many new ration components in which shelf-stable bread is a constituent are under development, including a range of sandwiches and sandwich-like products. Additionally, increased shelf-stability of baked products is of interest and of potential economic advantage to the food industry.

Increased shelf life of foods is generally achieved by controlling water activity and pH level in order to limit the growth of spoilage microorganisms. Shelf-stable bread is formulated to have relatively low water activity and pH level compared with commercial baked products that do not have as stringent shelf-life requirements. However, reducing moisture content to control water activity can have an adverse effect on texture (causing firming of the products) and, in turn, on acceptance. Other process or formulation parameters, such as production equipment that affect the level of shear imparted during processing, or the addition of humectants, can also alter physical structure, mechanical properties, and texture.

Bread dough is a highly associated polymeric network (Muller 1969) consisting of a continuous phase of gluten that encompasses a high-volume fraction of dispersed starch (Bloksma 1972, Amemiya and Menjivar 1992). The mechanical work involved in breadmaking (mixing, kneading, and molding) first forms, then determines the degree of alignment and interconnectedness of this gluten network. Molecular association and the length of polymeric concatenations are determined by disulfide bonds that break and reform during mechanical processing (Ewart 1968, 1977; Lindborg et al 1997). Hydrogen bonding among starch moieties is another important interaction that contributes to dough properties (Bloksma 1972, Amemiya and Menjivar 1992). An optimum level of association that results in maximum viscosity or development exists for each dough (Mani et al 1992). Prolonged work beyond this point leads to molecular scission and breakdown of the dough, thereby reducing dough viscosity (Launay and Bure 1973, Launay 1990, Lindborg et al 1997).

The degree of shear imparted by a bread production technique depends on process equipment and on operation parameters. Noticeable changes in products can become evident, for example, when a formulation tested on laboratory or pilot plant equipment is produced on production-scale equipment that imparts significantly greater energy to the dough. Process technique has been reported to alter baked loaf volume (Mani et al 1992), an effect that would expectedly influence texture perception and acceptance.

Plasticizers can also potentially alter texture because these additives serve as molecular spacers in a polymeric network, thereby increasing mobility and reducing mechanical stiffness (Levine and Slade 1992). Glycerol is such a constituent and can serve a dual function in bread by acting both as an humectant that lowers water activity (Linko et al 1985) and as a plasticizer. Conceivably, glycerol can reduce dough viscosity and shear stresses developed during dough forming, thereby mitigating mechanical scission and overdevelopment.

The textural properties of bread can be evaluated using uniaxial compression. Mathematical models that describe the stress-strain behavior of cellular or spongy materials have been proposed by Swyngdau et al (1991) and applied to bread products by Nussinovitch et al (1991). These functions take into account the three-part shape of the deformation functions, which includes linear elastic, plastic deformation, and densification regions, that characterizes these materials (Gibson and Ashby 1988).

Experiments in this study were designed to test a standard military bread formulation that contained various levels of glycerol and that was produced on equipment imparting relatively high or low levels of shear to the dough. Baked products were evaluated instrumentally and also subjectively, using a trained descriptive texture panel as well as a consumer panel. Predictive sensory-instrumental relationships were determined, as well as the optimal level of each sensory characteristic. The compressibility of the bread was also measured after various storage intervals to determine differences in degree of firming.

MATERIALS AND METHODS

Bread Production

Bread was produced according to a 4 × 2 (glycerol content × forming method) experimental design in which a standard military MRE (meal, ready to eat) formulation was varied so that samples containing nominally 0, 2, 4, or 6% glycerol by weight were obtained. Table I indicates the proportion of all ingredients except for glycerol. Dry ingredients were first mixed in a Hobart mixer (low speed), shortening was added, and then water or water plus

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Publication no. C-2000-0211-03R.

glycerol was slowly poured into the blend. Batches of 10 kg were produced.

The dough was mixed at medium speed to development (≈10 min), allowed to relax at room temperature (≈22°C) for 15 min, and then formed into 70-g round rolls using an Adamatic Fortuna A4-8670 dough divider (relatively low shear) or a Rheon KN300 dough extruder with a 36-mm nozzle (relatively high shear). The rolls were proofed at 95% rh and 30°C for 45 min, then baked for 40 min at 175°C in a rotary oven. The product was allowed to cool to <50°C, then packaged (six each) in trilaminate pouches with Multisorb oxygen scavengers. The rolls were maintained at –7°C, and then were brought to room temperature immediately before all mechanical, sensory, and physical analyses. Production was replicated for storage stability studies.

Mechanical Testing

Uniaxial compression was conducted using a TA.XT2 texture analyzer (Texture Technologies, Scarsdale, NY) interfaced with a Zenith 286 computer. Cylinders of 20 mm diameter were cut from the center of each roll using a cork borer and trimmed to 20 mm height using a razor. Two cylinders each were cut from three rolls for a total of six sample replicates. Samples were immediately wrapped in plastic wrap after cutting and kept covered until analysis to prevent moisture loss.

Specimens were compressed at a rate of 0.3 mm/sec to 10 mm deformation and decompressed at the same rate. Force vs. deformation data were automatically acquired at a rate of 12 points/sec.

Bulk Density Determination

The cylinders used for compression testing (6.28 cm^3) were weighed and density calculated.

TABLE I
Bread Formulation

Ingredient (Supplier)	%
Flour (ConAgra)	53
Water	31
Shortening (TemTex)	9.0
Yeast (Saf-instant)	2.5
Salt (Morton)	1.4
Sucrose ester (Ryoto)	1.1
Gum arabic (Kelco)	0.60
Calcium sulfate (ADM Arkady)	0.25
Xanthan gum (Kelco)	0.45
Glucono-delta lactone (BalChem Corp.)	0.70

Analysis of Compression Data

A Sigma Plot program was used to convert force-deformation data to stress-strain data and to fit the relationships (Swyngdau et al 1991) to the function:

$$y = [C1 \times x]/[(1+(C2 \times x)) \times (C3 - x)] \quad (1)$$

where y = stress in kPa, and x = Hencky strain. C1 = overall compressive resistance (firmness); C2 = deviation from linearity (prominence of the plateau region reflecting the buckling of cell walls, and thus plasticity); and C3 = densification strain. Figure 1 shows an illustrative stress-strain function for a spongy material.

The peak force developed at maximum compression was also recorded. Percent recoverable work, a measure of elasticity, was calculated by dividing the area beneath the decompression curve by that beneath the compression curve (Kaletunc et al 1991). Integration was performed automatically by the TA.XT2 program.

Measurement of Water Activity and pH Level

The water activity of interior crumb specimens was determined using an Aqualab a_w meter. The pH level of interior crumb specimens was determined using an Orion pH meter after extraction with ≈10× the sample weight of distilled water.

Descriptive Sensory Analysis

The sensory texture attributes of the samples were assessed by a trained descriptive panel consisting of 12 individuals. The panelists had previously received instruction in the use of the General Foods Texture Profile Method (Brandt et al 1963, Szczesniak 1963, Szczesniak et al 1963) and in the method of modulus-free, magnitude estimation to judge attribute intensities (Stevens 1953, Moskowitz 1977). In pretest training, the panelists were exposed to a variety of bread and baked-product structures, as well as to representative samples of the test bread formulations. On the basis of these pretest examinations, salient sensory textural characteristics were identified and definitions for each attribute were developed (Table II).

Sample evaluation involved partial compression of specimens with the molar teeth and mastication up through swallowing. Elasticity (percent recoverable work) was assessed by compressing the samples between the thumb and forefinger.

Panelists employed the psychophysical method of modulus-free magnitude estimation to evaluate the perceived magnitude of each attribute listed in Table II. This procedure involves assigning numbers to the first specimen tested to represent the perceived magnitude of each textural attribute. Subsequent assessments of attribute intensities are made in a ratio manner relative to the first

TABLE II
Sensory Attributes and Definitions

Visual Surface Evaluation	
1	*Cell size*: Perceived average size of cells in the cut surface.
2	*Cell uniformity*: Perceived degree to which cells in the cut surface are of a same, single size.
Oral Surface Evaluation	
3	*Particle removal*: Perceived quantity (number and size) of particles that can be removed from the surface of the bread when sliding the tongue over the cut surface.
4	*Roughness*: Perceived roughness of the surface of the bread when sliding the tongue over the cut surface.
Partial Compression	
5	*Springiness*: Perceived degree (time and extent) to which the sample returns to its original shape (thickness) after a 50% compression between the thumb and forefinger.
First Bite	
6	*Firmness*: Perceived force required to compress the sample between the molar teeth, prior to compacting.
7	*Denseness*: Perceived amount of bread material per unit volume during a single compression with the molar teeth.
Mastication	
8	*Moistness*: Perceived degree of moisture in the sample.
9	*Chewiness*: Perceived total effort required to repeatedly compress the sample through five chews.
10	*Cohesiveness during chewing*: Degree to which the sample holds together as a single mass during chewing.

sample. Panelists also judged a hypothetical optimal magnitude estimate for each attribute so that an ideal sensory profile could be determined.

Test samples were presented randomly with blinding codes on individual white, coded paper plates. All samples were presented as ≈3.5 cm cubes cut from the interior crumb of the bread. Samples were served at room temperature, shortly after slicing. Testing was conducted during two replicated sessions in which the full range of attributes was evaluated.

Sensory Data Analysis

Sensory data were normalized using modulus equalization (Moskowitz 1977) to accommodate differences in attribute scales used by the panelists. Using this procedure, geometric means across all samples for each attribute, panelist, and session are calculated, as well as the grand geometric mean across all samples and subjects for each attribute and session. Raw magnitude estimates for each panelist are multiplied by the ratio of the grand mean to the panelist mean for each attribute and session, thus bringing data onto a common scale.

Optimal data were subjected to the same transformation and normalization procedures described previously, so that ideal and actual sample data would be on the same scale and could thus be compared. Samples were ranked according to their correspondence with the ideal by summing the squares of the differences between actual and optimal sensory profiles (the array of 10 estimates corresponding to the 10 sensory attributes evaluated), according the procedure of Barrett et al (1997 and 1998). Significant sensory-instrumental relationships were identified by ANOVA and described by appropriate mathematical functions.

Consumer Testing

The bread samples were assessed by a consumer panel consisting of 38 volunteer members randomly selected from the employee population. These individuals had received no prior texture training and had no other involvement in the bread study. The consumer panelists used a nine-point intensity scale (1 = not at all, 9 = extremely) to rate the attributes of chewiness, firmness, and roughness. They also rated “liking of the texture” of the samples using a nine-point hedonic scale (Peryam and Pilgrim 1957). The panelists were presented with all eight (coded) samples and evaluated them in random order.

Textural Stability Study

Bread samples were placed in storage at 22°C and withdrawn after 2, 4, 6, 9, and 12 week intervals. Compression testing was conducted as described previously, and the firmness parameters C1 and peak force determined. Additionally, elastic modulus was calculated by determining the slope of the initial part (<20% strain) of the stress-strain function.

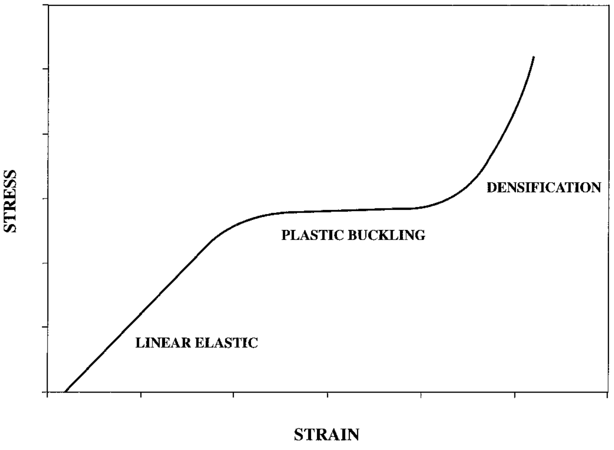

Fig. 1. Representative stress-strain relationship for spongy materials, illustrating linear elastic, plastic buckling, and densification regions.

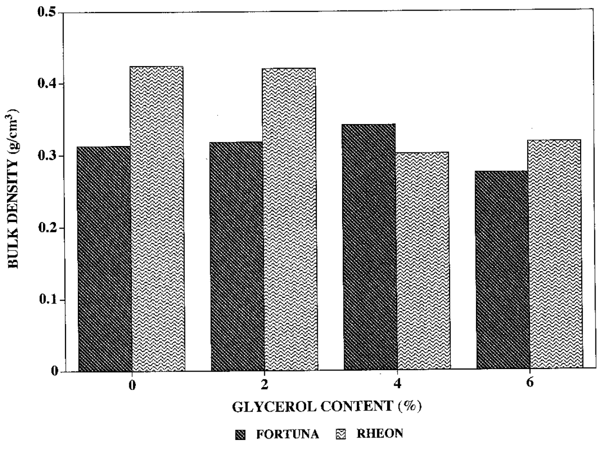

Fig. 2. Bulk density histograms for initial (nonstored) breads produced using two different formation methods and containing different levels of glycerol. Coefficient of variation = 8.6% ± 4%.

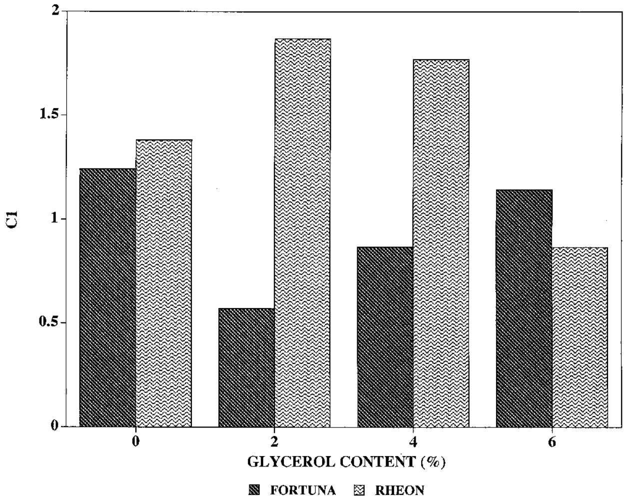

Fig. 3. C1 values (instrumental firmness) for initial (nonstored) bread produced using two different formation methods and containing different levels of glycerol. Coefficient of variation = 32% ± 6%.

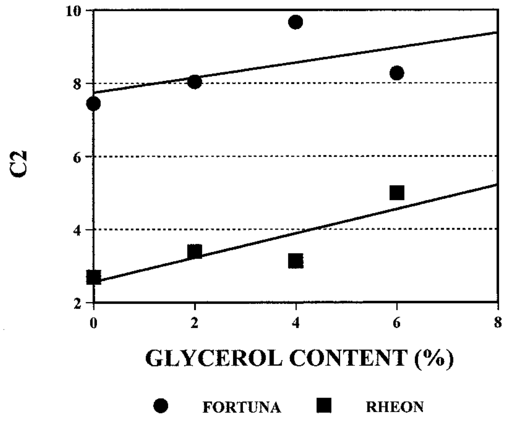

Fig. 4. C2 values (instrumental plasticity) for initial (nonstored) bread produced using two different formation methods and containing different levels of glycerol. Coefficient of variation = 53% ± 20%.

C1, peak force, and modulus were normalized for density (according to Gibson and Ashby [1988], mechanical strength of materially similar cellular solids is a function of bulk density) to isolate effects of formulation and process and fitted to the function:

$$y - y_o = A[1 - \exp(-bt)] \qquad (2)$$

where y = parameter value at a specific storage time, y_o = initial value, A = final asymptotic value, b = a kinetic constant reflecting fractional change per time, and t = storage time. For example, a higher value of A indicates a higher ultimate (instrumental) firmness after storage; a higher value of b indicates that ultimate firmness was achieved relatively quickly. Changes in wet-basis crumb moisture content due to storage were monitored using a Computrac moisture analyzer.

Statistical Analysis

Sensory-instrumental relationships were identified, and significance levels quantified, using ANOVA. Selected relationships were obtained by fitting the data to power-law functions using regression analysis capabilities provided by Minitab statistical software. Stability parameters were also determined using Minitab. Nonlinear regression analyses (to calculate C1 and C2 textural parameters) were accomplished using SigmaPlot software.

RESULTS AND DISCUSSION

All data presented are for interior crumb specimens taken from near the center of the rolls. Freshly thawed samples (except for storage study analyses) equilibrated to room temperature were used.

Physical and Mechanical Properties

Water activity and pH level. Glycerol content progressively reduced water activity in finished bread produced by either the Fortuna or Rheon equipment. Data pooled for both batches show the relationship:

$$a_w = 0.93 - 0.012\ (\%\ \text{glycerol})\quad r^2 = 0.90 \qquad (3)$$

The pH level of crumb samples was consistently 4.5–4.6.

Bulk density. Bulk density varied moderately (Fig. 2). Rheon-formed bread was higher, on average, in density ($P = 0.02$), most likely as a result of shear-induced reduction in the extensibility of the dough due to increased work. Glycerol had no consistent effect on bulk density.

Compressibility. Model parameters are plotted in Figs. 3 and 4. C1, or firmness, values (Fig. 3) were higher for the Rheon-formed bread than for Fortuna-formed bread at all glycerol levels except 6%. Interestingly, there is no relationship between C1 and density ($r^2 \approx 0$) as is typically found for foam structures (Gibson and Ashby 1988). Consequently, the observed differences in compressibility are partly attributable to differences in the intrinsic deformability of the cell wall material, reflecting both the nature of the gluten network and plasticization by glycerol. Cell structure may have also contributed to deformation behavior. A negative correlation ($r = -0.75$; $P = 0.02$) was found between C1 and perceived cell size, in keeping with structure-strength relationships observed for other cellular foods (Barrett and Peleg 1992, Barrett et al 1994).

The C2, or plasticity, parameter (Fig. 4) was consistently higher in bread formed by the Fortuna dough-dividing process than by extrusion ($P < 0.01$). The Fortuna-formed samples exhibited substantially greater buckling, or plastic deformation, of cell walls than did the Rheon-formed samples.

C3 (an indication of densification strain) was ≈1 for all specimens. Percent recoverable work varied randomly between 15 and 21% and was inconsistently influenced by either glycerol level or process procedure. Peak force at 10 mm deformation was roughly predicted by C1 ($r^2 = 0.79$).

Sensory Attributes: Texture Panel

Magnitude estimate scores. Three-way ANOVA (forming process × glycerol × session) was conducted on the normalized magnitude estimates for each sensory attribute to determine significant effects of these variables on perceived attribute intensities. There were no main effects of session on any attribute, and two- and three-way interaction effects were few and nonsystemic. As a result, the data were combined across sessions. The resulting geometric mean magnitude estimates for each attribute by process and by glycerol concentration are shown in Table III. The *F*-values, degrees of freedom, and significance levels for the main and interaction effects of process and glycerol concentration are shown in Table IV.

As Table IV shows, forming process had significant main effects on several sensory attributes. By averaging mean magnitude estimates across formulation (i.e., across all four glycerol levels for each formation technique), it is evident that Rheon processing decreased perceived cell size and increased perceived cell uniformity by ≈27% compared with Fortuna processing. Rheon processing also decreased perceived springiness by 33%, increased perceived firmness by 22%, and increased perceived denseness by 18%. It is likely that extrusion forming of the dough by the Rheon

TABLE III
Magnitude Estimates of Sensory Attributes

	Attribute[a]									
Sample	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Fortuna 0% glycerol	96.3	88.4	87.9	90.4	82.4	84.5	89.7	90.7	88.6	90.0
	(4.4)	(3.1)	(4.6)	(3.4)	(6.0)	(3.3)	(3.9)	(3.2)	(2.5)	(2.0)
Fortuna 2% glycerol	93.8	84.5	87.2	87.9	90.8	79.9	79.0	92.0	81.6	91.6
	(3.7)	(4.4)	(5.9)	(3.0)	(7.3)	(4.2)	(5.7)	(2.8)	(2.7)	(2.4)
Fortuna 4% glycerol	118	75.2	88.0	98.7	87.2	80.2	84.7	85.9	88.3	90.9
	(6.6)	(4.9)	(6.2)	(6.2)	(7.2)	(3.7)	(5.0)	(2.7)	(2.5)	(2.2)
Fortuna 6% glycerol	104	83.2	66.8	89.7	89.2	87.1	81.5	85.7	84.0	89.4
	(3.6)	(4.6)	(5.8)	(3.5)	(6.2)	(3.9)	(2.5)	(2.8)	(2.8)	(2.1)
Rheon 0% glycerol	44.5	142	72.9	81.1	53.1	101	104	90.5	102	99.8
	(4.7)	(12)	(5.3)	(5.8)	(4.7)	(4.5)	(5.1)	(4.1)	(4.2)	(3.7)
Rheon 2% glycerol	77.7	74.3	89.7	114	53.4	116	116	81.9	99.5	89.2
	(5.1)	(6.4)	(6.4)	(5.5)	(4.8)	(7.0)	(5.9)	(5.2)	(4.1)	(2.6)
Rheon 4% glycerol	92.6	101	76.8	83.8	79.4	98.2	87.7	77.8	90.3	87.1
	(3.4)	(7.1)	(3.7)	(6.7)	(5.0)	(4.7)	(3.4)	(3.6)	(2.5)	(2.9)
Rheon 6% glycerol	82.7	104	71.5	79.9	49.0	90.0	88.2	92.9	87.5	93.4
	(3.4)	(4.1)	(4.5)	(5.0)	(4.9)	(3.1)	(4.1)	(2.9)	(3.7)	(3.0)
Ideal	93.5	104	80.8	76.0	98.7	88.3	89.1	96.6	83.7	78.3
	(5.9)	(12)	(6.9)	(13)	(9.1)	(8.1)	(7.3)	(5.3)	(7.4)	(6.0)

[a] Attributes and definitions are listed in Table II. Standard errors are shown in parentheses.

(i.e., forcing the dough through a die) reduced extensibility due to increased working of the gluten matrix.

The results in Table IV also show significant main effects of glycerol concentration on six of the 10 sensory attributes. However, glycerol had an effect primarily on the Rheon-processed samples. While some of the effects were not monotonic with concentration, comparison of the average magnitude estimate for the two lower glycerol concentration samples with that for the two higher glycerol content samples showed a 44% increase in perceived cell size and a 28% decrease in perceived denseness.

Ideal attribute levels. Geometric mean ratings of ideal levels of each attribute are included in Table III. Ideal levels of perceived cell size, cell uniformity, particle removal, firmness, denseness, and chewiness all fall within the magnitude-estimate range of the tested samples, indicating that the sample selection provided at least some specimens that were close to the optimal levels of these attributes. However, the ideal levels for roughness, springiness, moistness, and cohesiveness during chewing were beyond the magnitude-estimate range for the tested samples, indicating that all specimens were excessively rough and cohesive as well as inadequately moist and springy.

Figure 5 shows the sums of squares (SSQ) of the differences between the actual sensory profiles for the eight products and the ideal profile. The Fortuna-formed samples, irrespective of glycerol level, are relatively closer to the ideal. At low glycerol levels (0 or 2%), difference SSQ for the Rheon samples are ≈700% greater than those for the dough-divided samples, indicating a significant deviation from ideal texture. However, at 4 and 6% glycerol levels, the sensory profiles for these products are close to those for Fortuna-formed products. These results reflect the observed interaction effects of glycerol and process on several individual sensory attributes and indicate that the addition of glycerol mitigates deleterious effects of Rheon extrusion on key textural properties of the finished product.

TABLE IV
***F*-Values for Main and Interaction Effects of Forming Process and Glycerol Content on Trained Panel Texture Attributes**

Attribute	Process (df = 11,1)[a]	Glycerol (df = 33,3)	Process × Glycerol (df = 33,3)
Cell size	27.41***[b]	22.90***	4.94**
Cell uniformity	24.33***	10.48***	9.69***
Particle removal	1.43	3.78*	1.09
Roughness	0.02	2.78	6.99***
Springiness	16.43**	2.89*	2.38
Firmness	12.23**	2.28	4.51**
Denseness	9.31*	5.27**	3.58*
Moistness	0.19	2.62	2.08
Chewiness	5.80*	3.24*	3.40*
Cohesiveness	1.09	1.91	1.87

[a] Degrees of freedom.

[b] *, **, *** = $P < 0.05, 0.01, 0.001$, respectively.

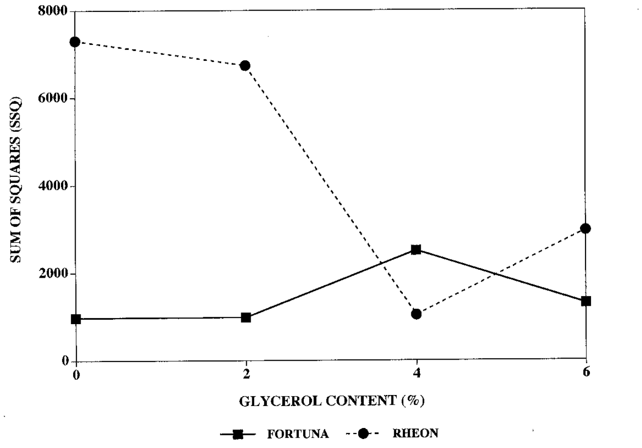

Fig. 5. Plot of difference sums of squares between actual sensory profiles and the ideal sensory profile for bread samples produced using Fortuna vs. Rheon forming. Fortuna-formed samples and Rheon-formed samples containing ≥4% glycerol show greater correspondence with the ideal sensory profile.

Sensory Attributes: Consumer Panel

Figure 6 shows the mean consumer ratings of texture liking-disliking, firmness, roughness, and chewiness as a function of glycerol content for the two forming processes. The results of two-way ANOVA conducted on these data are shown in Table V. Ratings of overall texture liking are, on average, lower for Rheon-formed products. However, the 4 and 6% glycerol content Rheon-formed samples rate as high as Fortuna-formed products (which were not affected by glycerol level), a result that is reflected in the significant glycerol content × process interaction effect (Table V).

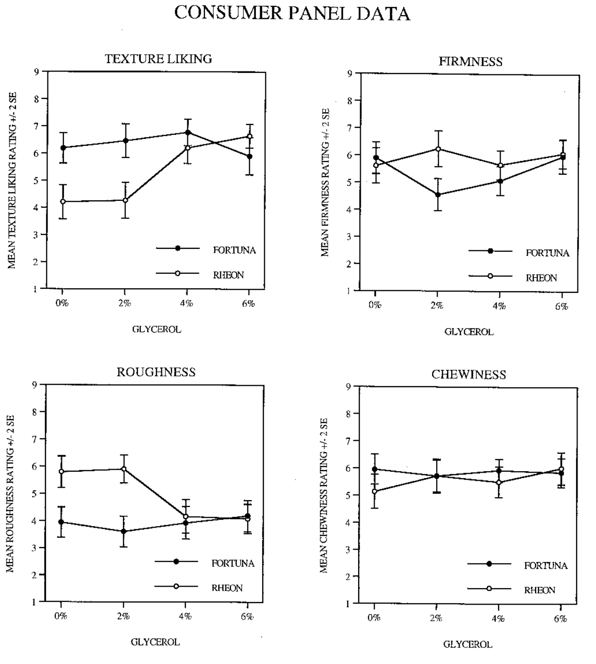

Fig. 6. Effects of forming method and glycerol level on consumer perception of firmness, roughness, chewiness, and overall liking.

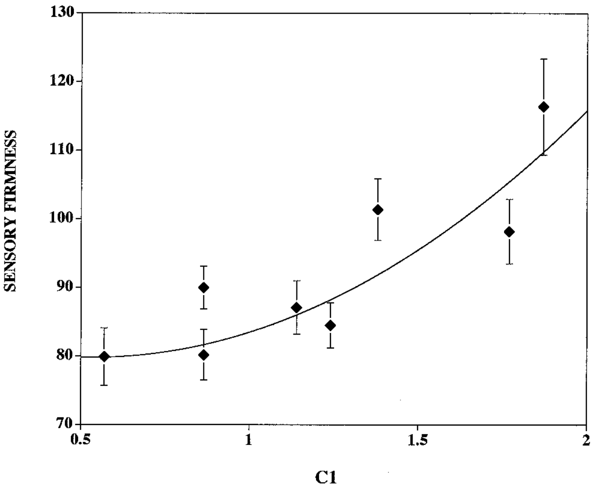

Fig. 7. Dependence of sensory firmness on C1 values (instrumental firmness). Line corresponds to the fit of a power-law function.

TABLE V
***F*-Values for Main and Interaction Effects of Forming Process and Glycerol Content on Consumer Panel Texture Attributes**

Attribute	Process (df = 37,1)[a]	Glycerol (df = 111,3)	Process × Glycerol (df = 111,3)
Liking-disliking	25.33***[b]	15.53***	11.75***
Firmness	6.64*	4.66**	5.23**
Roughness	23.03***	8.46***	14.55***
Chewiness	1.89	1.17	1.86

[a] Degrees of freedom.

[b] *, **, *** = $P < 0.05, 0.01, 0.001$, respectively.

TABLE VI
Significant Sensory and Instrumental Correlations[a]

Relationship	*t*-Value	*P*	r^2
Chewiness to density	4.9	0.003	0.77
Chewiness to peak force	3.6	0.016	0.59
Chewiness to C2[b]	2.9	0.031	0.50
Perceived denseness to measured density	4.7	0.004	0.74
Firmness to peak force	6.7	0.000	0.92
Firmness to C1[c]	4.0	0.007	0.69

[a] *t*-Value > 2 and $P < 0.05$ from linear regression.

[b] Fits power law function (see Eq. 7).

[c] Fits power law function (see Eq. 6).

This positive effect of glycerol at levels of 4 and 6% in Rheon-formed samples on consumer response is consistent with the trained panel results that show a better match to the ideal sensory profile in these two samples. And, as with trained panel results, glycerol had little effect on consumer liking ratings for Fortuna-formed samples (Fig. 6).

Glycerol level had no effect on ratings of chewiness but a statistically significant effect on ratings of firmness and roughness (Table V) due to relatively higher firmness ratings and relatively lower roughness ratings for the Rheon-processed samples at intermediate glycerol levels (Fig. 6). The effect of glycerol on perceived roughness may well have driven ratings of overall liking. While correlations of liking-disliking with firmness, roughness, and chewiness within data for individual consumers (and across the eight samples) were not of great predictive power, suggesting that consumer liking was driven by a number of factors not addressed in these three attributes, the correlation coefficient of liking-disliking with roughness had the highest absolute value and was highly significant ($r = -0.29$, $P < 0.001$). Moreover, the mean values for liking and roughness were strongly correlated ($r = -0.97$, $P < 0.001$) and could thus provide a predictive basis for consumer response.

Predicting consumer liking from sensory and instrumental parameters. Correlations of consumer liking-disliking with several trained panel attributes were highly significant. These relationships with liking included perceived cell size ($r = 0.77$, $P < 0.05$), firmness ($r = -0.84$, $P < 0.01$), denseness ($r = -0.88$, $P < 0.01$), and chewiness ($r = -0.87$, $P < 0.01$). Furthermore, regression analysis of the most highly correlated of these relationships yielded:

$$\text{Liking} = 12.4 - 0.7\ (\text{perceived denseness})\quad r^2 = 0.77 \tag{4}$$

Similarly, linear regression of consumer liking against instrumental measurements produced a simple function:

$$\text{Liking} = 11.0 - 15.2\ (\text{bulk density})\quad r^2 = 0.67 \tag{5}$$

Sensory-Instrumental Correlations

The magnitude estimates of three attributes (chewiness, firmness, and perceived denseness) were significantly correlated with physical or mechanical properties. Significance levels and regression coefficients are listed in Table VI. Additionally, the relationships between sensory firmness and the instrumental C1 parameter, and between sensory chewiness and the C2 parameter were determined to fit power-law functions:

$$\text{Firmness} = \text{firmness (min)} + 18.0\ (\text{C1} - \text{C1 (min)})^{1.92}\quad r^2 = 0.73 \tag{6}$$

and

$$\text{Chewiness} = \text{chewiness (max)} - 9.21\ (\text{C2} - \text{C2 (min)})^{-0.37}\quad r^2 = 0.67 \tag{7}$$

These relationships imply that firmness increases rapidly with increasing C1, or general compressive resistance, and that chewiness decreases initially with C2, or degree of buckling of cell walls. Actual and fitted data for these relationships are shown in Figs. 7 and 8. Ideal levels of firmness and chewiness were within the attribute level range provided by the specimens.

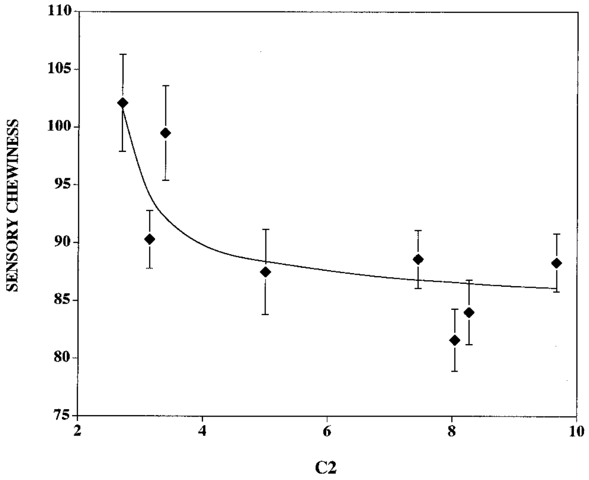

Fig. 8. Dependence of sensory chewiness on C2 values (instrumental plasticity). Line corresponds to the fit of a power-law function.

Textural Stability

Sample firmness, measured by the normalized values of C1, peak force, or modulus, increased markedly during storage. Sample crumb firmed most rapidly during initial storage, then reached a plateau, or final level. Data (averages for six replicates) for each formulation were fitted to Eq. 2, and model parameters were calculated (Table VII). Representative curves showing actual and fitted data for Rheon-formed samples are shown in Fig. 9. The upper curves correspond to the fit of the 0% glycerol results and the lower curves correspond to the fit of the 2, 4, and 6% glycerol results pooled together. Results for all glycerol-containing specimens are combined in the graphs because effects due to glycerol content were not monotonic. The curve fitting shows that glycerol both reduces ultimate firmness and also slightly retards the time to reach ultimate firmness. (The *b* values for C1 curves were 1.34 week^{-1} and 0.76 week^{-1} for the no-glycerol control and the glycerol-containing samples, respectively; *b* values for the peak force curves were 2.65 week^{-1} and 0.62 week^{-1} for the 0% glycerol control and the samples containing glycerol, respectively).

This firming behavior, at least in its initial stages, is most likely due to moisture redistribution from crumb to crust. (Crumb moisture content for freshly thawed samples was 34.1% [±1.2]; crumb moisture content after any period of storage was ≈10% lower at 24.0% [±1.2] to 24.9% [±1.5].)

Glycerol clearly lowered ultimate firmness, as quantified by any of the three firmness parameters (Table VII), an effect most likely due to plasticization of the macromolecular matrix. Formation process may have also affected ultimate firmness. Normalized C1 values are lower in Rheon-formed bread than in Fortuna-formed bread. However, normalized peak force values are com-

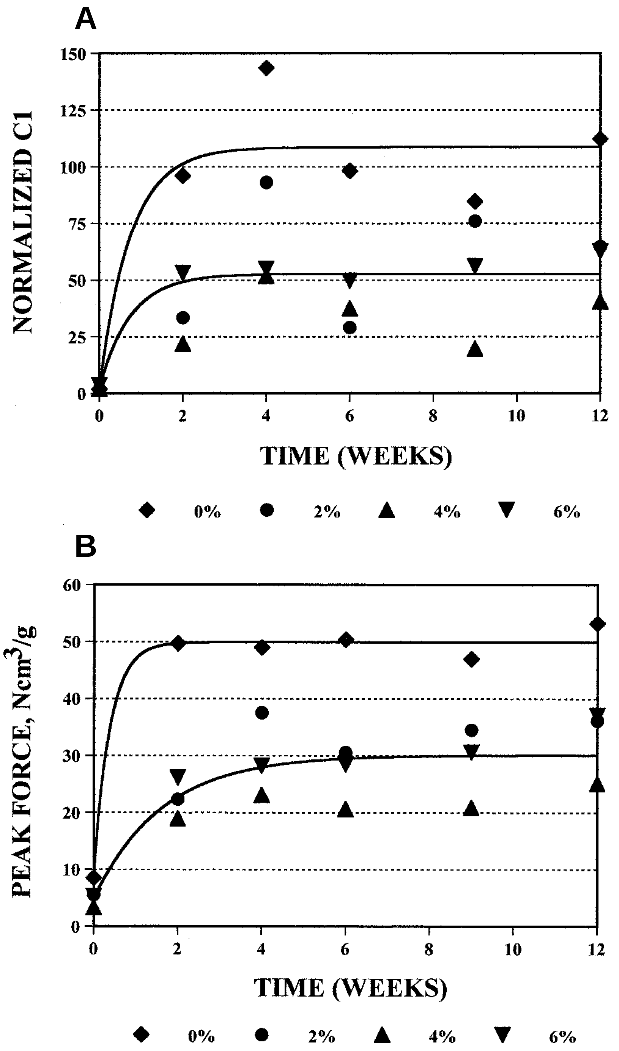

Fig. 9. Representative asymptotic relationships between firmness parameters and time, showing differences in firming rates due to the presence of glycerol. **A,** Rheon bread, normalized C1 (C1–cm^3/g). **B,** Rheon bread, normalized peak force (N–cm^3/g). Lines are fitted functions. Symbols for percentages refer to glycerol content. Data for 2, 4, and 6% glycerol are pooled for curve fitting.

TABLE VII
Fitted Final Firmness Parameters[a]

Formulation	C1[b]	Peak Force[c]	Modulus[d]
Fortuna 0% glycerol	222 (0.64)	43 (0.92)	0.071 (0.75)
Fortuna 2% glycerol	217 (0.93)	37 (0.88)	0.079 (0.86)
Fortuna 4% glycerol	185 (0.98)	31 (0.88)	0.057 (0.89)
Fortuna 6% glycerol	170 (0.52)	37 (0.96)	0.052 (0.74)
Rheon 0% glycerol	109 (0.82)	50 (0.94)	0.050 (0.95)
Rheon 2% glycerol	65 (0.55)	35 (0.89)	0.027 (0.62)
Rheon 4% glycerol	36 (0.60)	23 (0.92)	0.017 (0.81)
Rheon 6% glycerol	56 (0.96)	32 (0.88)	0.026 (0.96)

[a] Normalized for density and fit to Eq. 2 [$y - y_0 = A(1 - \exp(-bt))$] where y = parameter level, y_0 = initial parameter level, A = asymptotic parameter level, b = fractional change per time, and t = time. Regression coefficients for fit to Eq. 2 are shown in parentheses.

[b] C1–cm^3/g.

[c] N–cm^3/g.

[d] Pa–cm^3/g.

parable for both processes. This discrepancy between the two measurements is attributable to the fact that peak force is a single point measurement, while C1 is affected by the overall shape of the stress-strain relationship. For example, a more pronounced plateau, given similar peak force values, would necessitate a higher initial slope within the stress-strain function. Normalized modulus values calculated at low strain (Table VII) confirm that initial slopes of compression functions were higher for the Fortuna-formed product.

Considerable scatter existed in the data for measured firmness of stored products, as evidenced by some low r^2 values for fits to Eq. 2 (Table VII). This scatter was primarily attributable to sporadic outliers, or abnormally large values. Such variation in the data may indicate that firming does not progress uniformly within the bread but is, in part, a localized phenomenon. It is possible that effects due to slight variations in moisture content or moisture distribution, or due to differences in crumb-to-crust ratio, become manifest during storage. Additionally, average r^2 values for asymptotic fits to Eq. 2 were 0.91, 0.82, and 0.75 for peak force, modulus, and C1 data, respectively, indicating that scatter in the data increased as did the proportion of the stress-strain relationship used for analysis. Fits of individual stress-strain functions to Eq. 1 were generally good but were somewhat better for non-stored than for stored bread. Average r^2 values for data fitted to Eq. 1 (pooling data for all formulations and both processes) decreased from 99% for freshly thawed bread to 91% for samples stored for 12 weeks.

CONCLUSIONS

The use of dough-dividing forming, which imparted comparatively less shear to the dough than did Rheon (extrusion) forming, generally resulted in relatively less dense and (before storage) more deformable bread products. Conformance of the bread crumb to a panel-developed ideal profile, and consumer liking, was generally higher for rolls formed by the dough dividing process and for extrusion-formed rolls containing 4 or 6% glycerol. Glycerol may mitigate excessive working of dough and reduce firming that occurs during storage.

LITERATURE CITED

Amemiya, J. I., and Menjivar, J. I. 1992. Comparison of small and large deformation measurements to characterize the rheology of wheat flour doughs. J. Food Eng. 16:91-108.

Barrett, A. H., and Peleg, M. 1992. Extrudate cell structure-texture relationships. J. Food Sci. 57:1253-1257.

Barrett, A. H., Cardello, A. V., Lesher, L. L., and Taub, I. A. 1994. Cellularity, mechanical failure, and textural perception of corn meal extrudates. J. Texture Stud. 25:77-95.

Barrett, A. H., Cardello, A. V., Prakash, A., Mair, L., Taub, I. A., and Lesher, L. L. 1997. Optimization of dehydrated egg quality by microwave-assisted freeze drying and hydrocolloid incorporation. J. Food Process. Preserv. 21:225-244.

Barrett, A. H., Cardello, A. V., Maguire, P., Lesher, L. L., Taub, I. A., Defao, A., Briggs, J., Richardson, M., and Senecal, A. 1998. Optimization of shelf-stable meatstick texture by adjustment of water activity and fat levels: Sensory-instrumental correlations. Page 68 in: 1998 IFT Annual Meeting Book of Abstracts. IFT: Chicago.

Bloksma, A. H. 1972. Rheology of wheat flour doughs. J. Texture Stud. 3:3-17.

Brandt, M. A., Skinner, E. Z., and Coleman, J. A. 1963. Texture profile method. J. Food Sci. 28:404-409.

Ewart, J. A. D. 1968. A hypothesis for the structure and rheology of glutenin. J. Sci. Food Agric. 19:617-623.

Ewart, J. A. D. 1977. Re-examination of the linear glutenin hypothesis. J. Sci. Food Agric. 28:191-199.

Gibson, L., and Ashby, M. F. 1988. Cellular Solids. Pergamon Press.

Kaletunc, G., Normand, M. D., Johnson, E. A., and Peleg, M. 1991.

Degree of elasticity determination in solid foods. J. Food Sci. 56:950-953.

Launay, B. 1990. A simplified nonlinear model for describing the viscoelastic properties of wheat flour doughs at high shear strain. Cereal Chem. 67:25-31.

Launay, B., and Bure, J. 1973. Application of a viscometric method to the study of wheat flour doughs. J. Texture Stud. 4:82-101.

Levine, H., and Slade, L. 1992. Glass transitions in foods. Pages 83-221 in: Physical Chemistry of Foods. H. G. Schwartzburg and R. W. Hartel, eds. Marcel Dekker: New York.

Lindborg, K. M., Tragardh, C., Eliasson, A. C., and Dejmek, P. 1997. Time-resolved shear viscosity of wheat flour doughs—Effect of mixing, shear rate, and resting on the viscosity of doughs of different flours. Cereal Chem. 74:49-55.

Linko, P., Kervinen, R., Karppinen, R., Rautilinna, E.-K., and Vainionpaa, J. 1985. Extrusion cooking for cereal-based intermediate-moisture products. Pages 465-479 in: Properties of Water in Foods. D. Simitos and J. L. Multon, eds. Martinus Nijhoff: Dordrecht.

Mani, K., Eliasson, A. C., Lindahl, L., and Tradardh, C. 1992. Rheological properties and breadmaking quality of wheat flour doughs made with different dough mixers. Cereal Chem. 69:222-225.

Moskowitz, H. 1977. Magnitude estimation: Notes on what, how, when, and why to use it. J. Food Qual. 3:195-227.

Muller, H. G. 1969. Application of the statistical theory of rubber elasticity to gluten and dough. Cereal Chem. 46:443-446.

Nussinovitch, A., Steffens, M. S., and Chinachoti, P. 1991. Exponential model of the compressive stress-strain relationships of bread. Lebensm. Wiss. Technol. 24:266-269.

Peryam, D. R., and Pilgrim, F. J. 1957. Hedonic scale method of measuring food preferences. Food Technol. 11:9-14.

Stevens, S. S. 1953. On the brightness of lights and loudness of sounds. (Abstr.) Science 118:576.

Swyngdau, S., Nussinovitch, A., Roy, I., Peleg, M., and Huang, V. 1991. Comparison of four models for the compressibility of breads and plastic foams. J. Food Sci. 56:756-759.

Szczesniak, A. S. 1963. Classification of textural characteristics. J. Food Sci. 28:385-389.

Szczesniak, A. S., Brandt, M. A., and Freidman, H. H. 1963. Development of standard rating scales for mechanical parameters of texture and correlation between the objective and sensory methods of texture evaluation. J. Food Sci. 28:397-403.

[Received February 23, 1999. Accepted November 5, 1999.]