Effects of Glycerol and Moisture Redistribution on Mechanical Properties of White Bread

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ABSTRACT

Cereal Chem. 79(3):376–382

Effects of glycerol and moisture redistribution on mechanical properties of bread were investigated. Firmness increased in all bread crumb over storage time but firming rate was dependent on the initial moisture content, storage method (stored with and without crust), and the presence of glycerol. Faster firming was observed when bread crumb had low initial moisture content and high glycerol level, and was stored with crust. The effect of glycerol was more pronounced when stored with crust, suggesting a critical role of water loss. Firmness showed a good correlation ($r^2 = 0.95$) with the scale factor (C_1) from a mathematical model. Recoverable work rapidly decreased in first three days of storage and then remained relatively unchanged thereafter. Hardening of aged bread (but not fresh bread) by glycerol may be explained by local dehydration of bread polymer due to osmotic dehydration or competition for water, which in turn promote more rapid amorphous network formation but less amylopectin recrystallization.

Bread is a product with a short shelf-life mostly due to the loss in softness, moist texture, and flavor. It involves many physical and chemical phenomena that affect taste, aroma, and texture of the bread. Some of the contributing factors are changes in water sorption behavior and starch crystallization. Firmness has been commonly used to assess the extent of textural changes involved in bread staling (Pomeranz and Shellenberger 1971; Rogers et al 1988; He and Hoseney 1990; Martin and Hoseney 1991; Martin et al 1991; Piazza and Masi 1995). Mechanical properties of bread also include sponginess because bread has compressive behavior similar to that of solid foams and cellular solids (Ashby 1983; Peleg et al 1989). As shown in Fig. 1, the compressive stress-strain curve has been identified in three regions using a three-parameter model (Peleg et al 1989; Kou and Chinachoti 1991; Swyngedau et al 1991; Swyngedau and Peleg 1992; Peleg 1997). Compressive stress applied at a given strain can lead to a considerable cellular damage. After a compression-decompression cycle, compressive and decompressive effects can be measured from an area under the corresponding stress-strain curves. Recoverable work (amount of area under a decompression curve) has been used to characterize mechanical properties of breads (Hibberd and Parker 1985; Kou and Chinachoti 1991; Nussinovitch et al 1992a,b; Rao et al 1992). It is generally believed that starch recrystallization and retrogradation are the major causes of the textural effects of bread staling. Changes in other components such as water and gluten can also play important roles in water sorption behavior and water migration and redistribution (Leung et al 1983; Kim-Shin et al 1991; Piazza and Masi 1995; Ruan et al 1996).

Humectants such as glycerol have been used to extend the shelf-life of bread in military meals (ready-to-eat, MRE) mostly to reduce a_w to prevent mold growth and also to soften the bread (Berkowitz and Oleksyk 1991). Glycerol and water in bread act as plasticizers that could promote molecular chain mobility of starch, gluten, and minor components. Glycerol lowers thermomechanical transition temperatures in MRE bread (Hallberg and Chinachoti 1992; Taub et al 1994), in starch (Lourdin et al 1997), and in gluten (Cherian and Chinachoti 1996). Additionally, glycerol may have an impact on amylopectin retrogradation during staling (Hallberg 1996; Baik and Chinachoti 2001).

In our earlier investigations, effect of water and glycerol on starch retrogradation and thermomechanical properties of white bread were studied during staling (Baik and Chinachoti 2000, 2001). In this work, we hypothesized that hardening of bread crumb was influenced by glycerol both directly (direct plasticization) and indirectly by changing the way water is redistributed in bread. Redistribution of moisture is a dynamic property that occurs in bread during storage in a number of ways. Primarily, water may redistribute between starch and gluten over time (on stabilization of gluten and retrogradation of starch) (Leung et al 1983; Wynne-Jones and Blanshard 1986; Kim-shin et al 1991; Zobel and Kulp 1996). Additionally, water may migrate from crumb to crust accordingly to the moisture gradient. In this work, it was important to study stored bread with crust intact (where water would migrate out from crumb to crust) and without crust (where no moisture gradient allows flux or migration of water). Therefore, the investigation reported here shows the mechanical changes influenced by added glycerol under two transportation processes: 1) where there is moisture loss from crumb to crust, and 2) where there is no moisture loss from crumb.

The objective of this study was to investigate stress-strain relationships and recoverability of bread crumb containing glycerol and subjected to storage with and without crust in a hermetic pouch. In this study, the effects of glycerol and water redistribution from crumb to crust on mechanical properties of white bread were investigated to quantitatively elucidate the role of glycerol and moisture redistribution on bread staling.

MATERIALS AND METHODS

Bread

Wheat flour (unbleached, all-purpose, 10% protein, 73.3% carbohydrate [mostly starch], and 16.7% water), shortening, sugar, nonfat dry milk, active dry yeast, and salt were purchased at a local grocery. Potassium sorbate was purchased from Sigma Chemical (St. Louis, MO), calcium propionate was purchased from Pfizer (New York, NY), and glycerol was purchased from Fisher Scientific (Pittsburgh, PA).

White bread based on 0, 2.6, and 8.8 g of glycerol/100 g of wheat flour was made using an automatic breadmaking machine (Bread Bakery model SD-BT51P, Panasonic, Secaucus, NJ) and a general baking method (20 min of mixing time, 5 min of resting time, and 5 min of kneading, 160 min of rising, and 50 min of baking at 160°C). The formulation of the white bread is shown in Table I. Two water treatments were applied: 1) bread crumb with different initial moisture content after baking (i.e., same amount of water in the original formula with varying glycerol content and, after baking, glycerol breads showed lower moisture content than the control); and 2) bread crumb with same initial moisture content after baking (i.e., more water added to the original formula with increasing glycerol level to adjust moisture content to the same level [39.0%] after baking).

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Publication no. C-2002-0404-02R.

Five bread samples were used in this experiment: 1) control; 2) 2.6% glycerol bread with different initial moisture content after baking (lower than control); 3) 2.6% glycerol bread with same initial moisture content after baking as control; 4) 8.8% glycerol bread with different initial moisture content after baking (lower than control); 5) 8.8% glycerol bread with same initial moisture content after baking as control. After baking, two storage methods were used: 1) each loaf of bread was packaged with the crust intact; 2) each loaf of bread was sliced (15 mm thick) using a meat slicer and cut into 15 × 25 × 25 mm (height × width × length) shape from loaf center. Each bread sample was hermetically sealed in a trilaminated pouch (Cadillac Products, Chicago, IL) to prevent moisture loss to the atmosphere and then stored at 25°C. Specific volumes (Table I) of all samples (rapeseed displacement method) were not significantly different ($P \leq 0.05$).

Moisture Content

Moisture content was determined overnight using vacuum oven drying at 70°C and 29 in. of Hg (Approved Method 925.09, AOAC 1973) and calculating the weight change.

Mechanical Properties

Firmness, stress-strain relationship, and recoverable work measurements were determined using a universal testing machine (model 5540, Instron, Canton, MA) using a cylindrical plunger (50 mm diameter) and a plunger speed of 10 mm/min.

A modified Approved Method 74-10 (AACC 2000) was used to measure firmness. A sample (15 × 25 × 25 mm) was uniaxially compressed to 3.75 mm to achieve a 25% deformation. Force at 25% deformation was used to represent bread firmness.

For the stress-strain relationship, each sample (15 × 25 × 25 mm) was uniaxially compressed to 13.5 mm to obtain ≤90% deformation. Compressive stress-strain curve was recorded and analyzed using nonlinear regression curve fitting (Sigmaplot software, v. 4.01, Jandel Scientific, San Rafael, CA). Three parameters were obtained from curve fitting using the equations:

$$\sigma = C_1 \varepsilon/(1 + C_2 \varepsilon)(C_3 - \varepsilon) \tag{1}$$

$$\varepsilon = \Delta H/H_0 \tag{2}$$

where σ is stress, ε is engineering strain, ΔH is absolute deformation, H_0 is the initial specimen height, and C_1, C_2, and C_3 are constants. C_1 is primarily a scale factor representing cell wall rigidity (units are the same as stress [MPa]). C_2 is dimensionless and represents the height of flat region (cell wall buckling) or prominence of shoulder of the stress-strain curve. C_3 is the strain level where the sample is compressed to the point of densification (Peleg 1997). This analysis has been reported earlier (Attenborrow et al 1989; Peleg et al 1989; Kou and Chinachoti 1991; Swyngedau et al 1991; Swyngedau and Peleg 1992; Peleg 1997). In this work, C_1 and firmness (force at given deformation) were used to indicate the hardening of bread.

For recoverable work measurement, compression and decompression work were measured as described earlier by Kou and Chinachoti (1991). Each sample (15 × 25 × 25 mm) was uniaxially compressed at 10 mm/min to reach 20, 30, 40, and 50% deformation and then decompressed at the same speed. The force-deformation response was recorded (Merlin software, v. 2.13, Instron) and the area under both compression and decompression curves was calculated. The percent recoverable work for a given deformation level was calculated from the equation (Kou and Chinachoti 1991):

$$\begin{gathered}\text{Percent recoverable work} = \\ (\text{Area under the decompression curve/area} \\ \text{under the compression curve}) \times 100\end{gathered} \tag{3}$$

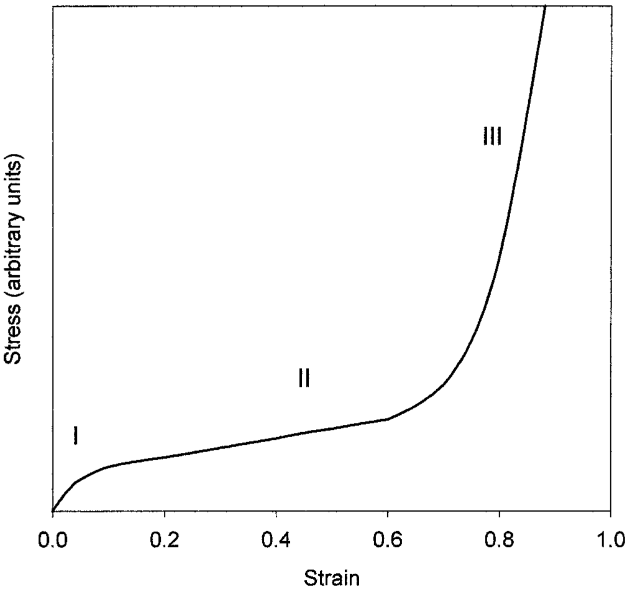

Fig. 1. Typical sigmoid shape of compressive stress-strain relationship of cellular solids. I, Small, primarily elastic deformation; II, shoulder representing buckling or fracture of cell walls; III, rapid stress increase when collapsed cell wall material is compressed (Peleg 1997).

TABLE I
Formulation of White Bread (g)

		Different Initial Moisture Content[a]		Same Initial Moisture Content[b]	
Ingredient	**Control**	**2.6% Glycerol[c]**	**8.8% Glycerol[c]**	**2.6% Glycerol[c]**	**8.8% Glycerol[c]**
Wheat flour	200.00	200.00	200.00	200.00	200.00
Water	120.00	120.00	120.00	128.90	142.70
Shortening	10.00	10.00	10.00	10.00	10.00
Sugar	9.40	9.40	9.40	9.40	9.40
Nonfat dry milk	6.00	6.00	6.00	6.00	6.00
Active dry yeast	5.40	5.40	5.40	5.40	5.40
Salt	4.50	4.50	4.50	4.50	4.50
Calcium propionate	0.96	0.96	0.96	0.96	0.96
Potassium sorbate	0.48	0.48	0.48	0.48	0.48
Glycerol	. . .	5.28	17.60	5.28	17.60
Initial moisture content	39.00 ± 0.10	38.00 ± 0.50	35.70 ± 0.80	38.50 ± 0.50	39.5 ± 0.40
Specific volume[d]	2.39 ± 0.06	2.28 ± 0.15	2.32 ± 0.09	2.35 ± 0.08	2.31 ± 0.05

[a] Same amount of water in original formula with varying glycerol content; after baking, glycerol breads showed lower moisture content than the control.

[b] More water added to original formula with increasing glycerol level to adjust moisture content to the same level (39.0%) after baking.

[c] Determined as g/100 g of wheat flour.

[d] Determined as mL/g of bread.

Statistics

Three loaves of breads were baked from three different machines simultaneously and used as three replicates for each experiment. All statistically significant tests were performed using Duncan's test (v. 6.12, SAS Institute, Cary, NC) at 95% confidence level. Regression analysis (rate constant calculation and linear regression) was performed using Sigma Plot software (v. 4.01, Jandel Scientific, San Rafael, CA) at 95% confidence level.

RESULTS

Stress-Strain Relationship

All compressive stress-strain curves showed a typical sigmoidal relationship (Fig. 2) consisting of three regions: 1) an initial linear elastic region or quasielastic deformation in the initial phase of compression; 2) a flat part of the curve (decreased slope) when the cell wall collapsed as a result of buckling or fracture, resulting in a relatively large deformation caused by a small increase in force; 3) a sharp rise in stress at a high strain level during densification or compression of cell wall materials (Peleg et al 1989; Kou and Chinachoti 1991; Swyngedau et al 1991; Peleg 1997). Relatively smaller stress levels at a given strain were observed in fresh than in aged

TABLE II
Moisture Content Change of Bread Crumb During Storage at 25°C for Two Weeks

Bread	Initial Moisture Content	Stored With or Without Crust	Storage Time (days)	Moisture Content (%, wb)
Control	. . .	W	0	39.0 ± 0.1
		W	3	37.1 ± 0.2
		W	7	34.9 ± 0.6
		W	14	30.5 ± 0.1
		W/O	0	39.0 ± 0.1
		W/O	3	37.4 ± 0.6
		W/O	7	37.5 ± 0.4
		W/O	14	38.8 ± 0.6
2.6% Glycerol	Different[a]	W	0	38.0 ± 0.5
		W	3	37.0 ± 0.6
		W	7	34.4 ± 0.9
		W	14	30.6 ± 0.3
		W/O	0	38.0 ± 0.5
		W/O	3	37.5 ± 0.4
		W/O	7	37.1 ± 0.0
		W/O	14	37.2 ± 0.1
2.6% Glycerol	Same[b]	W	0	38.5 ± 0.5
		W	3	37.5 ± 0.6
		W	7	35.0 ± 0.9
		W	14	31.2 ± 0.3
		W/O	0	38.5 ± 0.5
		W/O	3	38.0 ± 0.4
		W/O	7	37.6 ± 0.0
		W/O	14	37.7 ± 0.1
8.8% Glycerol	Different[a]	W	0	35.7 ± 0.9
		W	3	33.1 ± 0.2
		W	7	30.5 ± 1.0
		W	14	27.1 ± 0.6
		W/O	0	35.7 ± 0.9
		W/O	3	35.3 ± 0.7
		W/O	7	35.5 ± 0.5
		W/O	14	35.8 ± 0.6
8.8% Glycerol	Same[b]	W	0	39.5 ± 0.4
		W	3	39.0 ± 0.7
		W	7	36.3 ± 1.4
		W	14	33.9 ± 0.9
		W/O	0	39.5 ± 0.4
		W/O	3	39.0 ± 0.3
		W/O	7	39.4 ± 0.4
		W/O	14	39.0 ± 0.1

[a] Same amount of water in original formula with varying glycerol content; after baking, glycerol breads showed lower moisture content than control.

[b] More water added to original formula with increasing glycerol level to adjust moisture content to 39.0% after baking.

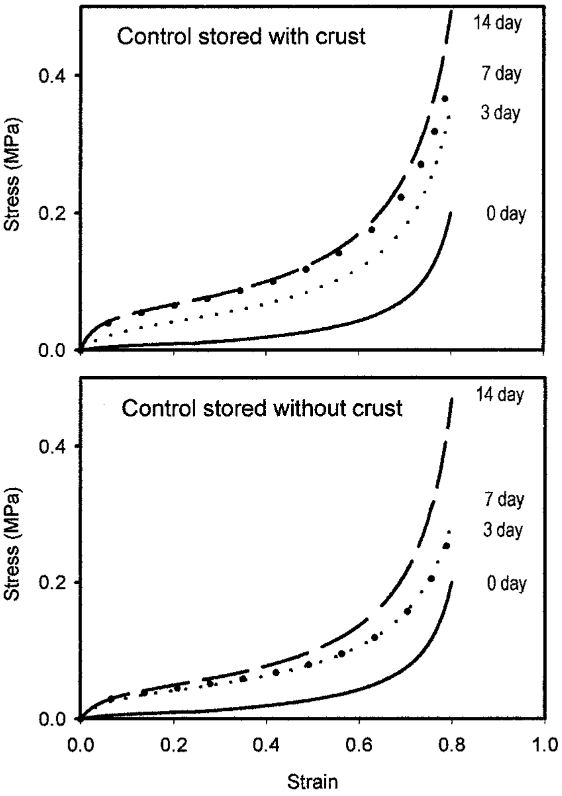

Fig. 2. Typical compressive stress-strain relationships of breadcrumbs.

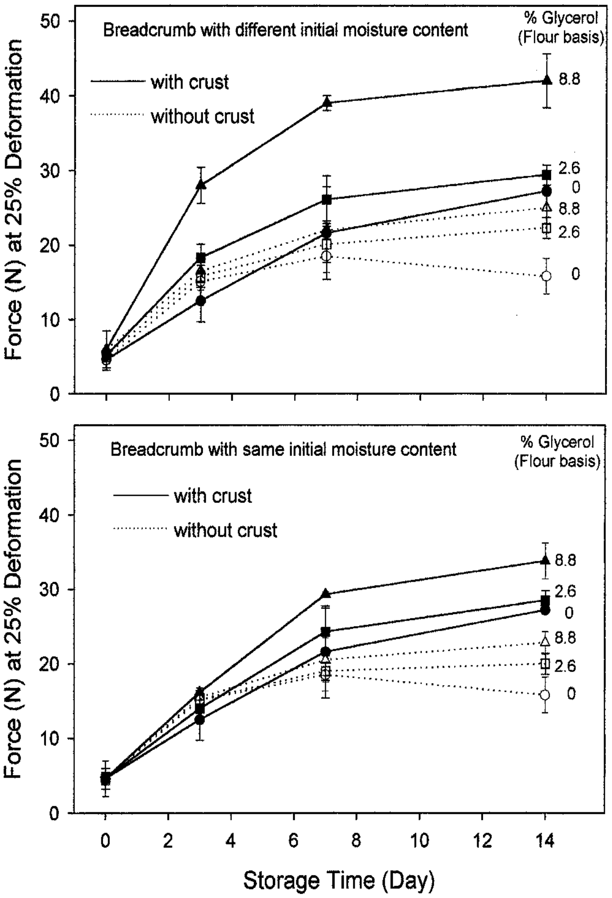

Fig. 3. Effect of glycerol on firmness of breadcrumb during storage at 25°C. Solid and dotted lines represent breadcrumb stored with crust (with moisture loss) and stored without crust (with no moisture loss), respectively.

bread crumb, indicating an increase in cell wall rigidity with storage time.

Firmness

Firmness expressed as a force at 25% deformation increased in all bread crumb during storage (Fig. 3). At 0 days of storage (fresh bread), all bread crumb samples had the same firmness. Over storage, firmness initially increased rapidly and leveled off after approximately seven days of storage. In general, firming rate was higher when bread crumb was stored with crust than when bread crumb was stored without crust. Bread crumb stored with crust showed a loss in moisture during storage due to moisture redistribution from crumb to crust (Table II), which could explain the relatively higher firming rate than bread crumb stored without crust (no moisture redistribution from crumb to crust during storage was expected). Bread crumb with different (low) initial moisture content showed relatively higher firming rate than bread crumb with same initial moisture content (Fig. 3).

The addition of glycerol increased firming rate but the effect was intensified in bread crumb stored with crust intact. When bread crumb was stored without crust (constant moisture) (Table II), no significant differences were observed among various glycerol levels except for 14 days of storage ($P \le 0.05$). The hardening (or antiplasticizing) effect of glycerol on white bread, particularly when there was a moisture loss from crumb to crust, suggested that the effect of glycerol was closely related to the hydration behavior of the bread components. However, in a previous study (Baik and Chinachoti 2001), glycerol delayed amylopectin recrystallization during storage. Therefore, the hardening effect over storage was less likely to be related to amylopectin recrystallization and more likely to be related to the change of amorphous regions in the presence of glycerol. Further investigation is needed to clarify those results.

Curve Fitting

The three-parameter empirical model (Eq. 1) was applied to the data to give constants C_1, C_2, and C_3 as summarized in Table III. C_1 was increased with increasing storage time in all samples in a manner similar to firming (Fig. 4). In fresh bread crumb, C_1 increased slightly with increasing glycerol content, although the values were not significantly different ($P \le 0.05$). At a given glycerol content, different initial moisture content treatments (lower initial moisture content than control) showed no effect on C_1 values ($P \le 0.05$). Again, no observable effect of glycerol on C_1 was found in fresh breads (similarly to earlier firmness data).

Figure 4 depicts C_1 as a function of storage time, showing a rapid increase over the first seven days, indicating that the cell wall gen-

TABLE III

Regression Parameters of Compressive Stress-Strain Relationships of Breads Using a Three-Parameter Empirical Model (Eq. 1)[a]

Bread	Initial Moisture Content	Stored With or Without Crust	Storage Time (days)	C_1 (MPa)	C_2 (–)	C_3 (–)
Control	· · ·	W	0	0.03 ± 0.01o	1.26 ± 0.15o	0.87 ± 0.12a
		W	3	0.61 ± 0.06n	12.85 ± 0.35n	0.90 ± 0.08a
		W	7	1.52 ± 0.08d–g	26.17 ± 1.21k	0.94 ± 0.05a
		W	14	1.72 ± 0.13cd	31.42 ± 1.25ij	0.91 ± 0.08a
		W/O	0	0.03 ± 0.01o	1.26 ± 0.15o	0.87 ± 0.12a
		W/O	3	0.83 ± 0.06m	22.23 ± 0.56l	0.92 ± 0.06a
		W/O	7	1.30 ± 0.09h–j	35.42 ± 2.53gh	0.93 ± 0.06a
		W/O	14	1.26 ± 0.18 h–j	30.42 ± 3.12ij	0.88 ± 0.09a
2.6% Glycerol	Different[b]	W	0	0.05 ± 0.01o	4.58 ± 0.25o	0.93 ± 0.04a
		W	3	1.22 ± 0.05i–k	18.54 ± 1.02lm	0.89 ± 0.08a
		W	7	1.88 ± 0.04c	32.64 ± 2.15g–i	0.92 ± 0.07a
		W	14	1.90 ± 0.09c	36.15 ± 2.51g	0.91 ± 0.06a
		W/O	0	0.05 ± 0.01o	4.58 ± 0.25o	0.93 ± 0.04a
		W/O	3	0.96 ± 0.03lm	20.16 ± 1.32l	0.91 ± 0.06a
		W/O	7	1.32 ± 0.13g–j	26.18 ± 1.24k	0.96 ± 0.02a
		W/O	14	1.46 ± 0.11e–h	32.15 ± 2.36h–j	0.91 ± 0.08a
2.6% Glycerol	Same[c]	W	0	0.06 ± 0.02o	3.26 ± 0.25o	0.90 ± 0.09a
		W	3	0.99 ± 0.06lm	16.45 ± 0.68mn	0.92 ± 0.05a
		W	7	1.60 ± 0.15de	28.59 ± 1.58jk	0.89 ± 0.07a
		W	14	1.91 ± 0.13c	36.45 ± 2.65g	0.93 ± 0.06a
		W/O	0	0.06 ± 0.02o	3.26 ± 0.25o	0.90 ± 0.09a
		W/O	3	0.88 ± 0.08m	20.65 ± 1.34l	0.94 ± 0.04a
		W/O	7	1.34 ± 0.09g–i	30.45 ± 2.52ij	0.89 ± 0.07a
		W/O	14	1.36 ± 0.12f–i	36.19 ± 2.14g	0.92 ± 0.04a
8.8% Glycerol	Different[b]	W	0	0.19 ± 0.03o	13.52 ± 0.84n	0.92 ± 0.06a
		W	3	1.23 ± 0.11h–j	44.23 ± 2.82ef	0.94 ± 0.04a
		W	7	2.38 ± 0.15a	50.35 ± 3.65ab	0.89 ± 0.12a
		W	14	2.54 ± 0.13a	51.64 ± 4.23a	0.93 ± 0.04a
		W/O	0	0.19 ± 0.03o	13.52 ± 0.84n	0.92 ± 0.06a
		W/O	3	1.12 ± 0.09j–l	46.59 ± 1.97b–e	0.93 ± 0.06a
		W/O	7	1.76 ± 0.15e–i	48.25 ± 3.46a–d	0.90 ± 0.08a
		W/O	14	1.89 ± 0.10c	44.36 ± 3.65d–f	0.94 ± 0.03a
8.8% Glycerol	Same[c]	W	0	0.11 ± 0.02o	12.23 ± 1.05n	0.89 ± 0.10a
		W	3	1.04 ± 0.03k–m	31.90 ± 2.61–j	0.97 ± 0.01a
		W	7	2.15 ± 0.06b	49.62 ± 3.18a–c	0.96 ± 0.02a
		W	14	2.38 ± 0.13a	42.05 ± 2.45f	0.98 ± 0.01a
		W/O	0	0.11 ± 0.02o	12.23 ± 1.05n	0.89 ± 0.10a
		W/O	3	0.97 ± 0.06lm	45.65 ± 1.88c–f	0.90 ± 0.08a
		W/O	7	1.56 ± 0.13d–f	46.41 ± 4.05c–e	1.00 ± 0.02a
		W/O	14	1.68 ± 0.12d	44.55 ± 2.18d–f	0.97 ± 0.03a

[a] C_1 is primarily a scale factor representing cell wall rigidity (MPa); C_2 (dimensionless) is height of flat region (cell wall buckling) or prominence of shoulder of the stress-strain curve; C_3 (dimensionless) is strain level when the sample is compressed to densification. Values followed by the same letter in the same column are not significantly different ($P < 0.05$).

[b] Same amount of water in original formula with varying glycerol content; after baking, glycerol breads showed lower moisture content than the control;

[c] More water added to original formula with increasing glycerol level to adjust moisture content to the same level (39.0%) after baking.

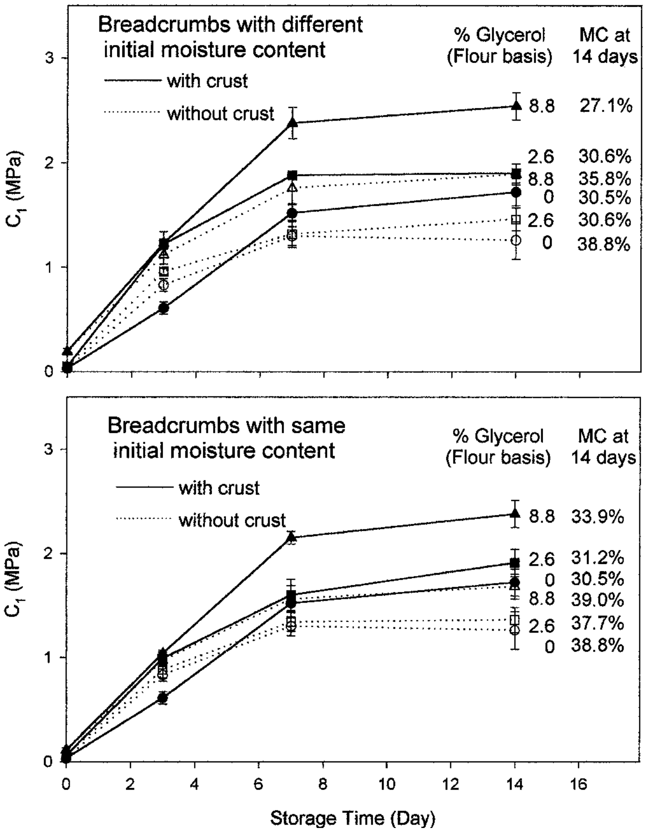

Fig. 4. Change of C_1 (scale factor in three-parameter model) during storage at 25°C. Solid and dotted lines represent breadcrumb stored with crust (with moisture loss) and stored without crust (with no moisture loss), respectively.

erally became more rigid in first seven days of storage. At a given glycerol level and storage time, bread crumb stored with crust (closed symbols, Fig. 4) showed significantly ($P \leq 0.05$) higher C_1 values than bread crumb stored without crust (open symbols, Fig. 4). Bread crumb with different initial moisture content showed higher C_1 values than bread crumb with same initial moisture content (Table III, Fig. 4a,b). These data suggested that low initial moisture content and loss in moisture during storage greatly increased cell wall rigidity.

In addition, the increase in firmness agreed with the C_1 data (Fig. 5). Although firmness is only a single-point measurement and C_1 is one of three parameters describing the entire stress-strain curve, good correlation between the two parameters was noted ($r^2 = 0.95$). This means that C_1 obtained from the compressive stress-strain curves can be a good indicator of firming in bread staling.

The C_2 values (shape index related to the prominence of the shoulder in stress-strain curve) also increased rapidly over the storage period in all samples (Table III), indicating the development of more prominent shoulder with aging. In fresh bread crumb with 8.8% glycerol (both different and same initial moisture content), C_2 was significantly higher ($P \leq 0.05$) than in the control and the 2.6% glycerol bread crumb. At a given glycerol content, varying the initial moisture content did not show significant difference ($P \leq 0.05$) in C_2.

At a given storage time, C_2 values increased with increasing glycerol content. In bread crumb with same initial moisture content, C_2 values were not significantly different ($P \leq 0.05$) between bread crumb stored with and without crust at a given glycerol content (Table III). But in bread crumb with different initial moisture content, significantly higher C_2 values ($P \leq 0.05$) were observed in bread crumb stored with crust at a given glycerol content. Thus, addition of glycerol influences the development of prominent shoulder in stress-strain curve, which is also dependent on the initial moisture content of bread.

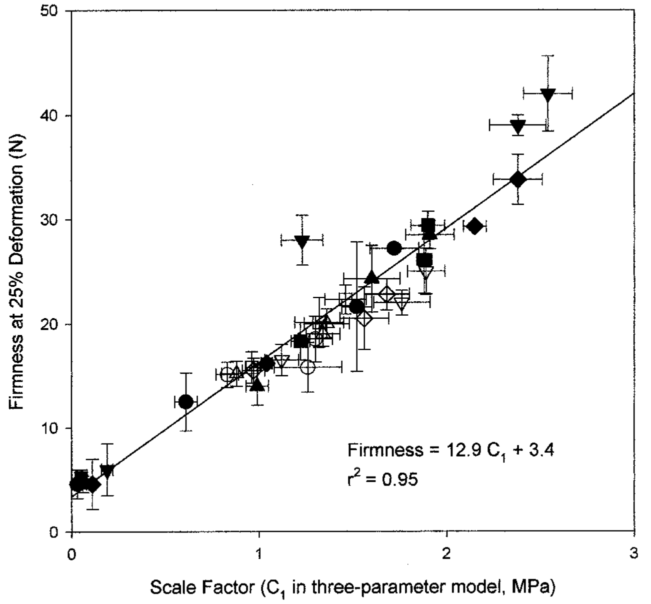

Fig. 5. Relationship between breadcrumb firmness and scale factor (C_1) in three-parameter model (listed in Table III).

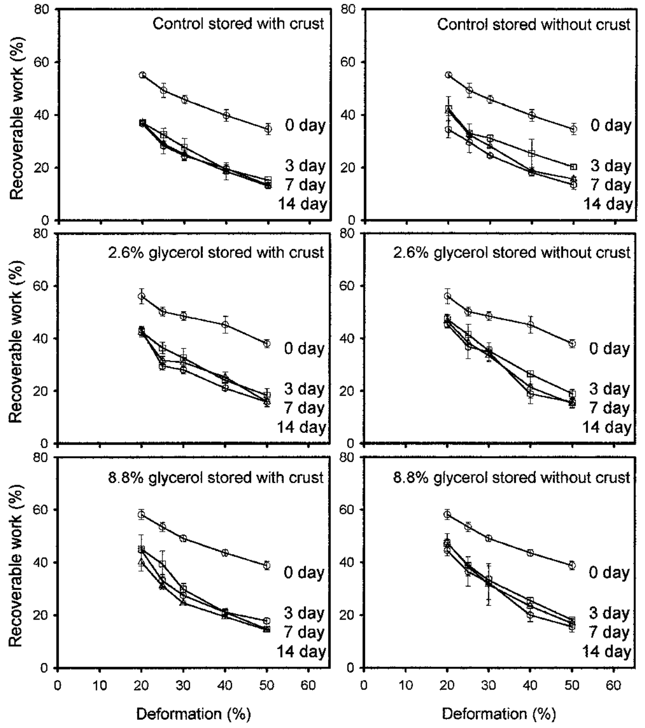

Fig. 6. Changes of recoverable work of breadcrumbs with different initial moisture content during storage at 25°C for two weeks.

All bread crumb showed densification strain of 0.87≈1.00 for C_3 values (Table III). However, there is no pattern of change in C_3 ($P \leq 0.05$) with storage time, glycerol, and moisture content.

Recoverable Work

In general, recoverable work decreased with increasing deformation level (Fig. 6), depicting increasing cell wall damage or fracture with increasing degrees of compression. Storage with and without crust as well as the difference in initial moisture control treatments did not seem to have an effect on recoverable-deformation curves. However, Kou and Chinachoti (1991) reported that moisture loss made a significant contribution to the increased rigidity in the cell wall structure and irrecoverable damage of a standard white bread. Recoverable work decreased rapidly at the first three days of storage when moisture loss (if any) was small (Table II). Because the test was done at ≥20% deformation, irrecoverable fracture of the cell wall materials could be extensive despite moisture.

At some extreme deformation level (40 and 50%), addition of glycerol led to a slight increase in recoverable work of the fresh bread crumb but not in aged bread crumb ($P \leq 0.05$). Thus, glycerol might have contributed to an overall increase in elastic component of fresh bread, perhaps by affecting the properties of gluten. Additionally, glycerol can influence the water sorption behavior of a protein and its thermostability during baking. Disulfide formation occurs during heating of gluten, which influences water mobility and thermal transition properties of the gluten (Cherian and Chinachoti 1996). Potential interaction between glycerol and polymers and between glycerol and water could also affect many other functions, such as starch swelling, gelatinization ability, and gluten physicochemical properties. Note that C_2 data also indicates a strong influence of glycerol on the prominent shoulder of the stress-strain curves, indicating a possible contribution to the change in elasticity.

DISCUSSION

Moisture loss during storage can greatly increase bread staling rate in terms of texture firming (Rogers et al 1988; Czuchajowska and Pomeranz 1989; He and Hoseney 1990; Martin and Hoseney 1991; Martin et al 1991; Piazza and Masi 1995; Davidou et al 1996). Firming of bread can be viewed as a process of cross-linking among partially solubilized starch, and possibly gluten, with water acting as a plasticizer (He and Hoseney 1990; Martin and Hoseney 1991; Martin et al 1991). However, the firming process is not entirely due to moisture loss (Davidou et al 1996). Our results demonstrated that moisture played an important role in affecting the way glycerol influences the staling process.

Bread became more rigid over time when glycerol was added (Figs. 2 and 4). Glycerol presented both antiplasticizing effect at <12% (w/w, ≈12% moisture content) and plasticizing effect at >12% on starch film, suggesting that in a water-glycerol-starch system, the roles of the two competing plasticizers are dependent on their respective concentrations (Lourdin et al 1997). We also observed bread hardening accelerated most when glycerol was added, accompanied by moisture loss.

Glycerol, although small in molecular weight (≈92), contains three hydroxyl groups enhancing its solubility in water. Thus, glycerol competes more effectively for water than bread polymer. When present in excess, it may osmotically dehydrate other domains. These resulting glycerol-rich regions have shown a phase transition at approximately –65°C (Hallberg and Chinachoti 1992; Taub et al 1994; Cherian et al 1995; Hallberg 1996; Lourdin et al 1997; Baik and Chinachoti 2001). Therefore, the hygroscopic property of glycerol may affect water partition or distribution among bread polymers and eventually lead to partial dehydration. This may, in turn, influence retrogradation and other networking among amorphous polymers, resulting in a more rapid staling rate. Further investigation on the state of hydration of various bread components during storage is warranted.

CONCLUSIONS

Sigmoidal stress-strain relationships of bread provided various empirical parameters for mechanical properties of bread. A strong correlation between firmness and the scale factor (C_1) was observed. Although adding glycerol did not affect the firmness of fresh bread, it accelerated the firming rate of bread polymers (osmotic dehydration or competition for water). The effect of glycerol was more pronounced when the bread was stored with crust (moisture loss from crumb to crust). When bread was stored without crust, the effect was not observable until 14 days of storage. Recoverability decreased significantly during the first three days of storage regardless of glycerol and moisture treatments. Glycerol led to an increase in recoverable work or C_2 of fresh bread, suggesting a contribution to elasticity. We concluded that application of other plasticizers (in this case glycerol) with water to white bread would increase staling, especially firming rate. Additionally, increase of firming rate and decrease of amylopectin recrystallization in the presence of glycerol suggests that bread firming may be related more to the change of amorphous region rather than the change of crystalline region.

ACKNOWLEDGMENTS

This work was supported by the Cooperative State Research, Extension Service, U.S. Department of Agriculture, Massachusetts Agricultural Experiment Station, under Project No. 00811. We acknowledge useful discussions with Micha Peleg.

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[Received March 30, 2001. Accepted December 14, 2001.]