Correlations Between Empirical and Fundamental Rheology Measurements and Baking Performance of Frozen Bread Dough

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ABSTRACT

Cereal Chem. 76(3):421–425

Empirical and fundamental rheology measurements were made on fresh and frozen dough to investigate the effects of freezing, frozen storage, and additives. These results were compared with results of a standard baking test. Four formulations were tested: a control dough, and doughs with additions of 100 ppm of ascorbic acid (AA), 0.5% sodium stearoyl lactylate (SSL), and 0.5% diacetyl tartaric acid esters of monoglycerides (DATEM). Rheological and baking tests were performed on fresh doughs and on doughs after two, five, and eight weeks of frozen storage. Resistance to extension was higher for doughs with additives in fresh and frozen doughs. There was a decrease in resistance to extension due to freezing. Complex modulus in fresh doughs was highest for doughs with SSL. There was a decrease complex modulus after freezing and thawing. In frozen doughs at 10 Hz, doughs with additives had higher complex modulus values and lower phase angle values when compared to the control. The additives used all had a positive effect on proof time, loaf volume, and crumb firmness, and all formulations deteriorated in quality during frozen storage. Resistance to extension and complex modulus were positively correlated with loaf volume ($r = 0.86$ and $r = 0.64$, $P < 0.01$). Phase angle was negatively correlated with loaf volume ($r = –0.74$, $P < 0.01$).

Frozen dough is becoming an increasingly popular alternative to conventional dough processing. Use of frozen dough allows the benefits of producing freshly baked products while saving on equipment and labor costs. In recent years, the quality of these products has improved due to advances in technology and formulation but there is still room for improvement. Problems associated with frozen dough include long proof time, low volume, poor texture, and variable performance. Yeast is necessary to provide sufficient gas production for dough leavening, and destruction of yeast cells results in a decrease in gas production. Varriano-Marston et al (1980) showed that freezing and thawing increased the number of disrupted yeast cells in dough. Weakening of the dough structure through damage to the gluten network reduces gas-retaining ability. Two theories have been proposed to explain dough weakening. The release of reducing compounds (mainly glutathione) from yeast cells that cleave disulfide bonds may cause weakening (Kline and Sugihara 1968). An alternative theory is that the gluten network is damaged due to disruption by the mechanical action of ice crystals during freezing (Varriano-Marston et al 1980, Berglund et al 1991). Frozen dough stability has also been related to freezing rates, final freezing temperature, and frozen storage temperature (El-Hady et al 1996, Hsu et al 1979b).

Additives are incorporated into frozen dough to counteract changes occurring during freezing, frozen storage, and thawing. The additives used in this study are well known for their effects in breadmaking. They have decreased final proof time, increased loaf volume, increased bread softness, and have had positive effects on dough rheological properties for fresh and frozen doughs. Ascorbic acid (AA) is an oxidizing agent that strengthens the gluten network by creating disulfide bonds (Nakamura and Kurata 1997). It reportedly gives large increases in ovenrise and bread score (Yamanda and Preston 1992). Sodium stearoyl lactylate (SSL) is a surfactant reported to maintain volume and softness in fresh and frozen dough products (Varriano-Marston et al 1980, Davis 1981, Wolt and D'Appolonia 1984, Armero and Collar 1996). Diacetyl tartaric acid esters of monoglycerides (DATEM) is a surfactant reported to produce a firm dough and an increase in baking volume (Adams et al 1994). Haehnel et al (1995) reported that DATEM forms hydrogen bonds with starch and glutamine.

Bread dough is a viscoelastic material. Rheological tests can be used to gain information about viscosity and elasticity. These properties of the dough are connected to proof time, loaf volume, and product quality. Empirical rheological tests, such as a farinograph or extensigraph, use relatively large forces to cause large deformations and therefore are suitable for describing the mechanical or processing properties of a material. One deformation force is used and the result is a single point measurement in arbitrary units. Fundamental rheological tests, such as a controlled stress rheometer, use small forces to cause small deformations to describe the physical or rheological properties of a material. A wide range of strains and strain rates can be used to give continuous or recurrent measurement in absolute units (Blocksma 1990, Weipert 1992).

The purpose of this study was to evaluate the suitability of fundamental and empirical rheological measurements for the prediction of baking performance of frozen dough. Four dough formulations were used: a control dough, and doughs with additions of 100 ppm of ascorbic acid, 0.5% SSL, and 0.5% DATEM. Rheological and baking tests were performed with fresh dough and after two, five, and eight weeks of frozen storage. The effects of freezing, frozen storage, and additives on proof time stability, loaf volume stability, and bread crumb firmness were analyzed. Empirical measurements were made on fresh dough with the farinograph and extensigraph to investigate the effects of additives. The extensigraph was used to measure rheological properties of frozen dough. It has been used by other workers for this purpose (Varriano-Marston et al 1980, Inoue and Bushuk 1992). Fundamental rheological measurements were made with the controlled stress rheometer using dynamic oscillatory measurements in the linear viscoelastic region. Dynamic oscillation is a relatively new technique in the area of frozen dough rheology (Autio and Sinda 1992).

MATERIALS AND METHODS

Materials

Commercial wheat flour (Odlum Group, Dublin, Ireland), with protein content of 12.7% (14% moisture basis) was used, along with compressed yeast (DCL Yeast Ltd. Clackmannanshire, UK). Additives included ascorbic acid (AA) (Sigma, St. Louis, MO); SSL, and DATEM (Quest Foods Carrigaline, Co., Cork, Ireland).

The basic control dough contained 2% salt, 6% yeast, 3% sugar, 3% shortening, and 58% water, all based on flour weight at 14% moisture. In addition, doughs with additives contained, 100 ppm of AA, 0.5% SSL, or 0.5% DATEM, based on flour weight at 14% moisture. Farinograms showed that additives only slightly affected

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Publication no. C-1999-0417-03R.

water absorption, therefore the same water addition (58%) was used in each formulation as it produced a slightly stiff dough with good handling properties suitable for frozen dough.

Testing

Doughs containing flour, water, and additives were tested with a farinograph according to the ICC standard method No. 115/1 (ICC 1995). Each result is the average of four measurements. The standard extensigraph test was used for fresh doughs containing flour, water, salt, and additives according to Approved Method 54-10 (AACC 1995). Each result is the average of six measurements.

Unyeasted doughs containing 1,500 g of flour, salt, sugar, shortening, water, and additives (according to the breadmaking recipe) were mixed for 110 sec in a high-speed mixer (Stephan u Söhne GmbH & Co., Hameln, Germany). Doughs were rested for 15 min, divided into 150-g pieces and molded in the molding unit of an extensigraph. For fresh dough measurements, three of the molded dough pieces were fermented in the proofing cabinet (30°C) for 45 min and stretched. Frozen doughs were prepared by blast freezing the remaining dough pieces after molding to a core temperature of –18°C. Dough pieces were vacuum-packaged and stored at –18°C. After two, five, and eight weeks, doughs were thawed at 2°C for 16 hr and equilibrated to 28°C in the extensigraph proofing cabinet (the same temperature as the fresh doughs after 45 min of fermentation). Resistance to extension was calculated from extensigrams. Each result is the average of six measurements.

Dynamic oscillation measurements were performed with a controlled stress rheometer (Bohlin Rheology AB, Lund, Sweden). Unyeasted doughs containing 10 g of flour, salt, water, and additives (according to breadmaking recipe) were tested. Dough was mixed for 70 sec using a Glutomatic 2200 (Falling Number AB, Stockholm, Sweden) without washing and using a modified mixing chamber without perforation. This system allowed reproducible mixing of small quantities of dough. Doughs were divided into 4.5 g of portions. Fresh doughs were rested for 15 min, placed between parallel plates (diameter 40 mm, gap 2 mm), trimmed, rested for 5 min, and measured. During resting and measuring, the system was covered and water-saturated cotton strips lined the inside of the cover to prevent drying out of the dough rim. Measurements were made in the linear viscoelastic region at target strain of 0.1%. Doughs were measured at 16 frequencies in the range of 0.01–10 Hz. Frozen dough samples were divided, rested for 15 min, packaged, blast frozen to a core temperature of –18°C and stored at –18°C. After two, five, and eight weeks, for each measurement, six doughs were selected and thawed for 30 min at 0°C and 20 min at 30°C. After placing between the plates, the sample was trimmed, rested for 5 min, and measured. The Bohlin software package was used to calculate complex modulus (G^*) and phase angle (δ).

A straight-dough baking procedure was used for the standard baking test. The ingredients were chilled before mixing so that the final dough temperature was 19–21°C Doughs containing 1,500 g of flour, salt, yeast, sugar, shortening, water, and additives (according to breadmaking recipe) were mixed for 110 sec in a high-speed mixer (Stephan u Söhne). Doughs were rested for 15 min at room temperature (19°C), divided into 65-g portions, molded, and placed in tins. Fresh doughs were proofed at 30°C and 85% rh to a standard dough height and baked in a convection oven (Zanussi, Milan, Italy) for 13 min. Remaining doughs were blast-frozen to a core temperature of –18°C, vacuum packaged, and stored at –18°C. After two, five, and eight weeks of frozen storage, doughs were thawed at –2°C for 16 hr, followed by proofing at 30°C and 85% rh

TABLE I
Effect of Dough Additives[a] on Farinograph Values

Property	Control	AA	SSL	DATEM
Absorption (%)	62a[b]	61.3b	61b	61.4b
Stability (min)	7.0b	4.5c	4.0c	8.5a
E10[c] (BU)	50a	45a	40a	25b
E20[d] (BU)	115a	90b	50c	75d

[a] Control dough and doughs with additions of 100 ppm of ascorbic acid (AA), 0.5% sodium stearoyl lactylate (SSL), and 0.5% diacetyl tartaric acid esters of monoglycerides (DATEM).

[b] Data in each row followed by the same letter are not significantly different ($P < 0.05$).

[c] Degree of softening after 10 min.

[d] Degree of softening after 20 min.

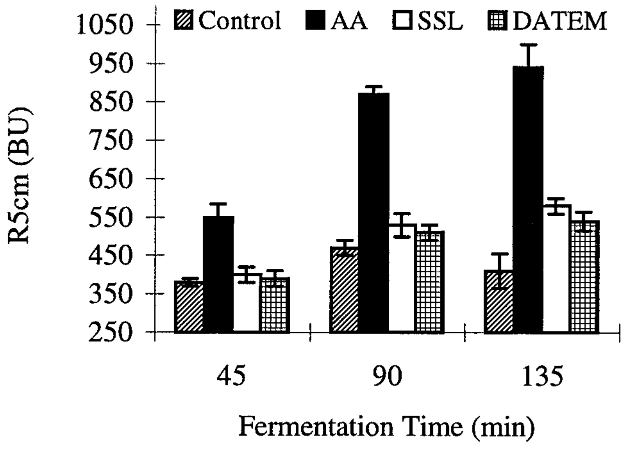

Fig. 1. Effects of additives on resistance to extension at 5 cm (R_{5cm}) after 45, 90, and 135 min of fermentation in fresh unyeasted doughs.

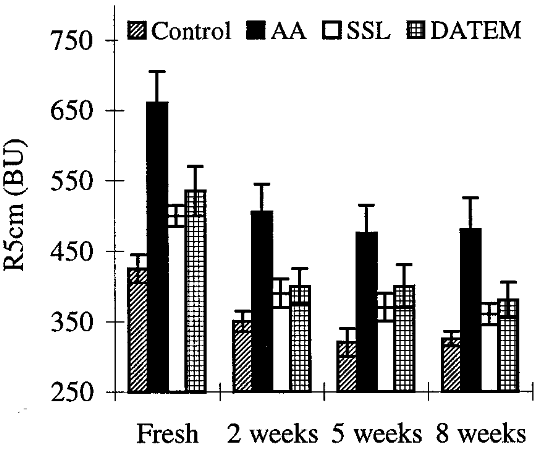

Fig. 2. Effects of freezing, frozen storage, and additives on resistance to extension at 5 cm (R_{5cm}) of unyeasted dough.

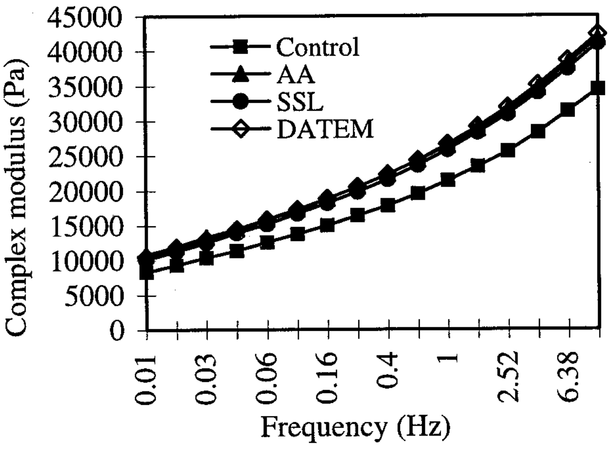

Fig. 3. Complex modulus (G^*) vs. frequency plots for doughs measured after eight weeks of frozen storage.

to a standard height and baking. Loaf volume was measured using rapeseed displacement 2 hr after baking. Bread crumb firmness was evaluated 3 hr after baking using a universal testing machine (Instron Ltd., England). The maximum force required to compress a 25-mm slice by 40% with a 12-mm diameter cylindrical probe was measured, and each result is the average of eight measurements. All baking data were obtained from two baking tests.

Statistical Analysis

A statistical software package (SPSS Inc., Chicago, IL) was used. All data were analyzed using analysis of variance and Tukey's post-hoc test to detect significant differences. Correlation analysis was conducted using Spearman's rank correlation coefficients.

RESULTS AND DISCUSSION

Empirical Rheology Measurements

Farinograms. Farinograph data are presented in Table I. Additives produced only slight variations in water absorption. DATEM significantly increased dough stability ($P < 0.05$), and all three additives reduced degree of softening, particularly DATEM after 10 min, and SSL after 20 min ($P < 0.05$). These results indicate that the additives increased dough tolerance to overmixing.

Standard extensigrams. Figure 1 shows the effect of additives on resistance to extension at 5 cm (R_{5cm}). After 45 min of fermentation, AA doughs had a significantly higher R_{5cm} ($P < 0.05$) than the control (170 BU higher), whereas SSL and DATEM showed no significant differences. After 90 and 135 min, all doughs with additives had a significantly higher R_{5cm} ($P < 0.05$) than the control, and AA had a considerably higher value than the others (300 BU higher). Differences between formulations became more pronounced with increasing fermentation time. R_{5cm} is an indicator of dough strength, and it is apparent from these results that all additives increased dough strength during fermentation of fresh doughs.

Extensigrams of fresh and frozen doughs. Figure 2 shows resistance to extension (R_{5cm}) values of fresh and frozen unyeasted doughs prepared according to the standard dough recipe and protocol. R_{5cm} of fresh doughs was significantly higher ($P < 0.05$) for doughs with additives than it was for the control dough. AA had the highest value, followed by DATEM and SSL. There was a significant decrease in R_{5cm} ($P < 0.05$) due to freezing and thawing for all formulations. In frozen doughs, the same trend was maintained, with the control dough having the lowest R_{5cm}. The differences between the control and doughs with additives were less pronounced in frozen dough than they were in fresh dough. There were no significant changes in R_{5cm} for any of the formulations during frozen storage. These results show that fresh and frozen doughs with additives were significantly stronger than the control, and all doughs weakened after freezing and thawing. Resistance to extension values did not show any weakening of the dough structure during frozen storage. Other authors (Inoue and Bushuk 1991, Inoue et al 1995) also reported a decrease in resistance to extension due to freezing. Inoue and Bushuk (1992) reported a gradual decrease in resistance to extension for some doughs over a 10-week period of frozen storage, whereas we observed no changes for any of the doughs tested.

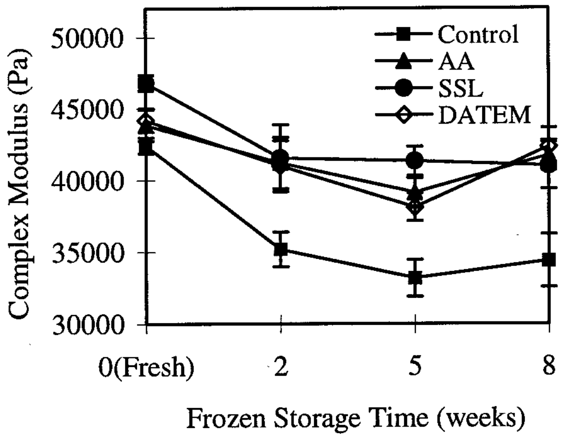

Fig. 4. Effects of freezing, frozen storage, and additives on complex modulus (G^*) values of doughs measured at 10 Hz.

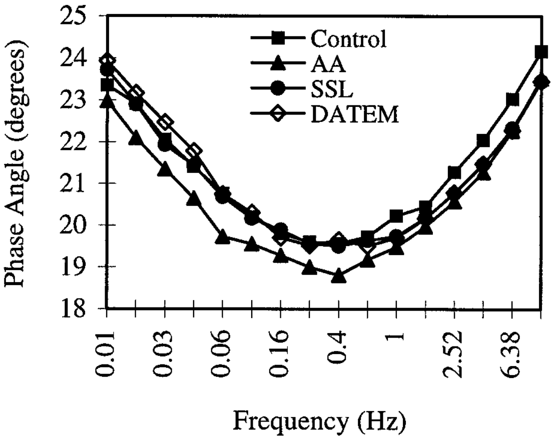

Fig. 5. Phase angle (δ) vs. frequency plots for frozen doughs measured after eight weeks of frozen storage.

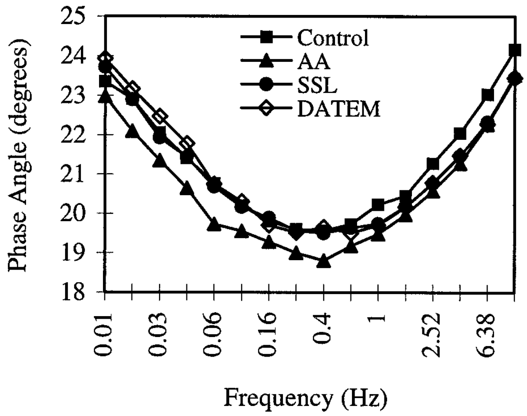

Fig. 6 Effects of freezing, frozen storage, and additives on phase angle (δ) of doughs measured at 10 Hz.

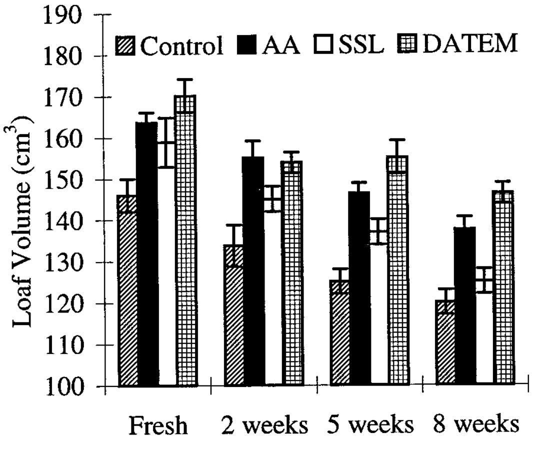

Fig. 7. Loaf volumes of bread made from fresh dough and after two, five, and eight weeks of frozen storage.

R_{5cm} values of doughs prepared according to the standard extensigraph method with SSL and DATEM did not differ from the control dough after 45 min of fermentation (Fig. 1), whereas doughs prepared using the breadmaking formulation and protocol with additives all had a higher R_{5cm} value than the control after 45 min of fermentation of fresh doughs (Fig. 2). This can be explained by differences in dough formulation and preparation techniques. The standard method used flour, salt, water, and additives and did not involve dough resting. The method used to evaluate frozen dough used shortening and sugar, and doughs were rested for 15 min before dividing and 5 min before molding.

Some authors reported an increase in resistance to extension due to freezing, frozen storage, and freeze-thaw cycles (Varriano-Marston et al 1980, Wolt and D'Appolonia 1984). This effect contradicts the theory that weakening of the gluten structure in frozen dough is caused by physical damage from ice crystals. This discrepancy could be due to differences in dough formula. Kulp (1995) proposed that this difference could be due to the different action of oxidants used.

Fundamental Rheology Measurements

Dynamic oscillation tests. In fresh doughs, at a frequency 10 Hz, complex modulus G^* values of control, AA, and DATEM doughs were similar, while SSL had a slightly higher value ($P < 0.05$). Differences between fresh control doughs and doughs with SSL were small but significant, whereas Kokelaar et al (1996) found no significant effect of SSL or DATEM on dynamic moduli of flour dough. In fresh doughs, phase angles were similar for all doughs at frequencies of 0.01–10 Hz, except for SSL which had a higher phase angle than the control at lower frequencies (data not shown).

Dynamic rheological measurements of doughs frozen for two, five, and eight weeks showed little variation. Figure 3 shows complex modulus values after eight weeks of frozen storage. Doughs with additives had significantly higher values than the control ($P < 0.05$) over the entire frequency range. Figure 4 shows the effects of freezing and frozen storage on complex modulus values measured at 10 Hz. There was a significant decrease in complex moduli of all doughs due to freezing and thawing ($P < 0.05$). After two, five, and eight weeks of frozen storage, complex moduli of doughs with additives were significantly higher ($P < 0.05$) than for the control. There were no significant changes in complex modulus as a result of increased frozen storage time. These results indicate that doughs with additives were firmer than the control and that there was a decrease in dough firmness due to freezing and thawing.

Figure 5 shows phase angle values of doughs frozen for eight weeks. Phase angle values of control frozen doughs were higher ($P < 0.05$) than for doughs with additives at frequencies of 2.52–10 Hz, whereas at lower frequencies (0.01–0.0631 Hz), AA doughs were lower than control, SSL, and DATEM doughs ($P < 0.05$). Figure 6 shows the effect of freezing and frozen storage on phase angle measured at 10 Hz. Phase angle of the control dough increased significantly ($P < 0.05$) due to freezing and thawing. Phase angle values of the control frozen doughs were significantly higher than those of frozen doughs with additives ($P < 0.05$). Phase angle did not change significantly during frozen storage for any of the formulations. These results show that doughs with additives were less viscous than the control, and the control dough became more viscous after freezing and thawing.

Autio and Sinda (1992) reported an increase in tan δ and a decrease in G' due to freezing and thawing, and suggested the reason might be a loss in polymer crosslinking. The decrease in complex modulus and increase in phase angle observed in our study due to freezing and thawing suggest a decrease in dough firmness and an increase in viscosity.

Standard baking test. Proof times for fresh and frozen doughs are shown in Table II. All three additives reduced proof time in fresh doughs. Doughs with DATEM and AA had the shortest proof times. Similar effects for SSL and DATEM were reported by Tsen and Weber (1981). Proof time for each formulation increased with frozen storage time. In frozen doughs, the same trend was maintained after two, five, and eight weeks of frozen storage; the control had the longest proof time and DATEM the shortest.

Figure 7 shows loaf volumes of fresh and frozen doughs. Fresh doughs with additives produced higher volume breads than the control, especially DATEM and AA ($P < 0.05$). Breads baked from frozen dough had a significantly lower volume than those from fresh doughs, and loaf volume for each formulation decreased significantly with frozen storage time ($P < 0.05$). AA and DATEM maintained higher volumes than the control after two, five, and eight weeks, whereas after eight weeks, the volume of SSL was similar to that of the control.

Figure 8 shows bread crumb firmness values. Breads with additives were softer than the control for fresh and frozen doughs. Crumb firmness values increased after freezing and thawing, and for each formulation, there was a gradual increase with frozen storage time, which is probably related to the decrease in volume. The difference in firmness between the control and breads with additives became more pronounced with increasing frozen storage time.

TABLE II
Proof Times of Fresh and Frozen Doughs[a]

Storage Time	Control	AA	SSL	DATEM
Fresh (0 weeks)	64f[b]	55g	59g	45h
Two weeks	85d	74e	78e	73e
Five weeks	96b	85d	89cd	76e
Eight weeks	105a	92c	97b	90c

[a] Control dough and doughs with additions of 100 ppm of ascorbic acid (AA), 0.5% sodium stearoyl lactylate (SSL), and 0.5% diacetyl tartaric acid esters of monoglycerides (DATEM).

[b] Data followed by the same letter are not significantly different ($P < 0.05$).

TABLE III
Correlation Coefficients Between Baking Performance and Rheological Data[a]

	Volume	Proof Time	R_{5cm}[b]	G^*[c]	δ[d]
Volume	· · ·	–0.91	0.86	0.64	–0.74
Proof time	–0.91	· · ·	–0.79	–0.65	0.74
R_{5cm}	0.86	–0.79	· · ·	0.72	–0.78
G^*	0.64	–0.65	0.72	· · ·	–0.67
δ	–0.74	0.74	–0.78	–0.67	· · ·

[a] Spearmans rank correlation coefficients all significant at $P < 0.01$.

[b] Extensigraph resistance to extension at 5 cm.

[c] Complex modulus (10 Hz).

[d] Phase angle (10 Hz).

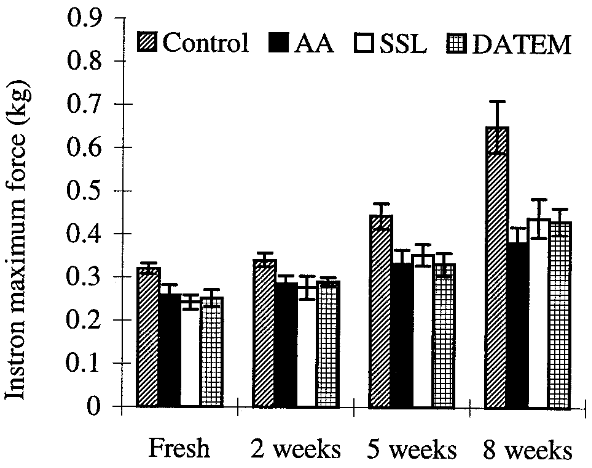

Fig. 8. Crumb firmness values of bread made from fresh doughs and after two, five, and eight weeks of frozen storage measured using a universal testing machine.

Correlations Between Rheological and Baking Data

Table III shows Spearman's correlation coefficients between baking and rheological data. There was a negative correlation between loaf volume and proof time. Resistance to extension was positively correlated with volume. This mainly reflects the decrease in both characteristics due to freezing. There was a positive correlation between volume and G^* and a negative correlation between volume and δ. Resistance to extension was positively correlated with G^* and negatively with δ. The negative correlation between G^* and δ in these experiments showed that firmer doughs were also more elastic.

CONCLUSION

Farinograph data showed that fresh doughs with additives were slightly stronger than the control and did not break down as much on overmixing. Standard extensigrams showed that doughs with additives offered more resistance to deformation during fermentation than did the control.

Resistance to extension and complex modulus were both positively correlated to loaf volume. There was a negative correlation between phase angle and loaf volume. These results indicate that frozen doughs that performed best in baking had a high resistance to extension, a high complex modulus, and a low phase angle. These doughs were stronger, firmer, and more elastic.

ACKNOWLEDGMENTS

This research has been part funded by grant aid under the food subprogramme of the operational programme for industrial development administered by the Department of Agriculture, Food and Forestry and was supported by National and E.U. funds. Many thanks to Kathleen O'Sullivan, Statistics Department, University College, Cork for her assistance with statistical work.

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[Received August 14, 1998. Accepted February 17, 1999.]