

# Shelf Life Determination of Frozen Bread Dough Stored under Fluctuating Temperature Conditions

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## ABSTRACT

The shelf life of frozen bread dough stored under both constant and fluctuating temperature conditions was investigated. Storage regimes were designed to mimic either good or poor practice likely to be experienced in the cold chain ( $-18 \pm 0.1^\circ\text{C}$ ,  $-18 \pm 1^\circ\text{C}$ ,  $-18 \pm 3^\circ\text{C}$  or  $-18 \pm 5^\circ\text{C}$ ). Gas production, dough water mobility and bread crumb characteristics were measured as quality parameters. The acceptability of bread made from frozen dough was monitored using a modified Weibull hazard sensory method. The shelf life results were considered from a kinetic standpoint with a focus on the effect of temperature on the acceleration of deterioration. Temperature fluctuations during storage accelerated deterioration in frozen bread dough. Large temperature fluctuations ( $-18 \pm 5^\circ\text{C}$ ) and storage at higher temperatures (a combination of  $-18^\circ\text{C}$ ,  $-13^\circ\text{C}$  and  $-8^\circ\text{C}$ ) during frozen storage resulted in significantly more rapid loss of dough and bread quality than storage at constant temperatures. A broken (nuclear magnetic resonance) peak of frozen dough stored under large temperature changes indicated greater separation of water bound to the starch-gluten matrix. The shelf life of frozen dough stored under large temperature fluctuations and higher temperatures was about 12 weeks, whereas the shelf life of the dough stored under constant or less fluctuating temperatures was greater than 16 weeks.

**Key words:** frozen bread dough, temperature fluctuations, frozen storage, Weibull hazard analysis, shelf life

## INTRODUCTION

Frozen bread dough is widely used in industrial bakeries to facilitate bread production and baking in retail outlets (Matuda *et al.*, 2005). The quality of the bread made out of frozen dough is influenced by dough formulation, as well as processing parameters such as dough mixing time, freezing rate, storage duration, thawing rate and also storage temperature. With a loss of stability during freezing, frozen storage and defrosting, the dough is exposed to stresses leading to a loss of dough strength and the viability of the yeast, an

increase in the proof time and a decrease in the loaf volume with poor bread characteristics, which result in a reduction of the quality of the final product (Neyreneuf and Delpuech, 1993; Basaran and Göçmen, 2003).

Generally, frozen dough should have 16 weeks of shelf life if the dough has not been temperature-abused during transportation and storage. However, a certain amount of temperature fluctuation during frozen storage is unavoidable (Berglund *et al.*, 1991). It has been postulated that temperature fluctuations during storage and distribution cause increased rates of quality

deterioration, particularly due to changes in the structure of ice crystals and recrystallization (Gormley *et al.*, 2002). Phimolsiripol *et al.* (2008) found that significantly-reduced CO<sub>2</sub> production of dough and increased crumb firmness of bread occurred after 16 weeks of frozen storage under large fluctuating temperatures. In addition, there can be increased moisture loss leading to a reduction in both quality and saleable weight (Laguerre and Flick, 2007).

However, there are limited data for the shelf-life determination of frozen dough stored under fluctuating storage temperatures. Moreover, the shelf life of frozen dough stored under temperature fluctuations must be confirmed by a sensory test. Due to the expense and the time-consuming nature of sensory testing procedures for food products, the use of staggered sampling designs for shelf life studies in foods has been proposed (Gacula, 1975). The technique consists of evaluating an increasing number of samples as storage time progresses. The advantages of a staggered design over the methods described above are that: all samples come from the one batch; the product is tasted throughout the whole storage period until unacceptable; and untrained consumers can be used for the evaluation. Staggered sampling methods have been used to determine the shelf life of coffee (Cardelli and Labuza, 2001). Therefore, the objectives of this study were to: investigate the effect of temperature fluctuations during storage on dough and bread quality parameters (gas production, dough water mobility and bread crumb characteristics); and to determine the shelf life with the application of a modified Weibull hazard sensory method.

## MATERIALS AND METHODS

### Dough preparation

Dough samples were prepared using a straight dough formula. Throughout the experiment, dough was prepared with commercial

wheat flour (12% moisture content, 0.67% ash 0.4%, 13% protein) and 55% water, 3.3% yeast, 3.3% sugar, 3.3% oil and 1.7% salt, calculated on a flour weight basis. Fresh baker's yeast (Pinnacle, New Zealand), *Saccharomyces cerevisiae* (30% db), was used. All ingredients were mixed in a dough mixer (Model 7MX, Delta Food Equipment, New Zealand) for 4 min at low speed and for 10 min at high speed. The dough temperature was  $18 \pm 1^\circ\text{C}$  at the end of mixing, as recommended by Basaran and Göçmen (2003) as a compromise between excessive pre-fermentation and the adequate development of the gluten network during mixing. After mixing, the dough was rested for 10 min and then divided into  $100 \pm 2$  g pieces, manually molded into round shapes (about 5 cm diameter), and placed into 170 mm  $\times$  180 mm snap lock polyethylene bags before freezing. The resting, shaping and packaging processes took about 35 min.

### Freezing and frozen storage regimes

The dough pieces were frozen in an air blast freezer operated at about  $-25^\circ\text{C}$  with an air speed of 2.5 m/s for 120 min. The freezing rate was estimated to be about  $-0.34^\circ\text{C}/\text{min}$  between  $-5^\circ\text{C}$  and  $-20^\circ\text{C}$ . After freezing, the dough pieces were allocated into different frozen storage regimes.

To achieve the various storage regimes, the samples were stored in cardboard boxes in a walk-in cold store at  $-28^\circ\text{C}$  that was automatically defrosted every 8 hours. Each box was 84 cm  $\times$  62 cm  $\times$  25 cm and was constructed of 0.7 mm thick corrugated cardboard. A light bulb (between 40 W and 200 W) and 2 PC computer fans were located in one corner of the box to provide both heating and air circulation to ensure uniform temperature conditions throughout the box. A total of 84 dough samples were placed into each box including dummy samples immediately adjacent to the light bulb location. The light bulb was controlled by an electronic thermostat with a

defined set-point and dead band. The size of the light bulb was selected to control the temperature fluctuations about the set-point in the range of 0.15 to 10 cycles per hour, depending on each storage temperature regime. For example, a 60 W light bulb gave a heating rate of about 0.13°C/min when controlled at -20°C. The cooling rate was about 0.13°C/min for all boxes at -18°C. Temperatures in the storage system were monitored using type T thermocouples connected to an Agilent datalogger (Model 34970A). The thermocouples were calibrated against an ice-point and a calibrated thermometer with  $\pm 0.1^\circ\text{C}$ .

Storage regimes were designed to mimic either good or poor practice likely to be experienced in the cold chain, but they were constrained by the characteristics of the storage equipment described above. The storage regimes were similar to those used by Ben-Yoseph and Hartel (1998). The storage regimes used were  $-18 \pm 0.1^\circ\text{C}$  (Control, C),  $-18 \pm 1^\circ\text{C}$  (Good Practice, G),  $18 \pm 3^\circ\text{C}$  (Poor Practice, P),  $-18 \pm 5^\circ\text{C}$  (Very Poor Practice, VP) and the cold chain (CC). For the cold chain regime, the temperature setpoints were  $-18 \pm 1^\circ\text{C}$  for 4 days,  $13 \pm 1^\circ\text{C}$  for 1 day,  $-8 \pm 1^\circ\text{C}$  for 1 day and then  $-18 \pm 1^\circ\text{C}$  for 1 day on a repeating weekly cycle. Three replicate dough pieces were prepared and subjected to each storage regime.

### Thawing and baking

After frozen storage, frozen dough samples were thawed prior to quality assessment by transferring them to a water bath which was controlled at 0°C. After thawing for 90 min, the dough pieces were put into 6 cm × 9 cm × 5 cm D2-Mini loaf pans (Wiltshire brand, item 9218, China) and proofed at  $37 \pm 2^\circ\text{C}$  (85% relative humidity, RH) for 60 min in the proofer (Satchwellsun Vic, New Zealand). The dough pieces were baked in a 37 cm × 42 cm × 55 cm oven (AR85, Electrolux, Steelfort Engineering Company Ltd., Palmerston North, New Zealand)

at 180°C for 15 min before cooling at 25°C for 60 min prior to quality assessment. The top of the dough was not cut before baking. Fresh dough was used as the overall quality level control.

### Gas production measurement

Gas production was measured using a risograph (R-Design, Pullman, WA) according to the method of El-Hady *et al.* (1996). The dough samples were taken for gas production measurement after 1 day and then also after 2, 4, 7, 10, 13 and 16 weeks of frozen storage. About 100 g of thawed samples were divided into 50 g samples. The 50 g samples of dough were placed into fermentation jars and then placed in a water bath at 30°C. The gas volume was measured every minute for 180 min after a 10 min delay (time zero was taken at the end of the 10 min delay). Total gas production was expressed as mL over the 180 min. The percentage reduction in gas production was calculated relative to fresh dough. Measurements were made in triplicate for each treatment.

### Dough water mobility determination

Dough water mobility was measured using a nuclear magnetic resonance ( $^1\text{H}$  NMR) Bruker Avance 400 MHz spectrometer according to the method of Esselink *et al.* (2003). After 1 day and 16 weeks frozen storage, samples were taken from the centre of the frozen dough, cut into a shape that was 4 cm long and 4 mm in diameter while frozen using a stainless puncture tube and then put into a special Teflon cell. Transverse proton relaxation times ( $T_2$ ) were measured using the Carr Purcell Meiboom Gill (CPMG) pulse sequence [ $90^\circ$ - $\tau$ - $180^\circ$ - $\tau$ -... $n$ ...echo]. An echo spacing ( $\tau$ ) of 100  $\mu\text{s}$  was used and the number of CPMG cycles  $n$  ranged from 2 to 130. Data were averaged over eight acquisitions with a recycle delay of 5 s.  $T_2$  relaxation measurements were performed at -20°C in a 10 mm RF coil.

### **Bread crumb image characteristics**

Bread crumb images were evaluated using a photocopier (HP 3300C, Hewlett-Packard Development Company, Japan). The photocopy image was subjectively assessed in terms of the size and uniformity of the crumb cell structure.

### **Sensory evaluation**

Bread samples baked from frozen dough, which had been stored under various fluctuating temperature conditions, were cut into half pieces of baked bread. The baked bread was presented to panelists 30 min after baking. To ensure that the samples were all the same temperature when the panelists received their samples, the samples were stored in a warmer oven held at 35°C and 70% RH before serving. Samples were then identified with random numbers and served to untrained panelists. The pool of 68 panelists consisted of 30 males and 38 females, ranging in age from 19 to 50. Two panelists were used at the beginning of the test. The number of panelists (C) was increased by 1 at each sampling time until half of the panelists found the samples unacceptable. After that the number of panelists for each period was increased by  $C = U$ , with  $U =$  number of unacceptable responses for the previous test time. The storage time was reduced by about 50% when the number of failures was more than 50%. The experiments were conducted for at least six sampling periods during the storage period. They were stopped when more than 50% of unacceptable samples were found at the next test time or the storage time reached 16 weeks, whichever came first. Panelists were requested to rinse their mouth with water and wait for 2 min between samples.

The sensory results were transferred for hazard calculation and then to a Weibull hazard plot as described by Gacula and Singh (1984). The end of sensory shelf life was set as the time when there was a 50% probability of untrained panelists judging the samples as being unacceptable. The

number of unacceptable scores was ranked from the week at which 50% were rejected, from left to right and from bottom to top. The hazard values were calculated as 100 divided by the rank (100/rank). Cumulative hazard values were summed for each storage regime. The plots of storage time versus cumulative hazard value were then fitted with a power law model. This probability corresponded to a cumulative hazard of 69.3. The shape factor ( $\beta$ ) was determined as 1/slope. The Weibull distribution was unskewed for  $2 < \beta < 4$ , which leads to better shelf life estimates. When the test was extended beyond the shelf life, most of samples were judged unacceptable, shifting  $\beta$  outside the optimum range. In these cases, the data was regressed using the least-square method up to 110% cumulative hazard.

### **Statistical analysis**

Analysis of variance (ANOVA) was performed to find out if the effects of different storage regimes and storage time on the quality characteristics of frozen dough and bread were significant ( $p < 0.05$ ). Duncan's multiple range test (DMRT) was performed for *post hoc* multiple comparisons using SPSS® version 11.5 software.

## **RESULTS AND DISCUSSION**

### **Storage temperature variations**

The variation of the air temperature in the controlled temperature boxes (ATB), the air temperature in the cold store (ATC), the dough center temperature (DCT) and the dough surface temperature (DST) of the C, G, P, VP and CC are given in Table 1.

The air temperature in the cold store was about  $-27.0 \pm 0.9^\circ\text{C}$ . Although the average air temperature of the C, G and VP regimes was nearly identical, DCT and DST differed by 0.3-0.4°C (Table 1). This apparent difference probably reflected offset and uncertainty in the temperature measurement rather than any significant actual

difference. For the VP regime, both the average air and the dough temperatures were slightly colder than for the other regimes. Despite significantly different levels ( $p < 0.05$ ) of variation in the air temperature for the C and G regimes ( $\pm 0.1^\circ\text{C}$  and  $\pm 0.6^\circ\text{C}$ ), the temperature variations of DCT and DST were very similar ( $\pm 0.07^\circ\text{C}$  and  $\pm 0.09^\circ\text{C}$ ). However, the average DCT and DST for the C and G regimes were significantly different ( $p < 0.05$ ) being about  $-17.9^\circ\text{C}$  and  $-18.3^\circ\text{C}$ , respectively. Excluding the dummy samples adjacent to the lights that were not part of the experimental plan, differences in temperature between samples in the same box at any time were less than  $0.25^\circ\text{C}$ .

### Gas production

Table 2 shows gas production as a function of the frozen storage time. The gas

production of the dough declined by about 7% compared to fresh dough. Under wide temperature fluctuation and high temperature storages (VP and CC regimes), the gas production of dough declined by about 43% and 55%, respectively after 16 weeks of frozen storage. The main effect of the storage regime was that the dough stored under the C, G and P regimes had a significantly higher ( $p < 0.05$ ) gas production than that stored under the VP and CC regimes. The corresponding dough volume appeared to be a function of the frozen storage regime and the storage period. This was consistent with the results of Le Bail *et al.* (1999) that showed that temperature fluctuations had a large influence on the dough volume. This result was probably due to ice recrystallization which was accelerated by temperature fluctuations, resulting in the reduction of yeast activity

**Table 1** Variations of air temperature and dough temperature under fluctuating conditions.

Regime	Set-point ( $^\circ\text{C}$ )	Air temperature ( $^\circ\text{C}$ )	Dough temperature ( $^\circ\text{C}$ )	
			Center	Surface
Control (C)	$-18 \pm 0.1$	$-18.1 \pm 0.1$	$-17.9 \pm 0.07$	$-17.9 \pm 0.07$
Good Practice (G)	$-18 \pm 1$	$-18.2 \pm 0.6$	$-18.3 \pm 0.07$	$-18.3 \pm 0.09$
Poor Practice (P)	$-18 \pm 3$	$-18.7 \pm 1.8$	$-18.5 \pm 0.39$	$-18.4 \pm 0.45$
Very Poor Practice (VP)	$-18 \pm 5$	$-18.3 \pm 3.3$	$-18.2 \pm 2.08$	$-18.1 \pm 2.11$
Cold Chain (CC) with a combination of $-18^\circ\text{C}$ , $-13^\circ\text{C}$ and $-8^\circ\text{C}$	$-18 \pm 1$	$-18.1 \pm 0.7$	$-18.1 \pm 0.09$	$-18.1 \pm 0.09$
	$-13 \pm 1$	$-13.2 \pm 0.8$	$-13.2 \pm 0.08$	$-13.3 \pm 0.09$
	$-8 \pm 1$	$-8.3 \pm 0.8$	$-8.4 \pm 0.09$	$-8.4 \pm 0.09$

Values are the mean and ( $\pm$ ) standard deviation of the measurements.

**Table 2** Gas production (%) of frozen dough stored under different storage regimes.

Storage period	Storage regimes				
	C	G	P	VP	CC
Fresh	$100.0 \pm 0.0$ a	$100.0 \pm 0.0$ a	$100.0 \pm 0.0$ a	$100.0 \pm 0.0$ a	$100.0 \pm 0.0$ a
1 day	$93.4 \pm 1.8$ a	$93.4 \pm 1.8$ a	$93.4 \pm 1.8$ a	$93.4 \pm 1.8$ a	$93.4 \pm 1.8$ a
2 weeks	$75.1 \pm 3.4$ bcde	$78.2 \pm 7.1$ bcde	$78.3 \pm 6.5$ bcd	$71.3 \pm 10.5$ bcdef	$80.5 \pm 6.8$ b
4 weeks	$74.6 \pm 7.7$ bcde	$72.8 \pm 6.5$ bcdef	$79.7 \pm 11.5$ bc	$71.2 \pm 3.1$ bcdef	$77.4 \pm 10.9$ bcde
7 weeks	$68.5 \pm 4.4$ cdefg	$73.3 \pm 7.9$ bcde	$70.8 \pm 5.7$ bcdef	$67.7 \pm 6.2$ defg	$75.6 \pm 7.9$ bcde
10 weeks	$68.4 \pm 6.7$ cdefg	$67.8 \pm 5.7$ defg	$68.9 \pm 8.2$ bcdefg	$61.5 \pm 5.4$ fgh	$68.8 \pm 8.2$ cdefg
13 weeks	$73.0 \pm 3.6$ bcde	$71.0 \pm 5.8$ bcdef	$66.9 \pm 4.3$ defgh	$58.9 \pm 2.2$ gh	$58.7 \pm 2.5$ gh
16 weeks	$69.6 \pm 1.6$ bcdefg	$72.6 \pm 2.9$ bcdef	$66.6 \pm 4.7$ efgh	$56.6 \pm 6.7$ h	$44.7 \pm 10.4$ i

Values are the mean and standard deviation of three samples. Mean values with different letters are significantly different ( $p < 0.05$ ).

(Neyreneuf and Delpuech, 1993). However, changes to the dough gluten network and its ability to retain gas due to ice recrystallization may also have contributed to this result.

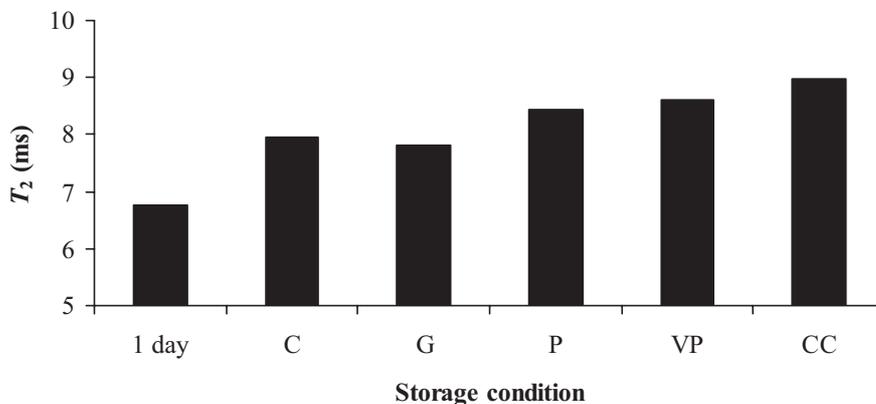
The glass transition temperature of dough ( $T_g$ ) has been reported as less than  $-30^\circ\text{C}$  (Laaksonen and Roos, 2000). Normal frozen storage temperatures and the temperatures used in this study were significantly higher than  $T_g$ . Therefore, relating the increased rate of deterioration to the increased mobility of the water with large fluctuating storage temperatures or high storage temperatures was a reasonable mechanistic explanation.

### Dough water mobility

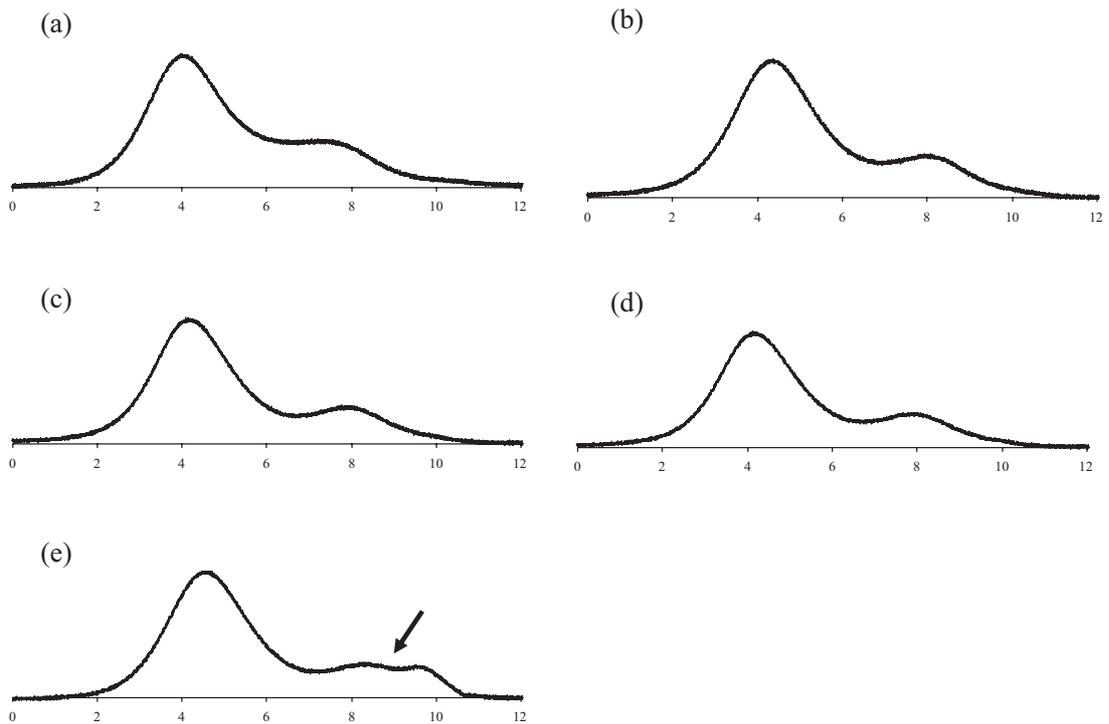
Dough water mobility was investigated using the spin-spin relaxation method which focused on the relaxation of the water and the fractions of exchangeable protons (Lucas *et al.*, 2005). The  $T_2$  relaxation times of frozen dough stored at different storage regimes after 1 day and 16 weeks are shown in Figure 1. The  $T_2$  values increased with increasing storage period from 6.7 min after 1 day of frozen storage to be about 7.8-8.9 min after 16 weeks of frozen storage. After 16 weeks, the  $T_2$  relaxation values of frozen dough stored at more constant temperature regimes (C,

G and P regime) were smaller than that of the frozen dough stored under the regimes with more fluctuating temperatures (VP regime) and a higher temperature (CC regime).

The longer  $T_2$  relaxation time of the dough stored under fluctuating temperatures indicated a greater separation of the water bound to the starch-gluten matrix. This water redistribution altered the properties of the gluten and the starch phase. The water may not return to its original state in the gluten matrix, resulting in an increase in the water mobility in the dough (Esselink *et al.*, 2003). Freezable water defines water that can form ice in a dough system when subjected to freezing and frozen storage. It is sensitive to the temperature variations which occur during dough processing and storage. Rasanen *et al.* (1998) indicated that a higher amount of freezable water results in a greater number of ice crystals. Lu and Grant (1999) also found that freezable water increased with an increase in the frozen storage period due to damage to the gluten network and the phase-separation of the ice from the gluten-water system by freezing and frozen storage. This can cause damage to the gluten-starch structure that can account for the poor baking performance of frozen dough.



**Figure 1**  $T_2$  values of dough after 1 day in frozen storage and stored under different fluctuating storage regimes after 16 weeks frozen storage.



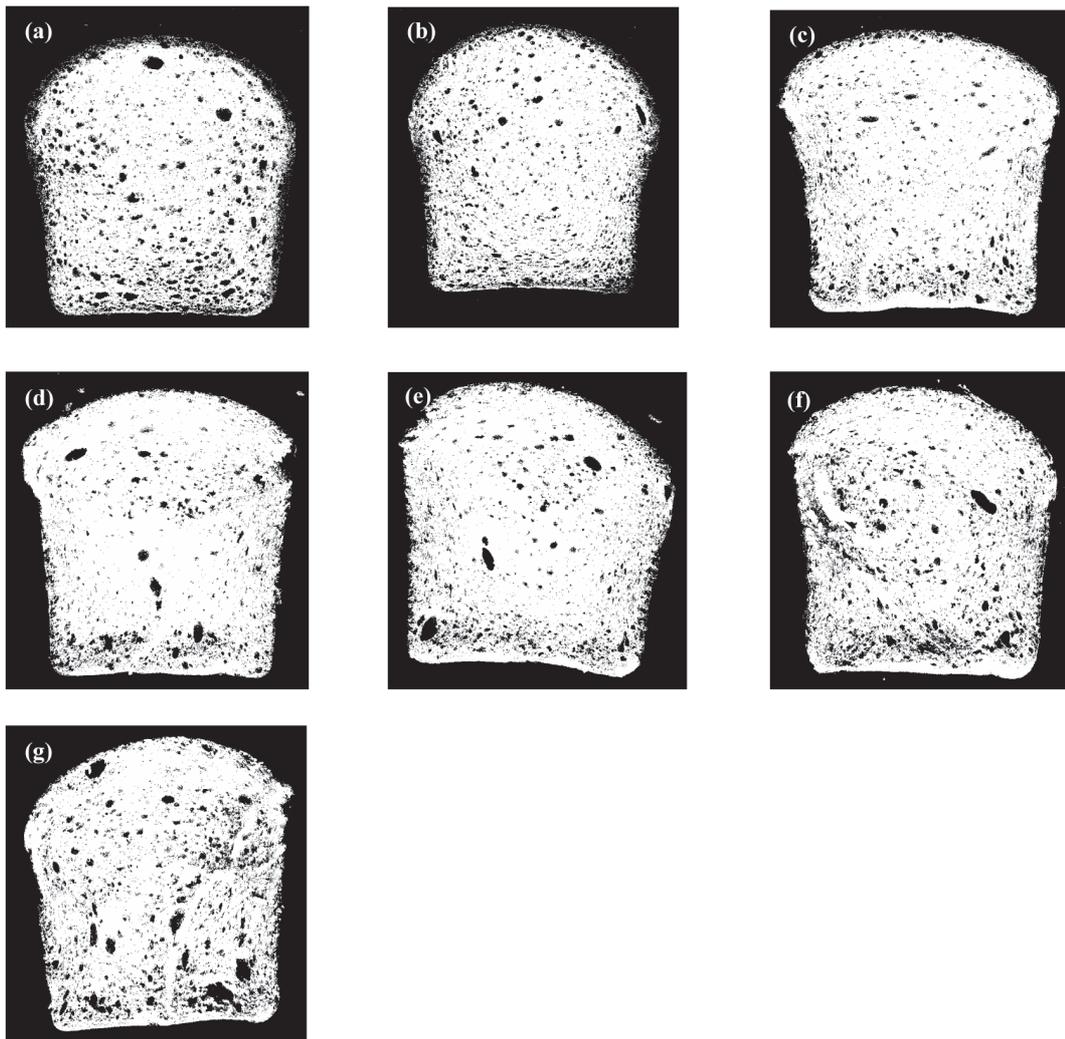
**Figure 2** NMR spectrum of frozen dough after 16 weeks storage. (a) C regime (b) G regime (c) P regime (d) VP regime (e) CC regime. Arrow indicates a peak, indicating phase separation in dough components.

Figure 2 shows the NMR spectrum of the dough stored under the C, G, P, VP and CC regimes. The NMR peak of the dough stored under C, G, P and VP showed a similar pattern. A peak separation was observed in the dough stored under the CC regime as shown in Figure 2e. This was attributed to the separation of components in the dough system due to temperature changes and fluctuation during frozen storage. Aibara *et al.* (2005) indicated that water in the continuous protein phase of the frozen dough migrated to the damaged starch granules in the disperse phase from the gluten matrix during the freeze-thaw treatment.

#### Bread crumb image characteristics

Differences in cell size and crumb structure for each bread variation were observed by comparing photocopies of each bread loaf half.

Bread crumb appearances for fresh and one day after freezing were similar (Figure 3). The bread crumb structure under different storage conditions had a different appearance. The crumb structure for the VP and CC regimes showed some non-continuous surface on and big holes in the structure. In addition, prominent blisters were observed on the crust surface and the crumb structure became more open. It is suggested that the unacceptability of a bread product is highly related to the uneven distribution of the crumb structure. This was probably due to temperature fluctuations during frozen storage, resulting in a loss of yeast activity and ice recrystallization. Bruinsma and Giesenschlag (1984) found that each successive freeze-thaw cycle caused the dough to become weaker, more difficult to handle and to have a moister appearance. The crumb grains became much less acceptable because of a harsher



**Figure 3** Bread crumb images baked from frozen dough under different fluctuating storageregimes. (a) Fresh (b) 1 day after freezing (c) C regime (d) G regime (e) P regime (f) VP regime (g) CC regime.

and coarser structure. Inoue and Bushuk (1991) found that bread subjected to successive freeze-thaw cycles was flat on the top of loaves. Naito *et al.* (2004) also reported that SEM images of the bread showed that the gluten fibrils formed within the gluten matrix were shorter, coarser and non-uniform with many knots. An increase in the number of freeze-thaw cycles increased both the coarseness of the gluten fibrils and also the size and number of the knots.

### Sensory test and shelf life prediction

The end of shelf-life at each temperature was determined by the Weibull hazard statistical method. The end of shelf life was defined as the time that corresponded to a cumulative hazard of 69.3% or a  $P_c$  of 50%. The overall results of the sensory test correlated well to the Weibull plot ( $r^2 = 0.90$ ).

Typical results and hazard values are shown in Table 3. Figure 4 shows a Weibull hazard

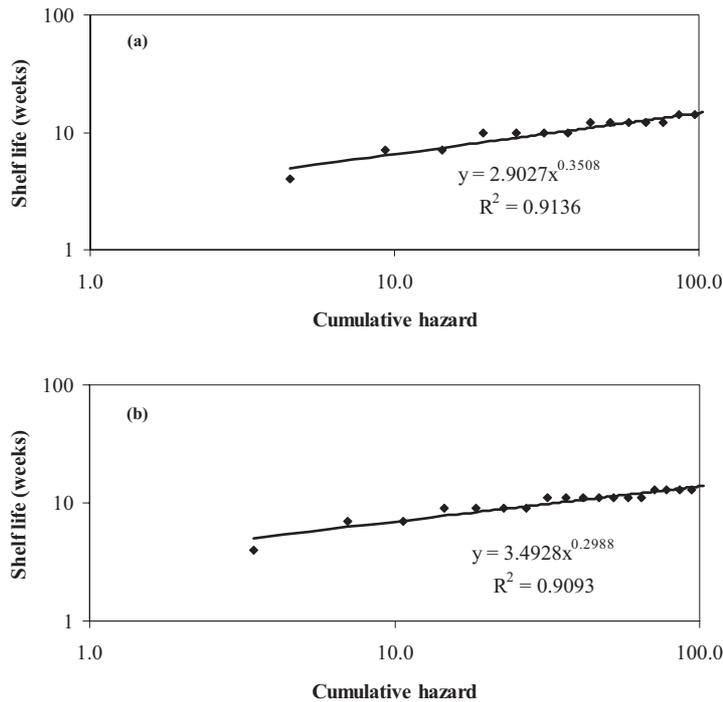
**Table 3** Weibull hazard ranking table for frozen dough stored under different fluctuating storage regimes.

Rank	Storage period (Weeks)					Sum of H value <sup>a</sup>				
	C	G	P	VP	CC	C	G	P	VP	CC
29					4					3.4
28					7					7.0
27					7					10.7
26					9					14.6
25					9					18.6
24					9					22.7
23					9					27.1
22				4	11				4.5	31.6
21				7	11				9.3	36.4
20				7	11				14.3	41.4
19				10	11				19.6	46.7
18				10	11				25.1	52.2
17				10	11				31.0	58.1
16				10	11				37.3	64.3
15				12	13				43.9	71.0
14				12	13				51.1	78.2
13				12	13				58.8	85.8
12				12	13				67.1	94.2
11			7	12	13			9.1	76.2	103.3
10			7	14	13			19.1	86.2	113.3
9		7	10	14	13		11.1	30.2	97.3	124.4
8	7	7	10	14	13	12.5	23.6	42.7	109.8	136.9
7	10	10	13	14	13	26.8	37.9	57.0	124.1	151.2
6	10	10	13	14	13	43.5	54.6	73.7	140.7	167.8
5	13	13	13	14	13	63.5	74.6	93.7	160.7	187.8
4	13	13	16	14	13	88.5	99.6	118.7	185.7	212.8
3	16	16	16	14	13	121.8	132.9	152.0	219.1	246.2
2	16	16	16	14	13	171.8	182.9	202.0	269.1	296.2
1	16	16	16	14	13	271.8	282.9	302.0	369.1	396.2

<sup>a</sup> Sum of H value = Cumulative hazard value calculated from H value (100/rank).

plot for time versus cumulative hazard for bread baked from frozen dough stored under the VP and CC regimes. The shelf-life results were analyzed from a kinetics viewpoint with a focus on the effect of temperature on the acceleration of deterioration. For the C, G and P regimes, the bread samples baked were acceptable after 16 weeks storage. However, 50% of the panelists rated the P regime bread unacceptable at 16 weeks storage. As

expected, the sensory shelf life decreased with an increase in the fluctuating storage temperature. A higher fluctuating storage temperature reduced the shelf life of frozen dough. From the Weibull hazard analysis, the plots of storage times versus cumulative hazard values had a good fit with the power law model as shown in Figure 4. The predicted shelf life of frozen dough stored under the VP and CC regimes was about 12.8 and 12.4



**Figure 4** Weibull hazard plot for bread baked from frozen dough stored under (a) VP regime (b) CC regime.

weeks, respectively. With large fluctuations ( $-18 \pm 5^\circ\text{C}$ ) or higher fluctuations (a combination of  $-18^\circ\text{C}$ ,  $-13^\circ\text{C}$  and  $-8^\circ\text{C}$ ), the shelf life of frozen dough reduced at a faster rate than that of frozen dough stored under constant or small temperature fluctuations ( $\pm 0.1^\circ\text{C}$  or  $\pm 1^\circ\text{C}$ ). The shelf life of frozen dough stored under more constant temperatures was greater than 16 weeks.

## CONCLUSIONS

Freezing, the frozen storage temperature and temperature fluctuations during storage generated a loss of dough and bread quality as reflected by a lower gas production, longer water mobility and a more uneven distribution of bread crumb structure. The application of a Weibull hazard sensory method provided a simple approach to determine shelf life as perceived by untrained panelists. Frozen storage with a constant

and small fluctuating temperature gave significantly better frozen dough and bread quality. The shelf life of frozen bread dough stored under a more constant temperature regime was greater than 16 weeks. The rate of quality loss was significantly faster when temperature fluctuations were large and/or storage temperatures were high, resulting in a reduction in shelf life by about four weeks. It is recommended that temperature variations for frozen dough during storage should be less than  $\pm 3^\circ\text{C}$  if a shelf life of over 16 weeks is required.

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