Bread Crumb Amylograph Studies. I. Effects of Storage Time, Shortening, Flour Lipids, and Surfactants[1]

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ABSTRACT

Sodium stearoyl lactylate, sucrose monopalmitate, diacetyl tartaric acid esters of mono- and diglycerides, monoglycerides, and petroleum ether-extracted flour lipids were added to a bread formula at the 0.5% level to make breads with and without shortening. Bread crumb compressibility was measured after one, two, and five days of storage at room temperature, and the crumbs were then used for amylograph studies. Compressibility increased with storage length and decreased with crumb moisture content and loaf volume. Amylograph readings of breads made with different additives were significantly different. Storage time of the bread did not significantly affect the crumb amylogram readings except, in some breads, the height of the plateau before the viscosity onset. The plateau was formed by progressive lowering of the initial viscosity, presumably caused by amylopectin retrogradation in bread crumb over the storage time. Amylograph readings of bread crumb were significantly correlated with crumb firmness. Storage days, loaf volume, and cooling-end or holding-end viscosity in the crumb amylogram were included in the best-fitting regression equations of crumb firmness. The relation of amylograph readings to crumb compressibility was attributed to effects of lipid materials on both amylograph readings and crumb compressibility.

The amylograph was first utilized by Yasunaga et al (1968) to study the pasting characteristics of bread crumb. The effects of storage times of bread on crumb amylograms have been investigated by several workers (Yasunaga et al 1968, D'Appolonia and MacArthur 1974, Kim and D'Appolonia 1977, Morad and D'Appolonia 1980, Kai 1985). They reported possible relationships between crumb amylogram readings and bread storage, but they did not obtain sufficient data to draw conclusions. The effects of shortening and certain surfactants on crumb amylograms were also studied to a limited extent, and further work seems necessary.

Bread crumb samples have been prepared for amylograph tests in two ways. D'Appolonia and co-workers (D'Appolonia and MacArthur 1974, Kim and D'Appolonia 1977, Morad and D'Appolonia 1980) used a lyophilizing-and-grinding method. Bread crumb was freeze-dried, ground, and then agitated in a Waring Blendor in water before the amylograph test. Since freeze-drying may exert an extraneous effect on bread crumb, this method may mask the effect of storage time. Yasunaga et al (1968) and Kai (1985) soaked bread crumb in distilled water for 1 hr and dispersed the crumb to a smooth slurry, but they did not report the procedure for measurement of the crumb moisture content before the amylograph tests. The solids concentration in the amylograph should be maintained at the same level for comparison. The two-stage AACC method 44-15A (AACC 1983) for moisture content measurement in bread takes one day and is thus unsuited for use with the amylograph test at different storage periods. A rapid method for moisture content measurement in bread crumb needs to be developed.

Therefore, this study was designed to develop and validate a rapid method for moisture measurement in bread crumb and to investigate the effects of storage time, shortening, flour lipids (FL), and surfactants on bread crumb amylograms and the relationships of bread crumb amylogram readings with crumb firmness.

The amylograms of bread crumb had some unique features that were usually not observed in starch or flour amylograms. A companion report, part two of this study, will address the cause of those unique properties.

MATERIALS AND METHODS

Materials

The flour was a commercial bread flour of 10.6% protein (14% mb) obtained from Archer Daniels Midland Co., Abilene, KS. The yeast used was Fermipan Instant Yeast from Gist-Brocades N.V., Holland. The unemulsified shortening, Bakeall (Bunge Edible Oil Corp., Kankakee, IL) was made from meat fats and vegetable oils. The surfactants used included sodium stearoyl lactylate (SSL) (100% over U.S. 20 mesh, m.p. 45–48°C, acid value 60–80, ester number 150–160, lactic acid 31–34%) and saturated distilled monoglycerides (MG) (90% over U.S. 60 mesh, m.p. 57–64°C, α-monoglyceride 90%, free glycerine 1%, iodine value 25–30) obtained from BREDDO Inc., Kansas City, KS; powdered diacetyl tartaric acid esters of mono- and diglycerides (DATEM) (V 35 922, E-472e, containing 20% tricalciumphosphate) and sucrose monopalmitate (SMP) (DK Ester F-140, HLB 14, Dai-Ichi Kogyo Seiyaku, Japan) purchased from Chemische Fabrik Gruenau, Illertissen/Bayern, Germany. The surfactants were added directly to other baking ingredients and thoroughly blended before mixing.

Flour Lipid Extraction and Fractionation

Flour lipids were extracted from the flour with petroleum ether using the Soxhlet apparatus over a 24-hr period. The composition of the extract was examined by fractionation using silicic acid column chromatography and thin-layer chromatography (Chung et al 1977). The petroleum ether-extracted FL were blended with flour in a mortar and pestle and used as an additive in the bread formula.

Baking Procedure

The straight dough method was used with the baking formula shown in Table I. The optimum mixing time and absorption were determined by preliminary baking tests. The optimally mixed dough was fermented at 86°F and 85% rh for 2.5 hr; the dough was punched at the end of the first 2 hr. After fermentation, the dough was divided into three equal pieces. Each piece was rounded and then rested for 20 min, followed by machine molding. The dough was then panned and proofed at 95°F and 95% rh until the dough height reached 1.5 cm above the pan. The bread was baked at 218°C for 25 min (Ke 1987). The weight and volume of each loaf were measured immediately after it came out of the oven. The loaf was cooled for 1 hr at room temperature and then placed in double polyethylene bags, each of which was tied.

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Firmness Measurement

After appropriate storage times, loaves were taken out of the double polyethylene bags and cut into nine 1-in. (2.54-cm) slices. The slices at both ends and in the middle were discarded. The remaining six slices were used for firmness measurement with a Voland-Stevens-LFRA Texture Analyser (Voland Corp., Hawthorne, NY). A cylindrical plunger of 2.54-cm diameter was used. The plunger speed was 0.5 mm/sec, and the compression distance was 4 mm. Each slice was put on the texture analyzer so that the moving direction of the plunger was toward the middle of the loaf along the longitudinal axis. The compression was aimed at the center of the slice. The six firmness readings were averaged to give a single firmness value for the loaf. Crumb firmness was expressed as a compressibility value (in grams).

TABLE I
Baking Formula

Ingredient	Baker's Percentage	Weight (g)
Flour	100	927.5[a]
Water	60, 62.5[b]	556.5, 579.7[b]
Yeast, instant	1	9.275
Sugar	6	55.65
Salt	2	18.55
Nonfat dry milk	3	27.825
Shortening	0, 3	0, 27.825
Additive	0, 0.5	0, 4.638

[a] 14% moisture basis.
[b] 60% or 556.5 g for the dough with shortening and 62.5% or 579.7 g for the dough without shortening.

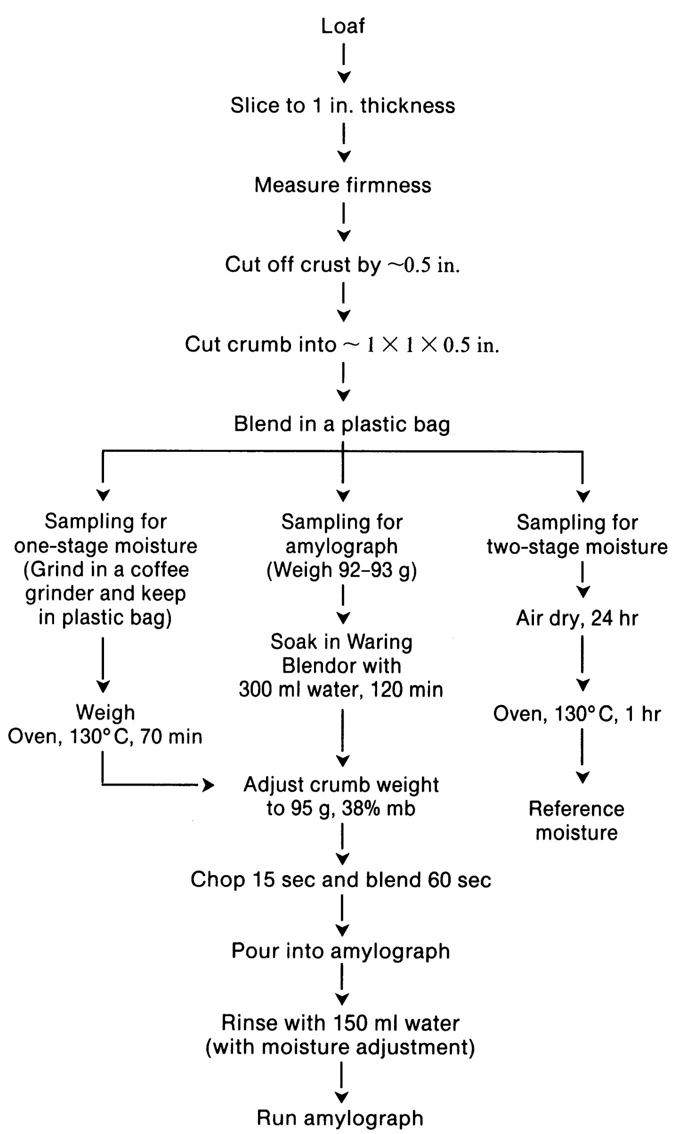

Fig. 1. Schematic diagram of sample preparation for bread crumb amylograph test.

Moisture Measurement

A one-stage method was used to obtain the moisture content of bread crumb before the amylograph test for the bread crumb was run after each storage period. Bread crumb was cut into pieces approximately 1 × 1 × 0.5 in., which were blended in a plastic bag. A sample was taken from the bag and ground in a coffee grinder. Four samples (~5 g each) were weighed quickly, put into aluminum pans, and heated in an air-draft oven at 130° C for 70 min. The pans with the dried samples were then cooled in a desiccator over Drierite (W. A. Hammond Drierite Co., Xenia, OH) and weighed for moisture calculation. The moisture content obtained by this one-stage method was compared to the standard two-stage AACC Method 44-15A (AACC 1983).

Amylograph

The Brabender Viskograph-E (C. W. Brabender Instruments, Inc., South Hackensack, NJ) was used. The bread crumb samples were prepared as shown in Figure 1. The samples were heated in the amylograph from 30 to 95° C at a rate of 1.5° C/min, held at 95° C for 30 min, and cooled to 30° C at the same rate. Viscosity was measured at a torque of 700 cm·g and recorded at a chart speed of 20 cm/hr.

Amylogram Characteristics

Figure 2 illustrates the amylogram characteristics. They included peak viscosity, viscosity at the end of the holding period (holding-end viscosity), viscosity at the end of the cooling period (cooling-end viscosity), the "bump" area (as measured with a planimeter), and the pasting temperatures. The existence or absence of the plateau before the onset of gelatinization viscosity rise and of the minor peak before the major peak were also considered to be amylogram characteristics. For measurement of the bump area, the base line of the bump was connected from the starting point to the ending point of the bump peak (Fig. 2). The pasting temperature was that at the intersection point of the horizontal and vertical tangential lines of the amylograph curve during the heating period (Fig. 2).

Storage Test Procedure

Breads from two batches of dough were stored in double polyethylene bags at room temperature for one, two, and five days. Each batch of dough consisted of three loaves of bread; one loaf from each batch was tested for firmness after each of the three storage periods. Crumbs from the two loaves were combined after the firmness measurement and the combined crumbs were used for the amylograph study according to the procedure given in Figure 1. The bread-making, storage, and amylograph tests were replicated twice.

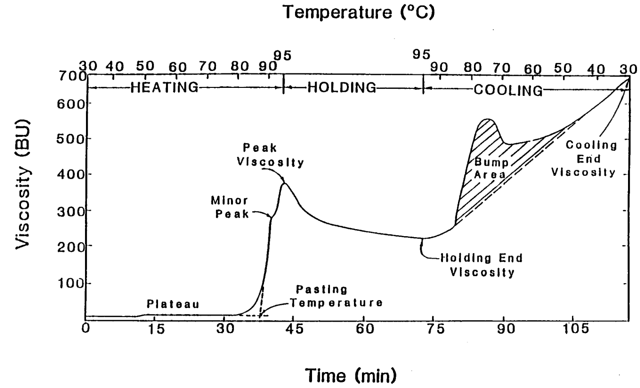

Fig. 2. A typical bread crumb amylogram showing the definitions of the amylogram characteristics used in this study.

Statistical Analysis

The SAS system (Helwig 1978) was used for the statistical analysis of data. Least significant difference (Ott 1984) was used to determine effects of storage days, shortening, surfactants, and FL on the crumb amylograph readings. The STEPWISE regression procedure (Ott 1984) was used to find the best equations of crumb firmness as a function of other variables.

RESULTS AND DISCUSSION

Flour Lipid Extraction and Fractionation

The extraction yield of the FL was 1.00%. The extracted FL contained 31% polar and 69% nonpolar lipids, as determined by silica gel chromatography; the polar lipids fraction was composed of approximately 35% phospholipids and 65% glycolipids, as determined by thin-layer chromatography.

Effects of Shortening, Surfactants, and Flour Lipids on Loaf Volume and Crumb Firmness

For no-shortening breads, loaf volume (LV) was increased greatly by the 0.5% additives, most by SSL, followed by SMP, DATEM, MG, and FL (Table II). The LV increases by surfactants were relatively smaller for 3%-shortening breads than for no-shortening breads. The four surfactants improved LV by 11–24% and 1–5% for 0%- and 3%-shortening breads, respectively.

The four surfactants effectively reduced the crumb firmness of no-shortening breads, while the additional FL showed no significant improvement (Fig. 3, top). The firming rates, as indicated by the slopes of the lines (Fig. 3, top), of breads containing surfactants (23–28 g/day) were lower than those containing no surfactants or just FL (38–44 g/day).

When 3% shortening was included in the bread formula, the reduction of crumb firmness by surfactants (Fig. 3, bottom) was not as great as in bread baked without shortening (Fig. 3, top), mainly because shortening alone greatly reduces crumb firmness of control bread, as reported previously by Pomeranz et al (1966). With shortening added, SSL reduced firmness and retained softness best; it was followed by DATEM and MG. SMP reduced firmness only in the first two days of storage. Flour lipids did not improve crumb firmness (Fig. 3, bottom).

The LV response to shortening was most with control breads, next with breads containing additional FL, and relatively small with breads containing surfactants (Table II), due to the shortening-sparing effects of surfactants reported by Finney and Shogren (1971) and Tsen and Hoover (1971). Similarly, crumb firmness reduction responses to shortening were also greatest for control breads at all three storage periods, followed by breads containing additional FL or MG (Table II). The addition of shortening in the presence of SMP or SSL exerted no further improvement on crumb softness and was rather detrimental (Table II). Crumb firmness reduction responses to shortening appeared to be inversely related to the LV of the breads without shortening.

Bread LV is an important factor in its keeping quality: it is positively related to bread softness, expressed as penetrometer value (Pomeranz et al 1984), or negatively related to bread firmness, expressed as compressibility value (Axford et al 1968; Pomeranz et al 1969). Our results also showed significantly high linear relationships ($r = -0.953$ to -0.971) between LV and crumb firmness. The slopes of the regression lines were −0.18, −0.24,

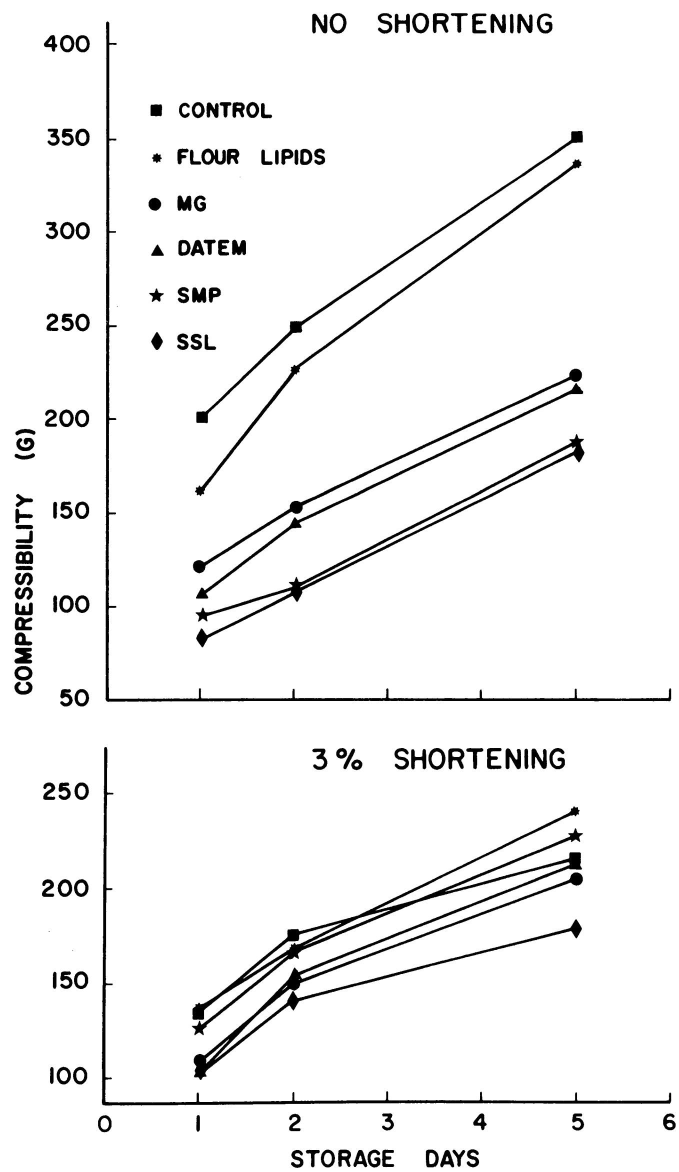

Fig. 3. Effect of storage days on crumb firmness (average standard deviation = 7.3 g), expressed as compressibility value of breads made with 0.5% flour lipids or surfactants with no shortening (top) and 3% shortening (bottom). MG = monoglycerides, DATEM = diacetyl tartaric acid esters of mono- and diglycerides, SMP = sucrose monopalmitate, SSL = sodium stearoyl lactylate.

TABLE II
Effects of Surfactants and Flour Lipids on Loaf Volume and Loaf Volume-Firmness Response to Shortening

0.5% Additive[a]	Loaf Volume,[b] cm³: 0% Shortening	Loaf Volume,[b] cm³: 3% Shortening	Response to Shortening[c]: Loaf Volume (cm^3)	Response to Shortening[c]: Firmness After Storage, g: One day	Two days	Five days
None	2,313	2,874	561	−66	−71	−137
FL	2,383	2,866	483	−25	−60	−97
MG	2,568	2,899	331	−12	−5	−18
DATEM	2,768	2,883	115	−7	8	−6
SMP	2,825	2,961	136	33	55	40
SSL	2,874	3,024	146	19	31	−7

[a] FL = flour lipids, MG = monoglycerides, DATEM = diacetyl tartaric acid esters of mono- and diglycerides, SMP = sucrose monopalmitate, SSL = sodium stearoyl lactylate.
[b] Averages of 12 loaves (six per replicate); overall standard error of mean = 49 cm^3.
[c] Obtained by subtracting the value without shortening from the one with 3% shortening.

and $-0.30\ g/cm^3$ for no-shortening bread stored for one, two, and five days, respectively, indicating faster firming of crumb of breads with smaller LV during the longer storage time. Bread made with 3% shortening did not have a wide range of LV (Table II) to show its effect on crumb compressibility.

Moisture Content of Bread Crumb and Its Effect on Crumb Firmness

For weight adjustment of bread crumb to maintain the same solids concentration in the amylograph, a rapid method for measurement of bread crumb moisture was developed, in which bread crumb was heated at 130°C for 70 min in one stage. The one-stage method was satisfactory because reliable crumb moisture contents could be obtained in a short time (~100 min). The difference between the one-stage method and the official two-stage method (AACC 1983) was not significant (Table III), even though the one-stage method generally gave slightly lower values. The correlation coefficient between moisture values measured by the two methods was 0.978 at a significance level of 0.0001.

The overall crumb moisture contents of breads made without shortening were higher than those of breads made with shortening (Table III). This was partly because of the higher water absorption (2.5 percentage points) for the dough without shortening. The addition of shortening decreased the absorption requirement. The moisture contents of the bread crumb consistently decreased with length of storage (Table III). This is in agreement with the results of other workers (Yasunaga et al 1968, Kai 1985, Pisesookbunterng and D'Appolonia 1983). This decrease appeared to be caused mainly by redistribution of water within the loaf, i.e., migration of moisture from the crumb to the crust, which is one of the phenomena of bread staling.

Surfactants generally enhanced the decrease of crumb moisture with storage time in bread without shortening, compared with the control (Table III). This is also in agreement with Pisesookbunterng and D'Appolonia (1983), who suggested that the absorption of surfactant onto the starch surface, as well as the formation of a starch-surfactant complex, restrained starch from taking up water released from gluten during bread aging, thus allowing the water to migrate from crumb to crust. However, this effect of surfactants was less pronounced for the breads with shortening.

Crumb compressibility was negatively related to its moisture content. There were three distinct regression groups for the no-shortening breads: the one with the steepest slope ($-67.8\ g/1\%$, $r = -0.988$) included bread containing 0.5% additional FL and control bread baked without additives; the middle group ($-35.9\ g/1\%$, $r = -0.984$) included breads containing MG and DATEM; and the third ($-31.0\ g/1\%$, $r = -0.973$) consisted of breads with SMP and SSL. On the other hand, the breads with shortening did not show distinct groups because of their narrower range of compressibility. However, a significant negative correlation was also present ($-30.3\ g/1\%$, $r = -0.879$). Therefore, crumb moisture plays an important role in crumb tenderness retention.

Effects of Additives on Crumb Amylogram Characteristics

Tables IV and V present amylogram data of bread crumbs made with various surfactants and FL with and without shortening. Analysis of variance showed that shortening significantly affected all the crumb amylogram readings (Table VI). Bread crumb with 3% shortening gave lower viscosities, much bigger bumps, and lower pasting temperature than bread without shortening. Without shortening, no minor peak appeared before the major peak (Table IV). If shortening was added, the appearance of the minor peak depended on the surfactant added: the control bread and breads containing DATEM and SMP showed the minor peak and those containing SSL, MG, and FL did not (Table IV).

All the amylogram readings were affected by the additives (Table V) at a significance level of 0.05, as indicated by the least significant difference analysis of the overall average amylogram readings (Table VI). In general, those additives with higher values in one reading also gave higher values in other readings: the linear

TABLE III
Crumb Moisture Content of Bread Made With and Without Shortening at Different Storage Times

0.5% Additive[a]	Storage Time (Day)	No Shortening: One-Stage Method[b]	No Shortening: Two-Stage Method[b]	3% Shortening: One-Stage Method	3% Shortening: Two-Stage Method
None	1	42.5	42.9	40.3	40.5
	2	41.7	42.3	39.5	39.5
	5	40.0	41.1	37.5	37.6
FL	1	42.9	42.8	40.6	40.7
	2	42.1	41.9	39.7	40.1
	5	40.7	40.9	38.3	38.2
MG	1	42.8	42.7	40.4	40.9
	2	41.5	41.6	39.6	40.1
	5	40.1	40.3	37.2	38.0
DATEM	1	42.8	42.9	40.9	41.2
	2	42.0	42.1	39.7	40.1
	5	39.5	39.6	37.6	37.7
SMP	1	42.4	42.4	40.4	40.4
	2	41.0	41.6	39.9	40.2
	5	39.2	39.1	37.9	37.5
SSL	1	42.5	42.4	40.7	40.6
	2	41.2	42.2	39.4	39.8
	5	39.3	39.0	37.6	38.0

Crumb Moisture Content[b] (%) of Bread

[a] FL = flour lipids, MG = monoglycerides, DATEM = diacetyl tartaric acid esters of mono- and diglycerides, SMP = sucrose monopalmitate, SSL = sodium stearoyl lactylate.
[b] Averages of eight determinations (four per replicate); overall standard error of mean = 0.03% for the one-stage method and 0.57% for the two-stage method.

TABLE IV
Appearances of Plateau and Minor Peak and Pasting Temperatures of Breads at Different Storage Times[a]

0.5% Additive[b]	Storage Time (Day)	Appearance[c]: Plateau 0[d]	Plateau 3[d]	Minor Peak 0[d]	Minor Peak 3[d]	Pasting Temperature, °C 0[d]	Pasting Temperature, °C 3[d]
None	1	Y	Y	N	Y	84.9	84.4
	2	Y	Y	N	Y	84.1	84.7
	5	Y	Y	N	Y	84.4	84.4
FL	1	S-Y	S	N	N	85.4	84.8
	2	Y	Y	N	N	85.5	84.9
	5	Y	Y	N	N	85.4	84.1
MG	1	N	N	N	N	91.7	91.2
	2	N	N	N	N	91.8	91.1
	5	N	N	N	N	91.8	91.4
DATEM	1	S	N	N	S	87.5	84.5
	2	Y	S-Y	N	S	86.8	84.4
	5	Y	Y	N	S	86.7	85.1
SMP	1	N	N	N	Y	89.6	87.2
	2	Y	S	N	Y	89.4	87.0
	5	Y	Y	N	Y	90.2	87.5
SSL	1	N	N	N	N	91.7	90.9
	2	N	N	N	N	91.7	91.0
	5	N	N	N	N	91.7	91.1

[a] Averages of two replicates; overall standard error of mean pasting temperature = 0.43.
[b] FL = flour lipids, MG = monoglycerides, DATEM = diacetyl tartaric acid esters of mono- and diglycerides, SMP = sucrose monopalmitate, SSL = sodium stearoyl lactylate.
[c] Y = yes, S = slight, N = no.
[d] Percent shortening.

TABLE V
Crumb Amylogram Characteristics of Breads at Different Storage Times[a]

0.5% Additive[b]	Storage Time (Day)	Bump Area, cm^2		Viscosity, BU					
				Peak		Holding-End		Cooling-End	
		0[c]	3[c]	0[c]	3[c]	0[c]	3[c]	0[c]	3[c]
None	1	2.1	9.8	319	195	289	159	582	509
	2	1.9	10.0	309	199	289	164	567	519
	5	2.4	10.0	307	193	283	174	571	544
FL	1	2.4	13.6	349	283	314	173	592	536
	2	2.5	13.5	341	276	313	173	589	536
	5	2.4	13.4	341	284	315	175	591	538
MG	1	1.2	20.1	505	387	419	348	815	701
	2	1.1	20.2	491	399	411	358	794	724
	5	1.0	20.8	489	395	411	361	818	734
DATEM	1	1.9	17.2	365	254	326	192	645	585
	2	2.2	17.7	373	286	334	208	661	633
	5	1.8	17.4	369	260	334	193	651	586
SMP	1	15.5	24.2	467	328	324	231	758	685
	2	15.5	23.8	452	331	325	239	746	689
	5	15.9	24.8	477	340	345	244	788	715
SSL	1	0.7	11.2	590	458	411	280	883	793
	2	0.7	11.3	582	457	403	280	855	796
	5	0.7	10.5	583	454	409	275	868	788

[a] Averages of two replicates; overall standard deviation = 0.91 cm^2 for bump area, 19.5 BU for peak viscosity, 12.5 BU for holding-end viscosity, and 27.8 BU for cooling-end viscosity.
[b] FL = flour lipids, MG = monoglycerides, DATEM = diacetyl tartaric acid esters of mono- and diglycerides, SMP = sucrose monopalmitate, SSL = sodium stearoyl lactylate.
[c] Percent shortening

correlation coefficient (r) values were 0.866 for the peak vs holding-end viscosities; 0.945 for the peak vs cooling-end viscosities; 0.888 for the peak viscosity vs the pasting temperature; and 0.777 for the holding-end vs cooling-end viscosities. Exceptions were the bump areas for the SSL and SMP crumbs: the SSL-crumb amylogram showed a smaller bump area with high pasting temperatures and viscosities (Tables V and VI) and the SMP-crumb amylogram gave exceptionally large bump areas compared with those of the other additives, even in the absence of shortening (Table V).

Effects of Storage Times on Crumb Amylogram Readings

The effects of bread storage times on the pasting temperatures and on the status of the minor peak and the plateau before the onset of the viscosity rise are shown in Table IV. Data on the amylogram bump area and viscosity readings are presented in Table V.

The statistical analysis showed no significant differences at a significance level of 0.05 between the overall average amylograph readings of different storage periods (Table VI). This seemingly contradicts results reported by previous workers, who either found decreases (Yasunaga et al 1968) or increases (Kai 1985) in viscosity with storage times. Morad and D'Appolonia (1980) attempted to relate bump area to storage time but did not make a firm conclusion. Length of storage was not correlated with bump area (Tables V and VI). During the heating period of the first cycle of bread amylogram, some crumbs gave a plateau before the rise in viscosity upon gelatinization. The existence of the plateau depended on the type of additives in the bread formulation, i.e., control breads and breads containing additional FL showed plateaus, whereas breads containing SSL or MG did not (Table IV). In the case of DATEM and SMP, the plateau increased with storage time.

The plateau before the abrupt viscosity increase, if present, was formed by a rise of the initial viscosity baseline beginning at approximately 48°C and stabilizing at approximately 52°C (Fig. 2). When an increasing height of plateau was observed in DATEM and SMP breads with storage, the change in its height

TABLE VI
Comparison of Overall Average Amylogram Readings Between Treatments[a]

Treatment	Pasting Temperature (°C)	Bump Area (cm^2)	Viscosity, BU		
			Peak	Holding-End	Cooling-End
Shortening					
0%	88.3 a	4.0 b	428 a	247 a	709 a
3%	87.2 b	16.1 a	321 b	235 b	645 b
Additives[b]					
None	84.5 e	6.1 d	254 e	226 e	549 e
FL	85.0 d	7.9 c	312 d	244 de	564 e
MG	91.4 a	10.7 b	444 b	384 a	764 b
DATEM	85.8 c	9.7 b	318 d	264 cd	627 d
SMP	88.5 b	19.9 a	399 c	285 c	730 c
SSL	91.3 a	5.9 d	520 a	343 b	830 a
Storage days					
1	87.7 a	9.9 a	375 a	289 a	673 a
2	87.8 a	10.0 a	374 a	291 a	676 a
5	87.8 a	10.1 a	374 a	293 a	683 a

[a] The same letter within each treatment under each amylogram reading represents the average values, which are not significantly different at the 0.05 level.
[b] FL = flour lipids, MG = monoglycerides, DATEM = diacetyl tartaric acid esters of mono- and diglycerides, SMP = sucrose monopalmitate, SSL = sodium stearoyl lactylate.

was actually caused by a progressive decrease in initial viscosity (after one day: 19–20 BU, after two days: 16–17 BU, and after five days: 13–15 BU) before the plateau while the level of the plateau (20 BU) was unchanged over the storage time. Those evidences suggest that the plateau was a result of the dissociation of retrograded amylopectin, as reported by Russel (1983) and Krog et al (1989). The lack of plateaus in amylograms of MG and SSL breads indicates that those two surfactants may have a greater inhibitory effect on amylopectin retrogradation than DATEM or SMP.

The increase in the plateau with storage times and the insignificant effects of storage time on amylogram readings indicate that after the crumb slurry reached a high temperature, either the staling effects were lost, or the effects were so small that they could not be precisely detected by the amylograph procedure. Varriano-Marston et al (1980) reported that compared with the methods of X-ray diffraction, polarization microscopy, and enzyme application, the amylographic method was the least reliable in determining starch swelling in baked goods.

Relation of Crumb Amylogram Readings to Crumb Firmness

Table VII shows correlation coefficients between crumb firmness and the parameters storage length, LV, crumb moisture content, and amylogram readings of breads for no-shortening, 3% shortening, and combined systems. These same variables except the pasting temperature were used in the STEPWISE procedure (Ott 1984) to find the best-fitting regression equations for crumb firmness to determine multiple factors related to crumb firmness (Table VIII) for the same systems. Every variable in the equations was significant at the 0.05 level based on the *t*-test (Ott 1984).

Storage time was highly correlated with crumb firmness (Table VII) and was a component of all the three equations (Table VIII). This was expected, since a major problem of bread staling is progressive firming of bread upon storage.

Loaf volume was inversely correlated with crumb firmness (Table VII) and was included with a negative parameter in the best-fitting equations for crumb firmness (Table VIII) in the no-shortening system and the combined system. This means that the crumb of a larger loaf would be softer, which is in agreement with others' results (Axford et al 1968, Pomeranz et al 1969). This is apparently because the density of bread is lower for bread with a larger volume, and there is less material resisting the compression. In the shortening system, LV was not significantly correlated with crumb firmness (Table VII) and was not a necessary component in the best-fitting equation (Table VIII). The LVs of breads with different additives in the presence of 3% shortening were similar (Table II), thus diminishing the importance of LV in determining crumb firmness.

Moisture content was inversely correlated with crumb firmness of breads for each of the two systems and the combined system (Table VII). This may be partially explained by the plasticizing effect of moisture on the structure in bread crumb, but the significant correlation was also due to the concomitant decrease of crumb moisture with storage time (Table III). Crumb moisture content was not a necessary component in the best-fitting equations for crumb firmness (Table VIII).

All amylogram readings other than bump area were significantly correlated with crumb firmness of the no-shortening breads, while no amylogram readings were significantly correlated with crumb firmness for the shortening system (Table VII). When both systems were considered together, pasting temperature and cooling-end viscosity showed significant correlations ($\alpha = 0.05$) with crumb firmness (Table VII). One amylogram viscosity reading was also included in each best-fitting equation: the no-shortening and combined systems included the viscosity at the end of the holding period, and the shortening system included the viscosity at the end of the cooling period (Table VIII). Higher viscosities accompanied lower compressibility values. When the STEPWISE procedure was run without amylogram variables, the R^2 values decreased drastically, confirming that amylograph properties of bread crumb were definitely related to crumb firmness in addition to storage length and LV.

It is known that certain surfactants or FLs complex with starch molecules (Schoch and Williams 1944, Krog 1971, Riisom et al 1984), thus restricting the swelling and pasting of starch (Krog 1973, Ghiasi et al 1982, Lonkhoysen and Blankestijn 1976, Eliasson 1985) including the starch in bread dough during baking (Schoch 1965, Morad and D'Appolonia 1980). The decrease of solubilized amylose during baking and the retarding of amylopectin retrogradation during storage by surfactants and lipids contribute to softer bread crumb and a slower firming rate (Krog and Davis 1984, Krog and Nybo Jensen 1970, Lagendijk and Pennings 1970, Eliasson 1984, Knightly 1988, Krog et al 1989). In the amylograph, starch in the bread crumb, which had been swollen and pasted to different degrees due to its interaction with different fatty additives, underwent further swelling and dispersion in the presence of the same additives. Therefore, those additives that have more starch-complexing power, giving softer bread crumb, would yield higher amylograph crumb pasting temperatures and viscosities. This would explain the negative correlations of crumb firmness with the viscosity parameters.

No significant correlation was found between bump area and crumb firmness. Part II of this study will report that the bump in the bread crumb amylograph is caused by interaction between solubilized amylose and fatty materials. The amylose-complexing capacity of a surfactant or FL retards the solubilization of amylose but on the other hand enhances the interaction with solubilized amylose. The former effect decreases the bump area but the latter increases it. These contradictory effects make bump area unrelated to crumb firmness.

CONCLUSIONS

The one-stage method for rapid measurement of bread crumb moisture was suitable for the amylograph study of the bread crumb. The storage time of bread had no significant effect on the amylogram readings of bread crumb. Instead, changes in bread formula in terms of shortening and surfactants or FL contributed significantly to the amylogram readings of bread crumb. An inverse relationship between crumb compressibility and crumb amylograph viscosities was found and was attributed to the formula changes.

TABLE VII
Linear Correlation Coefficients of Bread Crumb Firmness (Compressibility) and Other Variables

	r Value of Firmness[a]		
	No Shortening	3% Shortening	Combined System
Storage day	0.678***	0.908***	0.799***
Loaf volume	−0.692***	−0.208	−0.551***
Crumb moisture	−0.484**	−0.879***	−0.363**
Amylogram readings			
Pasting temperature	−0.583**	−0.216	−0.393**
Viscosity			
Peak	−0.593***	−0.229	−0.318*
Holding-end	−0.468**	−0.181	−0.117
Cooling-end	−0.592***	−0.203	−0.385**
Bump area	−0.235	0.035	−0.198

[a] *** indicates significance at the 0.01 level, ** at the 0.05 level and * at the 0.1 level.

TABLE VIII
Best-Fitting Regression Equations for Crumb Firmness

Baking System	Best-Fitting Regression Equation[a]	Degrees of Freedom	R^2
No-shortening	$F = 745.9 + 30.33$ Day $- 0.2629$ HV $- 0.2111$ LV	35	0.958
3%-shortening	$F = 172.3 + 22.82$ Day $- 0.1070$ CV	35	0.888
Combined	$F = 664.0 + 26.55$ Day $- 0.2326$ HV $- 0.1784$ LV	71	0.901

[a] F = crumb firmness expressed as compressibility (g); Day = storage day; LV = loaf volume (cm^3); HV = viscosity (BU) at the end of holding stage; CV = viscosity (BU) at the end of cooling stage.

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