

Effects of Baking Temperature on Crumb-Staling Kinetics

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ABSTRACT

Cereal Chem. 74(6):710–714

This study evaluated the effects of bread baking temperature on the staling kinetics of crumb. Bread dough was leavened and baked in sealed molds. Cooking trials were performed at various temperatures ranging from 90 to 110°C. The crumb samples were then stored at 20°C at constant moisture, and staling was evaluated by measuring crumb elastic modulus (using an Instron dynamometer) and starch retrogradation degree (using differential scanning calorimetry). Results show that the

cooking temperature greatly influences bread staling. The lower the cooking temperature, the lower the staling rate, both in terms of crumb hardening and of starch retrogradation. Starch and protein solubility was evaluated on crumb cooked at 90 and 110°C. An increase in cooking temperature resulted in an increase in protein insolubilization and starch granule disruption.

Bread staling has been extensively studied because of its importance in determining product acceptability and shelf life. Studies on staling have mainly concerned starch modifications and starch-gluten interactions in bread crumb (Maga 1975, Kulp and Ponte 1981). Various studies have shown that crumb firming is related to starch retrogradation during bread storage. The Avrami kinetic equation has been shown to fit crumb staling kinetics, both in terms of starch retrogradation and crumb firming (Conford et al 1964, Kim and D'Appolonia 1977a, Kulp and Ponte 1981). Besides starch retrogradation, other factors are involved in determining staling extent and kinetics (Willhoft 1971a, Willhoft 1973, Maga 1975, Kim and D'Appolonia 1977b, Martin et al 1991).

Water diffusion and redistribution among the protein-starch and crumb-crust fractions of bread, and water loss by evaporation have been related to staling, but the role of water has not been fully explained (Willhoft 1971b, He and Hoseney 1990). After baking, water migrates from crumb to crust and some water evaporates. This phenomenon is slowed a few hours after baking and stops after a few days (Zanoni et al 1993). Water loss causes crumb firming, but bread staling also occurs at constant moisture (He and Hoseney 1990, Martin et al 1991).

Little is known about the effects of operating conditions during the breadmaking process on bread staling (Lund 1984, MacRitchie 1985). In particular, the effects of the severity of heat treatment on crumb characteristics have been scarcely investigated, due to the fact that crumb temperature during conventional oven baking does not exceed 100°C, which is the temperature of the evaporation front at the crumb-crust interface (Zanoni et al 1993, 1994).

The surface temperature of the loaf and the rate of water evaporation can be varied by varying the oven temperature, but the temperature of the evaporation front (i.e., 100°C) cannot be varied at atmospheric pressure. As a result, crumb temperature always tends to 100°C, and the severity of heat treatment can be varied by varying the baking time.

It is well known that starch gelatinization and protein denaturation, which are the main modifications responsible for crumb structure, depend on the severity and time of heat treatment (Eliasson and Hoegg 1980, Schofield et al 1983, Dreese et al 1988). The gelatinization degree usually detected in bread is about 96% (Lineback and Wongsrikasem 1980, Dalla Rosa et al 1989).

Yasunaga et al (1968) evaluated the starch gelatinization degree during bread baking by viscometry. Their results indicate that gelatinization is higher near the crust than at the core of the loaf. This is a consequence of crumb heating occurring from the evaporation front at 100°C to the core of the loaf. During baking a temperature gradient occurs in the loaf, which is consequently subjected to a much more severe heat treatment near the surface than at the core.

Martin et al (1991) used an electric resistance oven to bake dough at various temperatures <100°C, with minimum water evaporation. More swollen starch granules and more soluble starch were detected in crumb cooked at 99°C than in crumb cooked at 95°C. According to these authors, more interactions occur between starch and gluten when starch granules are more swollen. This results in harder crumb.

Faridi and Rubenthaler (1984) studied the effects of oven temperature and length of cooking on starch gelatinization degree and staling rate of Egyptian-type bread. They observed that a higher staling rate corresponded to a higher degree of starch gelatinization. Bread was baked at various time-temperature profiles (1–6 min; 240–540°C oven temperature). The highest degree of starch gelatinization was obtained in bread baked under intermediate conditions (340°C for 3–4 min). This was ascribed to optimal moisture and temperature values for gelatinization. This bread was initially harder than the others, and maintained this characteristic during storage.

It is worth noting that higher water evaporation occurs during baking at higher oven temperature. This is important for staling because water content influences the rate of starch retrogradation in bread crumb (Zeleznač and Hoseney 1986).

The aim of this research was to evaluate effects of baking temperature on crumb staling kinetics. Suitable conditions were applied to obtain one experimental variable, crumb temperature during baking, and to avoid variations in other characteristics, such as crumb moisture and crust thickness, due to water diffusion and evaporation.

A particular system with sealed molds was set up. Baking was done at a product temperature of 90–110°C. Crumb firmness was determined on fresh crumb and during storage by compression test. Starch retrogradation was measured by differential scanning calorimetry. The effects of baking temperature on starch and protein fractions were evaluated by solubility measurements.

MATERIALS AND METHODS

Common wheat flour type "00" (Molini di Vigeveno SpA, Vigeveno, Italy) was used. Its composition was: moisture 14.5%, ash 0.53%, and protein (N × 5.7) 10.06% on wet basis. Compressed yeast (*Saccharomyces cerevisiae*) (Vinal, Gist-

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Brocades SpA, Casteggio, Italy) was used. The dough was baked in tin-plate cylindrical molds (73 mm diameter, 58 mm height, 0.16 mm thickness) (Capolo SpA, Reggio Emilia, Italy).

Breadmaking

Ingredients mixed were: 100 g of flour, 57 g of water (at 30°C), 3.5 g of yeast, 1.5 g of NaCl. Two kilograms of dough were prepared each time. The dough was kneaded in a Hobart mixer (model N-50) at speed 1 for 10 min. Dough portions (95 g) were placed into molds and allowed to stay in the leavening chamber (model HC0020, Heraeus-Votsch) at 30°C and 75% rh for 60 min. After that time, dough portions had risen to the top of the mold. The molds were then sealed (model A1, Bertuzzi SpA, Brugherio, Italy) before cooking. Cooking was performed at 90 and 95°C in a preheated waterbath, and at 100, 105, and 110°C in a retort (Fedegari SpA, Pavia, Italy). Temperature was monitored by two thermocouples during cooking. Type J thermocouple (1.6 mm diameter) was used to detect the temperature at the geometric center of the sample; it was fastened to the container by an air- and water-tight system. Type T thermocouple (1.8 mm diameter) was used to detect the temperature inside the waterbath and the retort. The cooking phase was stopped when the temperature at the core of the sample was 2°C lower than the temperature in the bath or in the retort. This required 30–35 min. The cooked samples were immersed into cold water (20°C), until the temperature at the geometric center had reached ≈30°C (about 30 min). After cooling, crumb samples were removed from the molds and her-

metically packed in double-welded polyethylene bags under light vacuum (absolute pressure inside the bags was ≈400 mbar). Packed samples were stored in a thermostated chamber at 20°C so that staling occurred under constant moisture and temperature conditions. This procedure allowed us to control and standardize the baking process, and to obtain the following results: 1) a crumb sample without crust was obtained, thus avoiding evaporation and overheating phenomena that characterize crust formation; 2) crumb temperature during cooking was controlled; 3) constant density and porosity of the product were obtained; 4) moisture variations during cooking and cooling were avoided.

Analytical Methods

Protein content is expressed as total nitrogen ($N \times 5.7$). To determine soluble protein, 10 g of crumb was homogenized with 90 g of NaH_2PO_4 buffer (50 mM, pH 6.0) in an homogenizer (Ultra Turrax T25, Janke and Kunkle) at 10,000 rpm for 2 min. The suspension was then stirred for 2 hr (model 713, ASAL), and centrifuged at 10,000 rpm for 30 min (Centrikon T 42-K).

Soluble protein was determined on the supernatant by Bradford method, by measuring absorbance at 595 nm in a 10-mm optical path cuvette against a blank (phosphate buffer plus Bradford reagent). Protein concentration was calculated against a calibration curve built with soluble proteins extracted from the uncooked dough (from the freeze-dried and finely milled dough by phosphate buffer, pH 6.0).

Each determination was made in duplicate on the extract obtained in duplicate from two different baking trials at the same

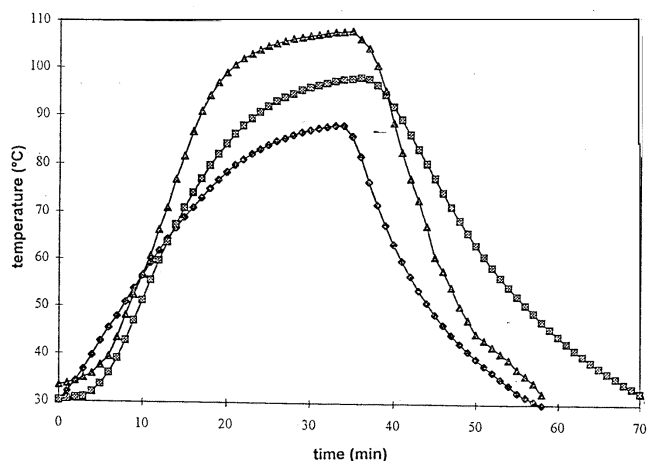


Fig. 1. Heat penetration curves at the geometric core of crumb samples during cooking at 90 (◆), 100 (■), and 110°C (▲).

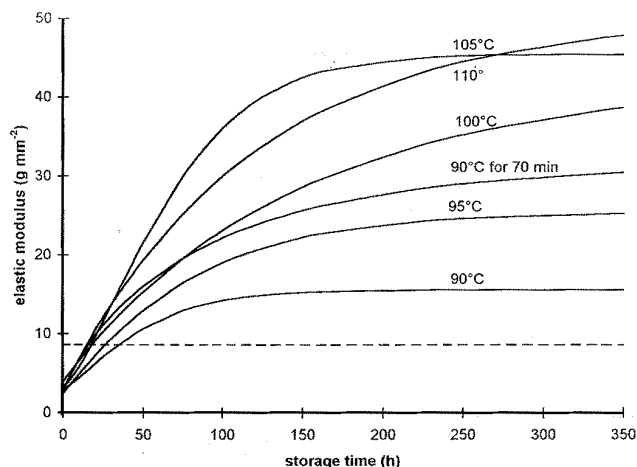


Fig. 2. Variation in elastic modulus during storage of crumb samples cooked at various temperatures.

TABLE I
Variation in Elastic Modulus and Retrograded Starch(ΔH) During Storage of Crumb Cooked at 90°C

Storage Time (hr)	Elastic Modulus (g/mm ²)	ΔH (J/g)
0.5	3.36 (0.31) ^a	0.445
5	3.61 (0.50)	0.317
12	5.45 (0.70)	ND
15	ND ^b	0.480
24	7.58 (0.44)	0.936
37	9.05 (0.60)	0.989
48	7.96 (0.61)	ND
71	14.30 (1.48)	1.266
93	13.78 (1.95)	ND
96	14.45 (1.24)	1.181
144	15.32 (1.55)	ND
168	ND	1.447
231	15.11 (1.07)	ND

^a Standard deviations in parentheses.

^b Not determined

TABLE II
Avrami Equation Coefficients^a for the Variation in Elastic Modulus of Crumb Cooked at Various Temperatures

Temperature (°C)	E_0 (g/mm ²)	E_∞ (g/mm ²)	k /hr	n	r^2
35 min					
90	3.03 (0.73) ^b	15.55 (0.99)	0.006 (0.008)	1.27 (0.31)	0.962
95	3.00 (0.92)	25.61 (0.78)	0.003 (0.003)	1.36 (0.25)	0.991
100	3.92 (1.29)	42.35 (4.57)	0.008 (0.005)	0.97 (0.15)	0.983
105	2.85 (1.09)	50.52 (2.79)	0.009 (0.004)	0.99 (0.10)	0.995
110	3.42 (1.32)	45.46 (1.27)	0.002 (0.001)	1.40 (0.18)	0.991
70 min					
90	2.50 (0.65)	31.54 (1.25)	0.023 (0.006)	0.85 (0.07)	0.996

^a E_0 is the elastic modulus at time 0 (fresh sample); E_∞ is the elastic modulus at equilibrium; k and n are equation constants; r^2 is the determination coefficient.

^b Standard error in parentheses.

temperature. Results, as the average of eight determinations, are expressed as milligrams of soluble protein per gram of sample.

Soluble starch was determined colorimetrically by adding iodine solution to a water extract of crumb. Crumb (2 g) was homogenized (2 min in an Omni Mixer) with 100 mL of deionized water. The suspension was centrifuged ($1,000 \times g$ for 10 min), and 1 mL of clear supernatant was mixed with 10 mL of water and 1 mL of iodine solution (2 g of KI + 0.2 g of bisublimated I_2 in 100 mL of water). Absorbance at 590 nm, which represents the maximum absorbance wavelength of the starch-iodine complex, was measured after 10 min in a 10-mm optic path cuvette against a blank (11 mL of water + 1 mL of iodine solution). Soluble starch concentration was calculated against a calibration curve built with a standard solution of soluble starch (Merck). Soluble starch determinations were performed as for soluble protein. Results, as the average of eight determinations, are expressed as milligrams of soluble starch per gram of sample.

Elastic Modulus

Compression tests were made with an Instron universal testing machine (model 4310) connected to a data processing computer (program series IX Automated Materials Testing System, release 4.1, Instron Corporation, 1992). A crumb cylinder (25 mm diameter and 30 mm height) was obtained from the center of a crumb loaf by an electric knife and a cylindrical sampler. Each crumb cylinder was subjected to compression under the following conditions:

loading cell 10 kg, ram diameter 80 mm, rate 20 mm/min, maximum deformation 25%. Five replicates were made for each experimental point. Data of stress versus strain were plotted, and the tangent to the linear segment of the curve, which corresponded to the elastic modulus, was calculated by linear regression (Quattro-Pro 123). The five replicates were mediated and statistically evaluated (relative standard deviation was 3–15%). Elastic modulus values are expressed as g/mm^2 . Data were collected periodically during 14 days of storage time.

Retrograded Starch

Retrograded starch after various storage times was determined by measuring the ΔH corresponding to the melting of retrograded starch. Calorimetric analyses were made using a differential scanning calorimeter (Mettler DSC20). The procedure defined by Schiraldi et al (1996) was followed. The endothermic peak corresponding to recrystallized starch fusion was subtracted from the baseline, and the area of the peak was calculated. ΔH was then obtained and related to the sample weight. This value was defined as "retrograded starch ΔH ". Two replicates were made for each analysis. Average results are expressed as J/g. Calorimetric analyses were performed periodically until the asymptotic value was reached.

Modeling of Staling Kinetics

Elastic modulus and ΔH values were processed according to the kinetic Avrami model by nonlinear regression by the Table Curve program (Jandel Scientific, release 1.0, 1993).

RESULTS AND DISCUSSION

Staling Kinetics

Experimental temperature profiles for cooking trials at 90, 100, and 110°C are shown in Fig. 1. Elastic modulus and ΔH variations were evaluated as an index of progressive crumb staling for the cooking trials at 90, 100, and 110°C. In the other trials, only elastic modulus variations were determined. Table I shows the variation of elastic modulus and ΔH during storage of crumb cooked at 90°C during storage. For the sake of brevity, data related to this trial only are shown. Experimental values were similarly collected for the other cooking temperatures.

Experimental points of elastic modulus were processed according to the Avrami equation: $E_t = E_\infty - [(E_\infty - E_0) \exp(-kt^n)]$, where

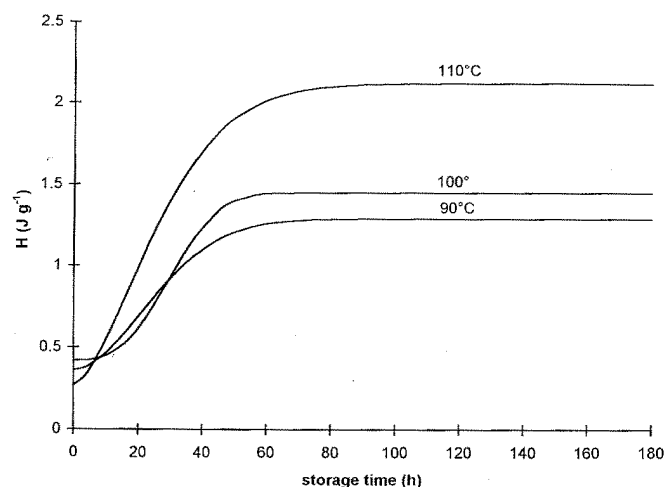


Fig. 3. Starch retrogradation kinetics of crumb cooked at 90, 100, and 110°C, measured as retrograded starch (ΔH) by differential scanning calorimetry.

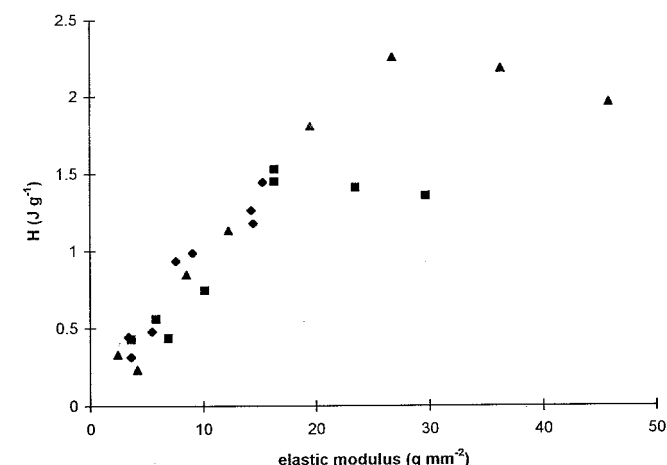


Fig. 4. Relationship between elastic modulus and ΔH values of crumb cooked at 90 (◆), 100 (■), and 110°C (▲).

TABLE III

Staling Rate Constants (Evaluated as Crumb Hardening) During the First 24 hr of Storage of Crumb Cooked at Various Temperatures

Temperature (°C)	Staling Rate Constant k' ($g/mm^2/hr$)	r^a
90	0.165	0.997
95	0.233	0.999
100	0.253	0.999
105	0.367	0.999
110	0.330	0.989

^a Correlation coefficient.

TABLE IV

Avrami Equation Coefficients^a for the Variation in Starch Retrogradation of Crumb Cooked at Various Temperatures

Temperature (°C)	ΔH_0 (J/g)	ΔH_∞ (J/g)	k/hr	n	r^2
90	0.36 (0.12) ^b	1.30 (0.09)	1.70×10^{-3} (6.00×10^{-3})	1.86 (1.06)	0.933
100	0.42 (0.06)	1.45 (0.05)	0.04×10^{-3} (0.12×10^{-3})	2.88 (0.93)	0.980
110	0.27 (0.13)	2.12 (0.10)	4.00×10^{-3} (6.02×10^{-3})	1.60 (0.44)	0.980

^a ΔH_0 is the value at time 0 (fresh sample); ΔH_∞ is the value at equilibrium; k and n are equation constants; r^2 is the determination coefficient.

^b Standard error in parentheses.

E_t is the elastic modulus at time t , E_∞ is the elastic modulus at equilibrium (corresponding to the asymptote), E_0 is the elastic modulus at time 0 (fresh sample), t is the time, and k and n are the equation constants. Curves obtained by nonlinear regression are shown in Fig. 2, and the Avrami equation coefficients E_0 , E_∞ , k , and n are reported in Table II, together with the curve correlation coefficient r^2 .

Conclusions

The high value of correlation coefficient confirms that the Avrami equation is a good model of elastic modulus variation.

E_0 , the initial elastic modulus, is similar for all samples, indicating that different heat treatments do not cause substantial differences in fresh crumb firmness.

On the contrary, the asymptote value E_∞ is strongly dependent on the severity of heat treatment. An increase in the maximum elastic modulus value reached by the crumb is observed when the cooking temperature is increased. This does not hold for samples cooked at 110°C.

Bread cooked at 90°C for 70 min shows staling kinetics intermediate between those observed in bread cooked at 95 and 100°C. This demonstrates that the effects of cooking on staling depend on both time and temperature, that is on the severity of heat treatment.

In agreement with published data, n value is close to 1 (Rhonda et al 1968; Kim and D'Appolonia 1977a,b).

In a previous work (Giovannelli and Pagliarini 1996), sensory tests on the same type of bread demonstrated that the first perception of staling by a trained panel corresponds to a threshold value of elastic modulus of 8.6 g/mm². This value is indicated in Fig. 2 by a horizontal line. This threshold value is reached within 15 hr for bread cooked at 110°C to ≈35 hr for bread cooked at 90°C. Nonindustrial bread, which is the most used in Italy, shows an optimal consumption period of few hours to 24 hr. In this case, slowing the staling rate such as to extend the consumption period by some hours would be of great commercial interest.

Elastic modulus data from the first 24 hr of storage were further analyzed. During this period, the increase in elastic modulus can be considered as linear and is described by the equation: $E = E_0 + k't$. Rate constants (k') were calculated for the various cooking temperatures by linear regression, obtaining values given in Table III. The k' values indicate that staling is ≈30% faster in bread cooked at 100°C than in bread cooked at 90°C, and that staling is ≈20% faster in bread cooked at 110°C than in bread cooked at 100°C.

Starch Retrogradation

The ΔH values were processed according to the Avrami equation: $\Delta H_t = \Delta H_\infty [(\Delta H_\infty - \Delta H_0) \exp(-kt^n)]$, where indices and constants have the same meaning as for the elastic modulus. Curves obtained for bread cooked at 90, 100, and 110°C are shown in Fig. 3. The corresponding Avrami coefficients are reported in Table IV. Crumb cooked at higher temperature shows faster, more extended starch crystallization during storage. This may be ascribed to the fact that greater starch retrogradation is obtained when the initial gelatinization degree is high (Faridi and Rubenthaler 1984). In all cases, the asymptotic value of ΔH is reached after 60–70 hr. This is a much shorter time than that required to obtain the asymptotic value in the crumb hardening kinetics. If elastic modulus values are related to ΔH values, it can be seen that the two phenomena follow a different trend (Fig. 4). Crumb hardening and starch retrogradation are only directly related at the beginning of staling. After that time, starch retrogradation stops, while crumb hardening continues during storage.

Soluble Protein and Soluble Starch.

Soluble protein contents (standard deviations in parentheses) were: 12.8 (1.06) mg/g from the uncooked dough; 6.1 (0.86) mg/g from crumb cooked at 90°C; and 2.2 (0.39) mg/g from crumb

cooked at 110°C. As expected, the soluble protein content decreases after cooking due to protein denaturation and polymerization and to larger interactions between proteins and starch (Eliasson and Hoegg 1980, Schofield et al 1983, Hosenev et al 1988, Weegels et al 1994).

Soluble starch contents show that the amount of soluble starch is greater after a more severe heat treatment (standard deviations in parentheses). The uncooked dough contained 3.1 (0.13) mg/g of soluble starch, while values raised to 5.3 (0.17) mg/g in crumb cooked at 90°C and to 9.7 (0.43) mg/g in crumb cooked at 110°C. A larger granule modification and disruption occurs at higher temperature. As a result, a larger starch amount expelled from the granule is available for solubilization (Faridi and Rubenthaler 1984, Martin et al 1991). Since starch molecules interact with protein molecules, it can be assumed that this interaction is stronger in bread cooked at higher temperature. This results in differences in the behavior of crumb during staling. Protein denaturation may cause a reduction in water affinity due to protein compacting and loss of hydrophilic sites. Water lost from the protein fraction would promote starch mobility and crystallization.

In conclusion, crumb staling extent and kinetics are strongly related to the severity of thermal treatment. From a technical point of view, it can be suggested that bread be baked under slight vacuum to obtain crumb cooking at temperatures <100°C. This may enhance the shelf life of bread.

ACKNOWLEDGMENTS

Research supported by national Research Council (CNR) of Italy, special project RAISA, sub-project No. 4.

LITERATURE CITED

- Conford, S. J., Axford, D. W. E., and Elton, G. A. H. 1964. The elastic modulus in linear compression in relation to staling. *Cereal Chem.* 41:216-229.
- Dalla Rosa, M., and Lerici, C. R. 1989. Sul grado di gelatinizzazione dell'amido in alimenti diversi. *Tec. Molitoria* 40:692-699.
- Dreese, P. C., Faubion, J. M., and Hosenev, R. C. 1988. Dynamic rheological properties of flour, gluten, and gluten-starch doughs. I. Temperature-dependent changes during heating. *Cereal Chem.* 65:348-353.
- Eliasson, A. C., and Hoegg, P. O. 1980. Thermal stability of gluten. *Cereal Chem.* 57:436-437.
- Faridi, H. A., and Rubenthaler, G. L. 1984. Effect of baking time and temperature on bread quality, starch gelatinization and staling of Egyptian Balady bread. *Cereal Chem.* 61:151-154.
- Giovannelli, G., and Pagliarini, E. 1996. Valutazione della soglia di raffermimento della mollica di pane. *Tecnol. Alimentari* 35:635-641.
- He, H., and Hosenev, R. C. 1990. Changes in bread firmness and moisture during long-term storage. *Cereal Chem.* 67:603-605.
- Hosenev, R. C., Dreese, P. C., Doescher, L. C., and Faubion, J. M. 1988. Thermal properties of gluten. Contribution 88-21-A. Kansas Agricultural Experimental Station: Manhattan, KS.
- Kim, S. K., and D'Appolonia, B. 1977a. Bread staling studies. II. Effect of protein content and storage temperature on the role of starch. *J. Sci. Food Agric.* 54:216-224.
- Kim, S. K., and D'Appolonia, B. 1977b. Bread staling studies. I. Effect of protein content on staling rate and bread crumb pasting properties. *Cereal Chem.* 54:207-215.
- Kulp, K., and Ponte, J. G., Jr. 1981. Staling of white pan bread: Fundamental causes. *CRC Crit. Rev. Food Sci. Nutr.* 15:1-47.
- Lineback, D. R., and Wongsrikasem, E. 1980. Gelatinization of starch in baked products. *J. Food Sci.* 45:71-74.
- Lund, D. 1984. Influence of time, temperature, moisture, ingredients and processing condition on starch gelatinization. *CRC Crit. Rev. Food Sci. Nutr.* 20:249-273.
- MacRitchie, F. 1985. Physicochemical processes in mixing. Pages 132-157 in: *Chemistry and Physics of Baking*. J. M. B. Blanshard, P. J. Frazer, and T. Galliard, eds., R. Soc. Chem.: London.
- Maga, J. A. 1975. Bread staling. *CRC Crit. Rev. Food Technol.* 5:443-492.

- Martin, M. L., Zeleznak, K. J., and Hosoney, R. C. 1991. A mechanism of bread firming. I. Role of starch swelling. *Cereal Chem.* 68:498-507.
- Rhonda, G., McIver, G., Axford, D. W. E., Colwell, K. H., and Elton, G. A. H. 1968. Kinetic study of retrogradation of gelatinized starch. *J. Sci. Food Agric.* 19:560-563.
- Schiraldi, A., Piazza, L., and Riva, M. 1996. Bread staling: A calorimetric approach. *Cereal Chem.* 73 :32-39
- Schofield, J. D., Bottomley, R. C., Timms, M. F., and Booth, M. R. 1983. The effect of heat on wheat gluten and the involvement of sulphhydryl-disulphide interchange reactions. *J. Cereal Sci.* 1:241-253.
- Weegels, P. L., Verhoek, J. A., De Groot, A. M. G., and Hamer, R. J. 1994. Effect on gluten of heating at different moisture contents. II. Changes in physico-chemical properties and secondary structure. *J. Cereal Sci.* 19:39-47.
- Willhoft, E. M. A. 1971a. Bread staling. I. Experimental study. *J. Sci. Food Agric.* 22:176-180.
- Willhoft, E. M. A. 1971b. Bread staling. III. Measurement of the redistribution of moisture in bread by gravimetry. *J. Sci. Food Agric.* 22:647-649.
- Willhoft, E. M. A. 1973. Mechanism and theory of staling of bread and baked goods, and associated changes in textural properties. *J. Texture Stud.* 4:292-322.
- Yasunaga, T., Bushuk, W., and Irvine, G. N. 1968. Gelatinization of starch during bread-making. *Cereal Chem.* 45:269-279.
- Zanoni, B., Peri, C., and Pierucci, S. 1993. A study of the bread-making process. I. A phenomenological model. *J. Food Eng.* 19:389-398.
- Zanoni, B., Pierucci, A., and Peri, C. 1994. Study of the bread-making process. II. Mathematical modelling. *J. Food Eng.* 23:321-336.
- Zeleznak, K. J., and Hosoney, R. C. 1986. The role of water in the retrogradation of wheat starch gels and bread crumb. *Cereal Chem.* 63:407-411.

[Received October 23, 1996. Accepted June 20, 1997.]