Moisture Redistribution Throughout the Bread Loaf During Staling and Its Effect on Mechanical Properties

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ABSTRACT

The change of the moisture profile within a bread loaf and bread texture during storage up to 300 hr at 25°C were investigated. Three different types of bread were considered: 1) bread from straight dough using conventional baker's yeast fermentation; 2) one-stage sour-dough bread from starter culture of *Lactobacillus brevis;* and 3) bread from straight dough acidified with lactic acid. An attempt to correlate bread-staling kinetics to water migration was made by considering the mass transport phenomena involved in the process. To evaluate bread staling, the stress-strain behavior of bread during aging was investigated. By considering the moisture profile within the bread loaf, a correlation between local moisture content and texture of stale bread was found. The experimental results proved that, to prevent staling, it is more important to slow down the dehydration phenomena rather than it is to increase the initial moisture content in the bread.

Baked products are perishable foods that undergo severe physical, physiochemical, sensory, and microbial changes during storage that result in a rapid loss of freshness. Staling generally refers to those changes occurring during storage and not to those associated with microbial contamination that causes the waste of baked products. The economic losses caused by bread staling are extremely important, so considerable attention has been focused on this problem. Much effort has been put into trying to develop methods to delay the staling process or to minimize its effect (Spicher 1983, Ghiasi et al 1984, Jankiewicz and Michniewicz 1987, Joensson and Toernaes 1987, Stear 1990a, Avital el al 1990, Hebeda et al 1991).

Although bread staling has been extensively studied, the phenomena responsible for this mechanism are not completely understood (Whilloft 1973; Roewe et al 1982; Hoseney 1985; Zeleznak and Hoseney 1986; Rogers et al 1988, 1990; He and Hoseney 1990; Martin et al 1991; Martin and Hoseney 1991; Slade and Levine 1991; Hoseney 1992). However, many results indicate that bread staling is mostly associated with the change in hydrophilic properties of the crumb that occur during aging (the solubility of colloids and other bread components diminishes) (Ghiasi et al 1979). Moreover, the staling process results in extensive textural and organoleptic modifications such as crumb hardening and crust softening.

Firmness, the resistance of bread crumb to deformation, is the textural attribute commonly used to assess the staling of bread (Pomeranz and Shellenberger 1971). Bread firmness is commonly evaluated by organoleptic tests, where the bread crumb samples are squeezed between the finger or eaten, or by instrumental analysis, where the bread samples are compressed and the force used is measured. This type of test is commonly conducted using an Instron UTM, submitting the sample of a given shape to uniaxial compression between parallel plates. Tests may involve one compression or compression cycles (Shakra and Sherman 1984, Hibbered and Parker 1985, Redlinger et al 1985, Baker et al 1986, Leite et al 1990, Kou and Chinacotti 1991, Swyngedau et al 1991, Nussinovitch et al 1992).

In general, measurements of crumb firmness are made over storage periods of 8–10 days. Because the modifications of the crumb's mechanical characteristics within this period of time are macroscopic, results of molecular modifications of the major components of bread crumb (water varies the most with time), it is possible to hypothesize a close relationship between the bread consistency and the water content and its distribution within the bread loaf. Many researchers have found that the center slice of the loaf tends to be firmer than the outer slices, but no direct correlations have been proposed with the local moisture content (Ponte et al 1962, Short and Roberts 1971, Redlinger et al 1985, Persaud et al 1990). This article considers the rheological response of bread during aging, taking into account the effective water content in the various areas of the bread.

MATERIALS AND METHODS

Bread

Three types of soft wheat flour bread (Molini di Vigevano, Vigevano, Italy) containing 12.37% protein, 0.44% ash, and 14.75% water were produced. The first type was straight-dough bread made with conventional baker's yeast (Vinal, Casteggio, Italy) fermentation (Fig. 1). The formula consisted of 100 g of soft wheat flour, 60 g of water, 1.5 g of NaCl, and 2 g of compressed baker's yeast. The dough was mixed with a spiral arm mixer (Sottoriva, Marano Vicentino, Italy) for 7 min; after 10 min of rest, it was cut in 150-g pieces. Loaves were proofed at 30°C for 60 min in a climatic cell (Heraeus HC0020, Votsch GmbH, Badingen, Germany), 70% rh and baked for 25 min at 220°C in a forced convection oven (Moretti, Mikro, Marotta, Italy). Baked loaves were cooled down at room temperature for 60 min, wrapped in a plastic film sprayed with an antimold solution (Nizoral Ketoconazole, Janssen, Latina, Italy), and then stored at room temperature.

The second type was a one-stage sour-dough bread *(Lactobacillus brevis* bread) (Fig. 2) made with a pre-ferment containing flour, water, and freeze-dried ferments of a starter culture of *L. brevis* (L-62, Chr. Hansen, Horsholm, Denmark 7). To the basic ingredients was added (in the proportions outlined in Table I) a starter prepared by mixing 800 g of flour with 1,200 ml of water and 1 g of freeze-dried starter culture of *L. brevis* that was left to ferment for 16 hr in a thermostated chamber at 37°C. The optimum time for fermentation was determined on the basis of the kinetic decrease in the pH.

The third type was straight-dough bread with chemical acidification (Lactic acid) (Fig. 3). The dough was prepared as for yeast bread, with the only difference being that lactic acid (CCA Biochem. Chem., D.V. Gorin, Holland) was added to the other ingredients to obtain a dough with a pH value equal to that of *L. brevis* bread.

Moisture Content of the Loaf

The moisture distribution within the central slice of bread loaves of different ages was evaluated. At the end of the cooling stage

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to which the bread was submitted after baking, and after 8, 24, 48, 120, and 300 hr of aging, two samples of each type of bread were unwrapped, keeping the central portion (~2-mm slice). The central portion was divided in seven parts as shown in Figure 4. The slices were assumed to be representative of the crust, the near-crust, the middle zone, and the central zone of the loaf. The moisture content of each zone was evaluated after oven-drying for 12 hr at 105°C; the slices corresponded to the different regions taken from two samples for each of the three bread types examined.

Force-Deformation Tests

Force-deformation tests were conducted using a UTM (Instron 4301, Instron Ltd., High Wycombe, U.K.) equipped with a 10 N load cell and parallel plate device. The dynamometer was interfaced with a PC for automatic data collection and presentation. Force-time response were formatted as ASCII files and analyzed with Lotus software. Original data were converted into strain vs. Henky's deformation, and the modulus of elasticity was calculated from the initial linear region of the curve. Uniaxial compression tests were performed by using 10 samples of each type of bread. Each sample was obtained from the central part of a loaf, cutting a slice 25-mm high by using a miter box, and taking a cylindrical sample at the center of the slice by means of a cork borer. Specimen preparation was done carefully to minimize pretest deformation. The samples were left to relax 5 min before the test in a box covered with a plastic film to avoid significant moisture losses. The test was conducted using a cross-head speed of 50 mm/min. The specimens were deformed to 25% their initial height. The test lasted 7.5 sec and, consequently, moisture changes can be neglected.

Crumb Water Adsorption Index

A crumb suspension in water with a crumb-to-water ratio of 1:3 (w/w) was prepared by soaking bread crumbs in distilled water for 1 hr at room temperature. The suspension was homogenized in a blender (Waring Products, New Hartford, CN) operating for 15 sec at low speed and for 60 sec at high speed. The water adsorption index was evaluated by measuring the amount of water that separates from the suspension after centrifugation for 30 min at 13,000 rpm (3229 centrifuge, Passoni, Milano, Italy). The adsorption index was expressed as percentage of water separated after centrifugation, with respect the initial weight of the suspension.

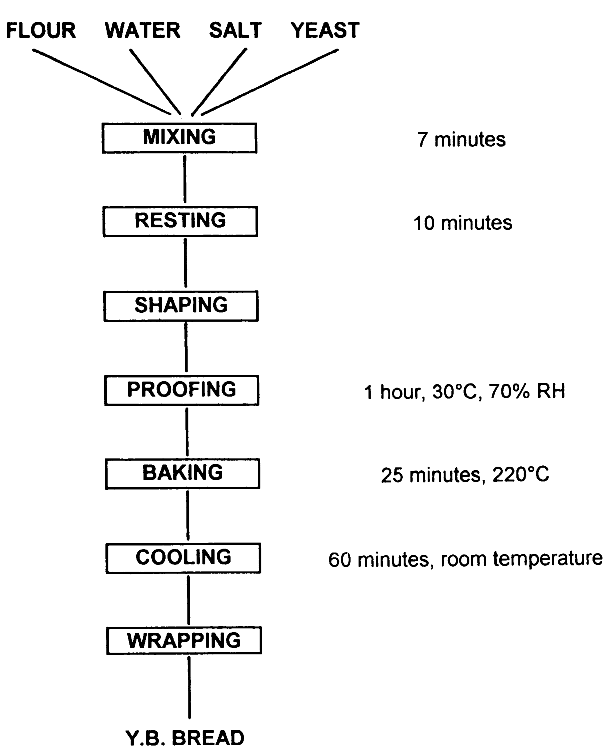

Fig. 1. Flow diagram for preparation of straight-dough bread (YB).

RESULTS AND DISCUSSION

Once the bread is removed from the oven, consistent changes in the moisture content of the loaf occur during the cooling stage. A temperature gradient exists within the bread loaf; the temperature of the crust and of the layers near the crust is noticeably smaller than that of the internal region of the loaf. As a consequence, vapor pressure varies noticeably between the loaf crust and the internal part of the loaf, promoting moisture migration from the crumb to the crust (Stear 1990b). Besides the internal moisture transport, during the cooling stage, part of the moisture migrates from the crust to the surrounding atmosphere at a rate that depends on the mass transfer resistance that subsists at the interface between the bread crust and the atmosphere around it. In industrial applications, as the cooling is performed under forced-convection conditions, the transport

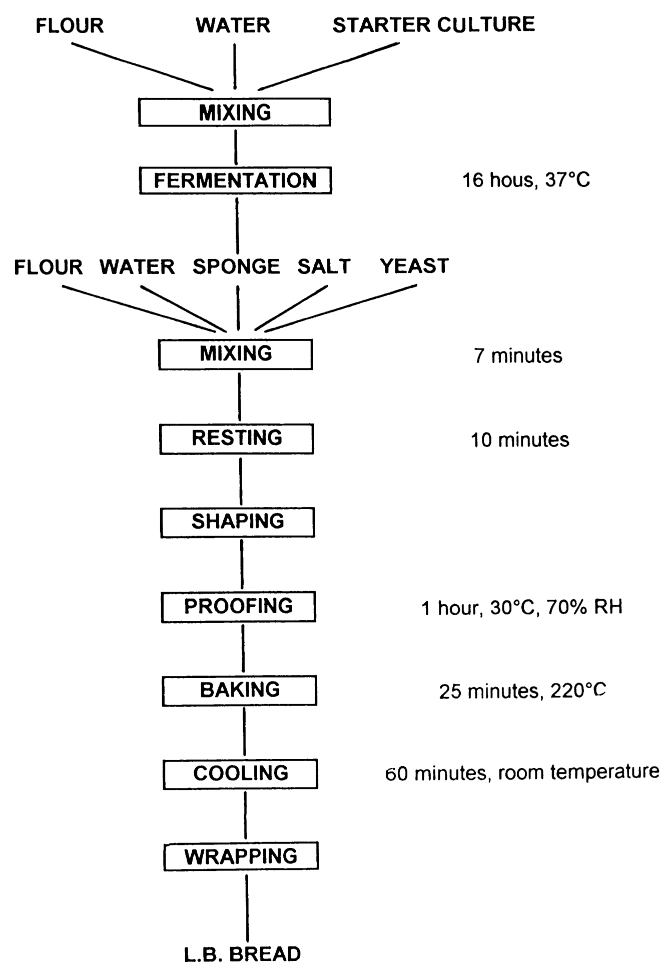

Fig. 2. Flow diagram for preparation of sour-dough bread (LB).

TABLE I
Dough Formulation

	Dough Composition		
Ingredients	**Yeast Bread**	**Sour-Dough Bread**	**Lactic Acid Bread**
Flour (g)	100	100	100
Water (ml)	60	48	60
Yeast (g)	3.75	4.3	3.75
Salt (g)	1	1	1
Extra ingredient (ml)		Starter 36	Lactic Acid 1

resistance is quite low and the equilibrium of both heat and mass transport phenomena is rapidly achieved. In the case of this experiment, thermal equilibrium was reached slowly. Therefore, to avoid any interference of water movement or migration by thermal-diffusion, the starting point of the kinetics was considered to be the end of the cooling stage, or 1 hr after the bread loaves were removed from the oven. Figure 5 shows the bread moisture as a function of the reduced thickness *(X/L)* of bread loaves of different ages. The data presented in Figure 5 refer to lactic acid bread (LA). Similar behavior was obtained for yeast bread (YB) and for sour-dough bread (LB).

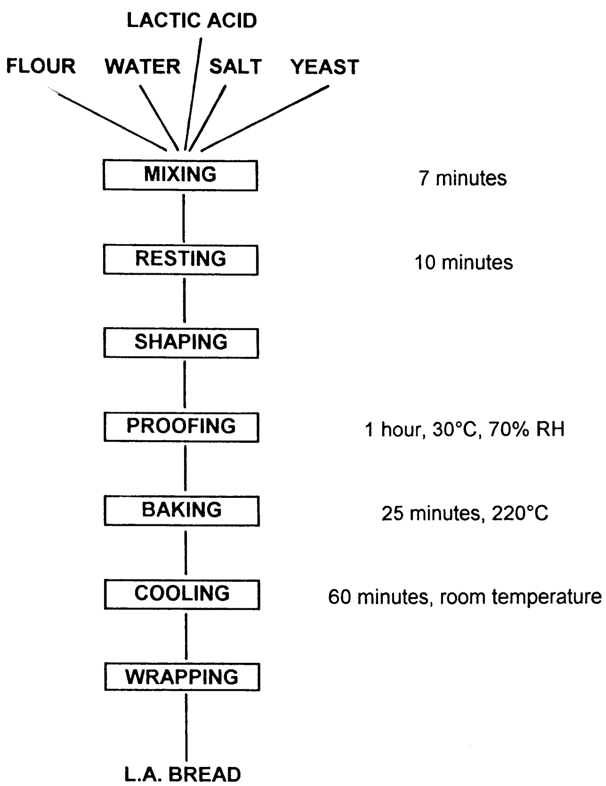

Fig. 3. Flow diagram for preparation of straight-dough bread acidified with lactic acid (LA).

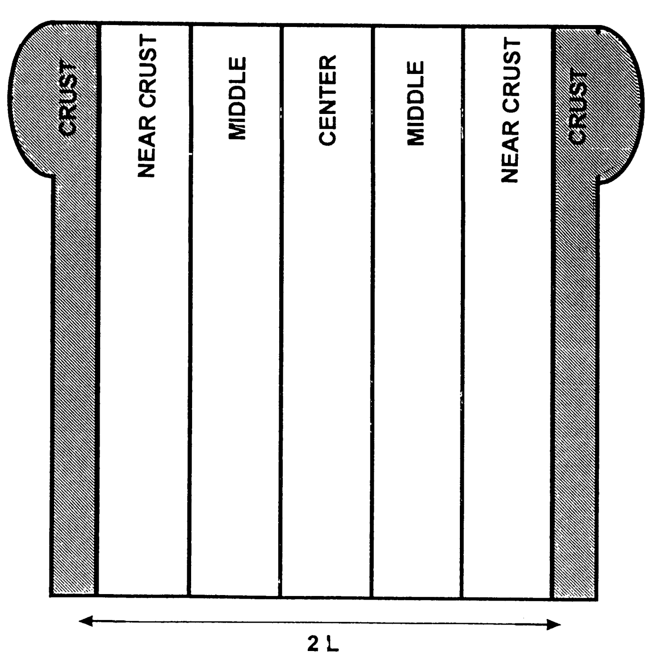

Fig. 4. Location of portions of the central slice from of bread loaf.

The moisture content in the external zone of the loaf increases with the time, while, by contrast, the moisture content corresponding to the central layer diminishes with time. Consequently, the moisture profile levels off as bread aging proceeds. Note that although the moisture profile levels off during aging, after 300 hr of storage, there are still large differences in the moisture content between the central and the external regions of the bread loaf.

When the bread is removed from the oven, the crust is practically moisture free. During the cooling stage, the moisture content of the crust rapidly increases because of moisture migration from the crumb. Although the moisture content in the region near the bread surface further increases during aging, moisture uptake from the crust during storage is quite small compared to rehydration occurring during cooling. In addition, because of the moisture-proof packaging material, mass transfer from the crust to the surrounding area basically stops, while it helps keep the moisture level of the crust low in unpackaged bread. Thus, moisture-proof packaging materials permit the retention of larger amounts of moisture within the crust, which is a quite different situation with respect to unpackaged bread. For simplicity, the local changes in moisture content shown in Figure 6 are for the crust, near the crust, the middle zone, and the central portion.

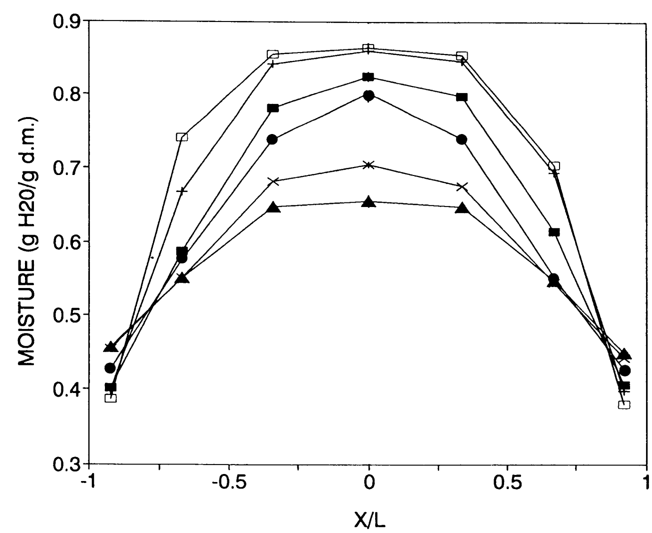

Fig. 5. Effect of time on the moisture profile of lactic acid type bread as a function of reduced thickness (X/L). □ = 0 hr; + = 8 hr; ■ = 24 hr; ● = 48 hr; × = 120 hr; ▲ = 300 hr.

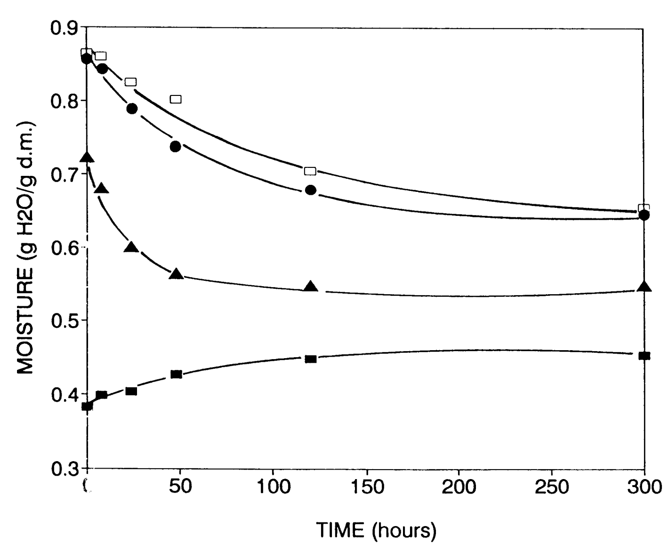

Fig. 6. Effect of time on the moisture of lactic acid type bread in the various region of the central slice. ■ = crust; ▲ = near-crust; ● = middle; □ = center.

During the earlier hours of storage, the moisture level of crumb layers near the crust falls much more rapidly than those located near the center of the loaf.

Figure 7 shows the evolution of the average moisture content of the central portion of the central slice of the bread loaf with the aging time for the three different types of bread. Even though the three types of bread had been formulated by keeping the flour-water moisture ratio constant, the staling kinetics relative to YB, LB, and LA breads start from a different moisture content. This difference is quite evident between YB and the other two types of bread while it is much less significant between LB and LA bread.

This leads to the conclusion that the breadmaking procedures that had been adopted give rise to breads that differ in moisture content and softness. However, these differences do not provide any insight on the behavior of different bread types during aging.

From the consumer's point of view, bread staling is largely associated with the effect of time variations on the textural properties, particularly firmness, of bread. The correlation between bread firmness and moisture content (He and Hoseney 1990) means that the relationship between the staling rate and the dehydration rate subsists. A consumer would consider a bread with a rapidly diminishing moisture content during cooling and storage to become stale faster than another bread with a lower moisture content that dehydrates slowly, although the latter would be judged the less soft. To estimate the bread's aptitude to dehydrate is to describe, by means of suitable phenomenological models, the mass transport phenomena taking place during storage. By assuming that water diffusion throughout the bread follows Fick's law, and that water leaves the crust by natural convection, the simplified solution of the equation of Fick's second law can be used to describe the variation with time of the moisture content of the bread loaf:

$$(X(t) - X_\infty)/(X_o - X_\infty) = \exp(-kt) \tag{1}$$

where k is a parameter for the diffusion rate and the geometry; X_o is the initial mean moisture content of the bread; $X(t)$ is the actual value and X_∞ is the equilibrium value the system approaches as time towards infinity. By plotting the experimental data according to Equation 1 in a semilogarithmic diagram, a straight line should be obtained whose slope provides values for the parameter k.

Figure 8 shows the moisture data relative to the three different types of bread examined, plotted according to Equation 1. As the model predicts, the data follows a straight line and data scattering is in the range of experimental error. The estimated values of the parameter k, $[1/s]$, were: 0.018 for YB ($R2 = 0.966$); 0.010 for LB ($R2 = 0.936$); 0.016 for LA ($R2 = 0.994$). According to these results, LA bread dries fastest, followed by YB, while LB dehydrates the slowest.

These experimental results suggest that textural properties of LA change with aging faster than those of YB or LB. Moreover, the textural properties of the LB vary less when compared to those of the others. To confirm this hypothesis, the development of bread firmness during aging was evaluated by submitting bread to uniaxial compression tests. Because the moisture content within the bread loaf is not uniform, samples were taken only from the central portion of the bread slice; the samples were small to keep the moisture content reasonably uniform.

Figure 9 shows the modulus of elasticity of the three types of bread as a function of storage time. As expected, as the storage time of the bread increases, the rigidity increases, although it is not clear which type of bread has the greatest variation over time. Figure 10 shows the reduced modulus of elasticity calculated by dividing the actual values of the modulus of elasticity by the value of that corresponding to 0 hr of storage. The curves in Figure 10 reveal that the LA bread shows the most variation in rigidity and that the LB bread has the least increase in rigidity during aging.

As a consequence of the different formulations and of the different technologies, bread samples at the end of the cooling stage present different moisture contents and exhibit different behavior with respect to moisture migration in the course of aging. However, breads also differ in the hydrophylic properties of the

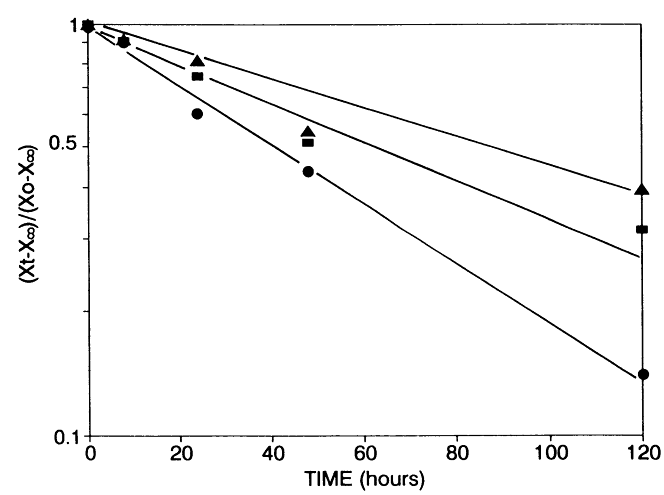

Fig. 8. Bread drying curves plotted according to Equation 1. ■ = yeast bread; ▲ = sour-dough bread; ● = lactic acid bread.

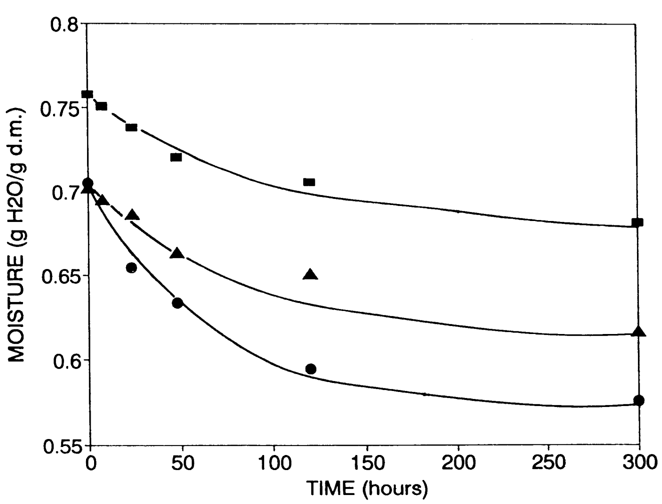

Fig. 7. Average moisture content of the central slice of bread loaf. ■ = yeast bread; ▲ = sour-dough bread; ● = lactic acid bread.

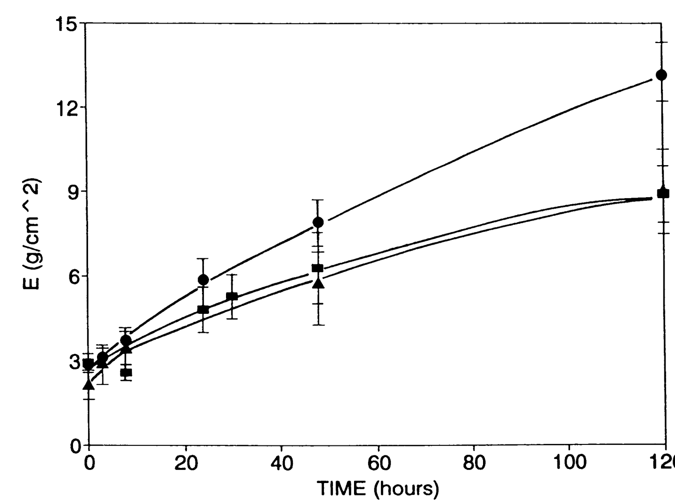

Fig. 9. Modulus of elasticity vs. bread age. ■ = yeast bread; ▲ = sour-dough bread; ● = lactic acid bread.

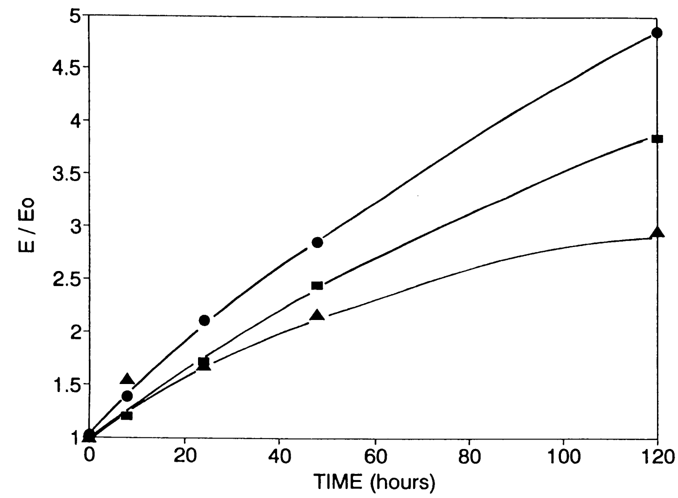

Fig. 10. Reduced modulus of elasticity vs. bread age. ■ = yeast bread; ▲ = sour-dough bread; ● = lactic acid bread.

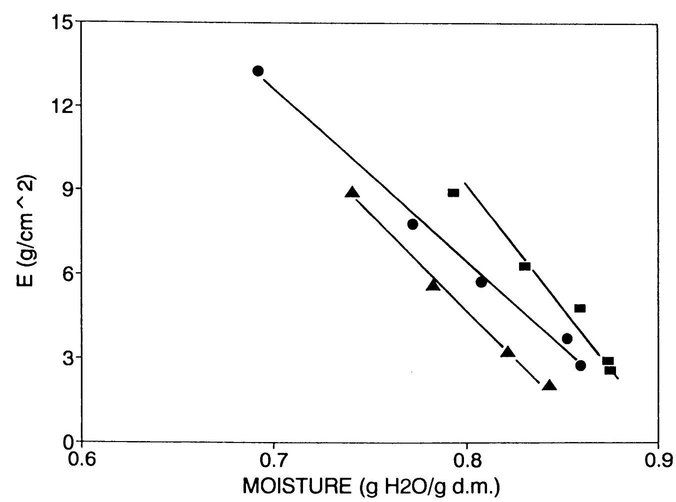

Fig. 11. Modulus of elasticity vs. bread moisture content. ■ = yeast bread; ▲ = sour-dough bread; ● = lactic acid bread.

constituents (Kulp et al 1985, Lonner and Preve-Akesson 1989; Stear 1990b) and in the degree of starch gelatinization. Thus, bread firmness may be influenced by these additional factors and not only by water content.

Figure 11 shows values of the modulus of elasticity for the three type of breads (previously presented in Fig. 9) plotted against the average moisture content of the samples. As expected, the rigidity increases for each bread as the moisture level decreases. However, at a given moisture content, there are large differences of rigidity among the three types of bread. In particular, the LB bread always turns out much softer, regardless of the moisture content. Independent of the moisture content, YB bread is more rigid than is LA bread. However, its rigidity increases more slowly with time. Moisture diffuses more slowly in YB bread than it does in LA. This suggests that the ability of YB to retain water molecules is greater than that of LA. Figure 12 shows the amount of water in the bread that separates after centrifugation while increasing the age of the bread. According to the above hypothesis, the amount of water that separates from suspensions made with LA bread is always larger than that which separates from suspensions containing LB and YB bread.

CONCLUSIONS

The evolution of moisture distribution throughout the loaf during bread staling, and the study of the relationship between transport and mechanical properties represent an interesting

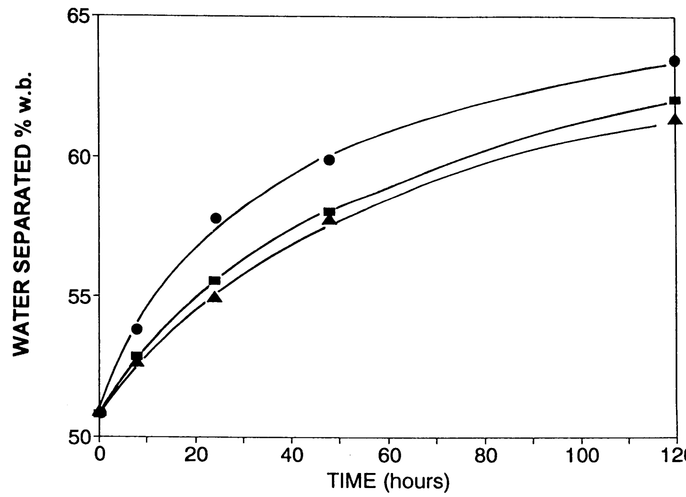

Fig. 12. Percentage of water separating from bread in water suspensions after centrifugation. ■ = yeast bread; ▲ = sour-dough bread; ● = lactic acid bread.

experimental approach to investigate different solutions for an hypothesis to slow down the staling rate. We have explored the possibility of describing the bread staling process of bread by mathematical models of water migration and equilibration between crumb and crust of the loaf. A phenomenological evaluation of the process have been proposed. The experimental data indicate the close connection between residual moisture content in the loaf and the hardening process during storage. Processes, formulations, or additives that either prevent or delay the onset of staling may hinder dehydration by slowing down diffusion phenomena within the loaf. This study provided further evidence that the accumulation of substances with an acid reaction derived from fermentation produce a definite antistaling action, as opposed to the role of lactic acid of chemical origin.

Further biochemical investigation is necessary to explain the behavior observed. Particular attention must be paid to modifications in the hydrophilic properties and to swelling and breakdown of proteins induced by dough acidification.

LITERATURE CITED

AVITAL, Y., MANNHEIM, C. H., and MILTZ, J. 1990. Effect of carbon dioxide atmosphere on staling and water relations in bread. J. Food Sci. 55:413.

BAKER, A. E., DOERRY, W. T., and KEMP, K. 1986. Instron factors involved in measuring crumb firmness. Cereal Foods World 31:193.

GHIASI, K., HOSENEY, R. C., and LINEBACK, D. R. 1979. Characterization of soluble starch from bread crumb. Cereal Chem. 56:485.

GHIASI, K., HOSENEY, R. C., ZELEZNAK, K., and ROGER, D. E. 1984. Effect of barely starch and reheating on firmness of bread crumb. Cereal Chem. 61:281.

HE, H., and HOSENEY, R. C. 1990. Changes in bread firmness and moisture during long-term storage. Cereal Chem. 67:603.

HEBEDA, R. E., BOWLES, L. K., and TEAGUE, W. M. 1991. Use of intermediate temperature stability enzyme for retarding staling in baked goods. Cereal Foods World 36:619.

HIBBERED, G. E., and PARKER, N. S. 1985. Measurement of the compression properties of crumb. J. Texture Stud. 16:97.

HOSENEY, R. C. 1985. Components interaction during heating and storage of baked products. Page 216-226 in: Chemistry and Physics of Baking. J. M. V. Blanshard, P. J. Frazier, and T. Galliard, eds. Royal Society of Chemistry: London.

HOSENEY, R. C. 1992. Interaction of protein and starch in dough and bread. Communication. 9th Int. Cereal and Bread Congress: Paris.

JANKIEWICZ, M., and MICHNIEWICZ, J. 1987. The effect of soluble pentosans isolated from rye grain on staling of bread. Food Chem. 25:241.

JOENSSON, T., and TOERNAES, H., 1987. The effect of selected surfactants on bread crumb softness and its measurements. Cereal Foods World 32:482.

KOU, Y., and CHINACHOTI, P. 1991. Structural damage in bread staling as detected by recoverable work and stress-strain model analysis. Cereal

Foods World 36:888.
KULP, K., CHUNG, H., MARTINEZ-ANAYA, M. A., and DOERRY, W. 1985. Fermentation of water ferments on bread quality. Cereal Chem. 62:55.
LEITE, D. M. B., PIAZZA, L., and MASI, P. 1990. Characterization of bread staling process by means of an Instron universal testing machine operating in dynamic mode. Pages 311-319 in: 3rd European Rheology Conference. D. R. Oliver, ed. Elsevier Applied Science: Barking, England.
LONNER, C., and PREVE-AKESSON, K. 1989. Effects of lactic bacteria on the properties of sour-dough bread. Food Microbiol. 6:19.
MARTIN, M. L., ZELEZNAK, K. J., and HOSENEY, R. C. 1991. A mechanism of bread firming. I. Role of starch swelling. Cereal Chem. 68:498.
MARTIN, M. L., and HOSENEY, R. C. 1991. A mechanism of bread firming. II. Role of starch hydrolyzing enzymes. Cereal Chem. 68:503.
NUSSINOVITCH, A., ROY, I., and PELEG, M. 1990. Testing bread slices in tension mode. Cereal Chem. 67:101.
PERSAUD, S. N., FAUBION, J. M., and PONTE, J. G., JR. 1990. Dynamic rheological properties of bread crumb. I. Effects of storage time, temperature and position in the loaf. Cereal Chem. 67:92.
POMERANZ, Y., and SHELLENBERGER, J. M. 1971. Sensory attributes and bread staling. Page 169-189 in: Bread Science and Technology. Y. Pomeranz and J. M. Shellenberger, eds. Avi: Westport, CN.
PONTE, J. G., JR., TITCOMB, S. T., and COTTON, R. H. 1962. Flour as factor in bread firming. Cereal Chem. 39:437.
REDLINGER, P. A., SETSER, C. S., and DAYTON, A. D. 1985. Measurements of bread firmness using the Instron universal testing instrument: Differences resulting from test conditions. Cereal Chem. 62:223.
ROEWE, P., LORENTZ, K., and KULP, K. 1982. Staling of variety breads. Lebensm. Wiss. Technol. 15:263.
ROGER, D. E., ZELEZNAK, K. J., LAI, C. S., and HOSENEY, R. C. 1988. Effect of native lipids, shortening, and bread moisture on bread firming. Cereal Chem. 65:398.
ROGER, D. E., DOESCHER, L. C., and HOSENEY, R. C. 1990. Texture characteristics of reheated bread. Cereal Chem. 67:188.
SHAKRA, A. M., and SHERMAN, P. 1984. Evaluation of bread firmness by Instron compression tests. Rheol. Acta 23:446.
SHORT, A. L., and ROBERTS, E. A. 1971. Pattern of firmness within a bread loaf. J. Sci. Food Agric. 22:470.
SLADE, L., and LEVINE, H. 1991. Starch retrogradation, the kinetics of staling and the effect of sugar-moisture management aspect on staling. In: Beyond water activity: recent advances based on an alternative approach to the assessment of food quality and safety. CRC Crit. Rev. Food Sci. Nutr. 30:115-360.
SPICHER, G. 1983. Bread quality and preservation. Page 70-76 in: Biotechnology, Vol. 5. Food and Feed Production with Microorganisms. G. Red, ed. Verlag Chem.: Weinheim, Germany.
STEAR, A. C. 1990a. Chemical changes in yeasted doughs during fermentation. Pages 479-491 in: Handbook of Breadmaking Technology. Elsevier Science: Barking, England.
STEAR, A. C. 1990b. Moisture movements during the cooling and maturation of bread. Pages 641-649 in: Handbook of Breadmaking Technology. Elsevier Science: Barking, England.
SWYNGEDAU, S., NUSSINOVITCH, A., ROY, I., PELEG, M., and HUANG, V. 1991. Comparison of four models for compressibility of bread and plastic foams. J. Food Sci. 56:756.
WHILLOFT, 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.
ZELEZNAK, K. J. and HOSENEY, R. C. 1986. The role of water in the retrogradation of wheat gels and bread crumb. Cereal Chem. 63:407.

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