Several authors (Baker and Mize 1939, Walden 1955, Audidier 1968) have shown the temperature profile of bread baked in a conventional oven. According to their results, any specific point in the internal crumb passed through the 58–78°C temperature range in less than 3 min. Baking pup-loaves with a linear rate of heating in an ERO extended the window of enzyme activity to 7 min.

During baking, starch granules swell, and amylose is partially leached from the granules. Starch granules are embedded in a continuous gluten matrix. During heating, the partially leached amylose at the surface of the granule may entangle with gluten fibrils. Fewer swollen starch granules and solubilized starch molecules in ERO bread may have fewer and/or weaker entanglements with gluten.

If the slow rate of heating (and thus the longer window of activity) resulted in bread not firming, then heating at a rapid rate would eliminate differences between conventional-oven and ERO breads. Applying a higher voltage across the electrodes resulted in a rapid temperature rise. Baking bread at the maximum rate of heating in an ERO resulted in a 1-min window of activity. However, rapid baking in the ERO did not change the firming profile relative to a slower baking rate. Similarly, extending the window of activity to 15 min did not slow the rate of firming (Fig. 5). Therefore, the mechanism by which ERO bread expressed an antifirming effect was not a result of an increased window of enzyme activity.

Effect of Baking Time on Crumb Properties

Degree of starch swelling (pasting) is known to be affected by the quantity of water present and by the temperature (Derby et al 1975). Baking time may also affect the water-hydration capacity of bread crumb (Yasunaga et al 1968). Time and temperature were monitored during ERO baking. As baking time above 95°C increased, firmness on day 1 and water-hydration capacity increased. The effects of variation in baking time on moisture content, water-hydration capacity of crumb, and firmness of ERO-baked bread are shown in Table II. Interpretation of firmness values is confounded by changes in moisture and baking time. Low-moisture bread is known to firm at a fast rate; however, ERO bread firmed at an even faster rate within 24 hr of storage than would be expected for conventional-oven bread. With ERO bread, a 10% decrease in moisture content resulted in a 540 *g* increase in force in crumb firmness. Rogers et al (1988) air-dried conventionally baked bread. Interpretation of their results indicated that a similar 10% variation in moisture resulted in a difference of about 200 *g* of force (firmness) on day 2.

Effect of Moisture Migration

One characteristic of ERO-baked bread is the absence of a dry crust. The exterior 5–10 mm of ERO bread had 47% moisture, whereas the interior crumb had 35% moisture. The water relationship between crumb and crust is opposite to that of conventionally baked bread. Pup-loaves baked in a conventional oven had 44% moisture in the freshly baked crumb and less than 10% moisture in the crust. The basic principles of vaporization and condensation can explain the difference in moisture between ERO and conventional-oven bread (Sluimer and Krist-Spit 1987). The increased moisture in the exterior region of ERO bread is a result of moisture condensation. The outer edges of ERO bread are in contact with cool surfaces (plexiglass and the metal electrodes). During baking, water vaporizes and subsequently condenses on cooler surfaces.

During baking in a conventional oven, heat penetrates from the exterior to the interior of the loaf. Water condenses on cooler surfaces; therefore, as heat is conducted to the interior, water first condenses on the cooler, or less heated, internal crumb. More water available to starch granules in the interior of the loaf may permit more starch swelling. This may be one explanation for the greater hydration capacity of bread baked in an ERO vs. a conventional oven.

A Role of Monoglyceride

It is well known that bread supplemented with monoglyceride firms at a slower rate than does bread without shortening. The effect of lipids on bread firming is shown in Figure 6. Bread supplemented with 2% monoglyceride without the addition of shortening had a firming profile similar to that of bread baked with 3% shortening. Breads baked without shortening or from defatted flour without added shortening firmed at the same rate during five days of storage.

The hydration capacity of bread crumb indicated that

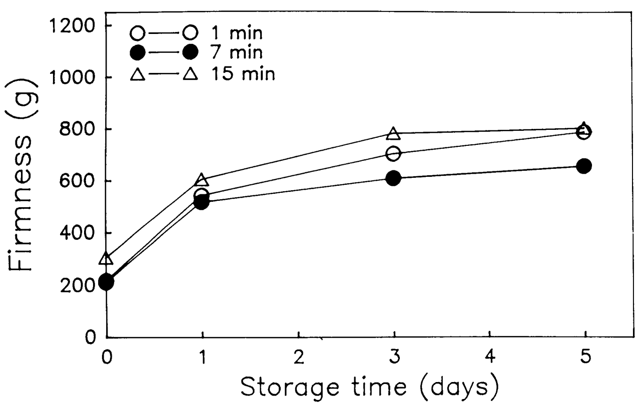

Fig. 5. Effect of heating rate (and, thus, length of window of activity) on bread firmness.

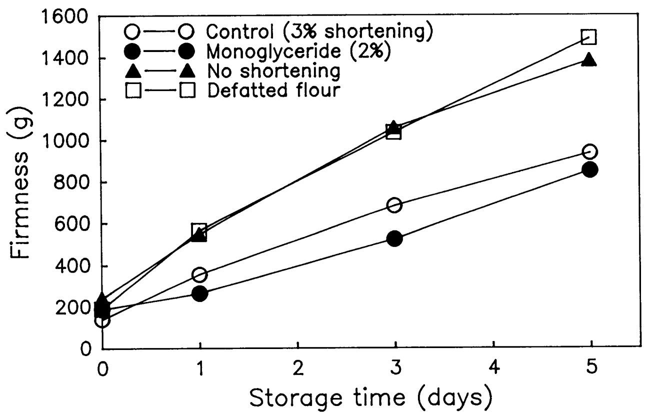

Fig. 6. Effect of lipids on firming profile of conventionally baked bread during five days of storage.

TABLE II
Effect of Baking Time on Crumb Properties of Bread Baked in an Electric Resistance Oven

Heating Time Above 95°C (min)	Moisture (%)	Firmness on Day 1 (*g*)	Hydration Capacity[a]
1	35.5	300	2.56 ± 0.06
8	30.1	523	2.75 ± 0.02
21	26.6	840	2.98 ± 0.08

[a]SD within the same day.

TABLE III
Effect of Lipids on Starch Swelling

Treatment	Hydration Capacity[a]
Control (3% shortening)	3.02 ± 0.08
Monoglyceride (2%)	3.03 ± 0.08
Defatted flour	3.28 ± 0.03
Without shortening	3.27 ± 0.02

[a]SD between days.

shortening and monoglyceride decreased starch swelling during baking relative to that of bread baked without shortening. No significant difference was noted in crumb hydration capacity between breads baked without shortening and bread baked from defatted flour (Table III).

A Theory of Bread Firming

Rate of heating in an ERO was not a factor that affected bread firming. However, temperature and baking time above 95°C were directly related to bread firming, as was hydration capacity of bread crumb. Antifirming substances such as shortening and monoglyceride restrict starch swelling during baking. The evidence presented here suggests that starch swelling is a factor involved in determining the rate of bread firming. The effect of protein quality on bread firming (Maleki et al 1980) may be explained in terms of interactions among swollen starch granules, partial solubilization of starch molecules, and protein. He and Hoseney (1991) demonstrated that poor quality flours (low loaf volume) had more hydrophilic properties than did good quality flours. Given that poor quality gluten would interact more strongly with starch granules in dough, then these interactions would also be stronger during and after baking. Therefore, bread from poor quality flour firms at a faster rate.

During baking, interactions (cross-links) occur between gluten and starch. During staling, as the crumb loses kinetic energy, interactions increase in number and strength. Gluten is the continuous phase, and remnants of starch granule are the discontinuous phase. Because refreshening bread restores freshness, the cross-links between gluten and starch that contribute to bread firming must be relatively weak, possibly hydrogen bonds. A model depicting a mechanism of bread firming and the role of starch swelling is presented in Figure 7. The protein fibrils represent the continuous gluten phase. The discontinuous phase is represented by starch remnants and partially leached amylose.

During baking, monoglycerides and shortening interact with starch molecules and decrease starch swelling. Because starch granules are less swollen, less solubilization of starch molecules occurs. With less surface area exposed to gluten, fewer and/or weaker cross-links occur with protein; therefore, the firming rate is reduced. Theoretically, monoglyceride, shortening, and water can plasticize gluten and decrease bread firmness. In summary, fewer and/or weaker entanglements and cross-links between starch and gluten result in reduced bread firming.

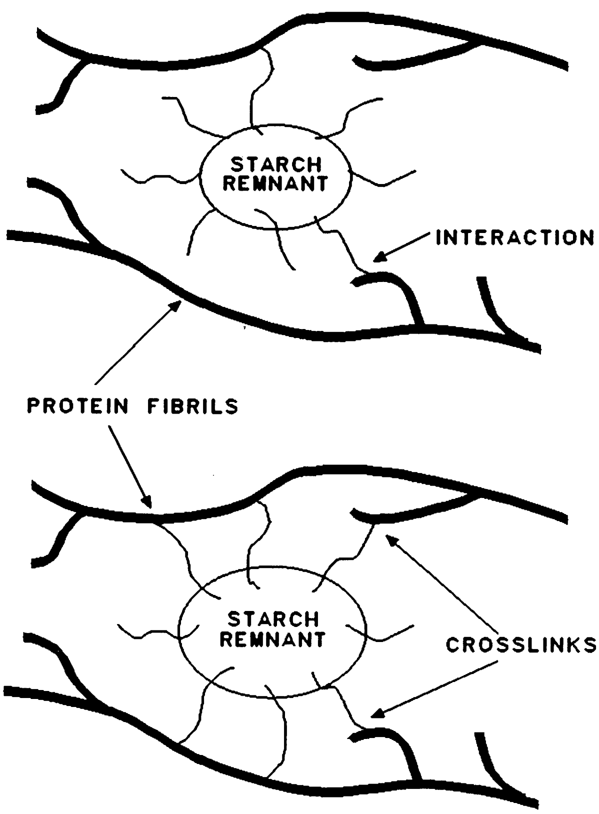

Fig. 7. Model of a mechanism of bread firming and the role of starch swelling.

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