



**HAL**  
open science

## Impact of the chilling conditions on the kinetics of staling of bread

Alain Le-Bail, Guénaelle Leray, Annick Perronnet, Guillaume Roelens

► **To cite this version:**

Alain Le-Bail, Guénaelle Leray, Annick Perronnet, Guillaume Roelens. Impact of the chilling conditions on the kinetics of staling of bread. *Journal of Cereal Science*, 2011, 54 (1), pp.13-19. 10.1016/j.jcs.2010.10.007 . hal-02562013

**HAL Id: hal-02562013**

**<https://hal.science/hal-02562013>**

Submitted on 18 Sep 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Impact of the chilling conditions on the kinetics of staling of bread

Alain Le-Bail<sup>a,b,c,\*</sup>, Guenaelle Leray<sup>a,b,c</sup>, Annick Perronnet<sup>d</sup>, Guillaume Roelens<sup>e</sup>

<sup>a</sup> ONIRIS, UMR 6144 GEPEA CNRS, Nantes F-44307, France

<sup>b</sup> CNRS, Nantes F-44307, France

<sup>c</sup> LUNAM, Université Nantes Angers Le Mans, France

<sup>d</sup> Institut de Recherche en Génie Civil et Mécanique (GeM), UMR CNRS 6183, Équipe Etat Mécanique et Microstructure, C.R.T.T., UNAM, 37 Bd de l'Université, BP406 44602 St-Nazaire cedex, France

<sup>e</sup> Université de Nantes, CRTT, UMR GEPEA, CNRS 6144, LUNAM - 37, Bd de l'Université, BP406 44602 St-Nazaire cedex, France

Breads were chilled at room temperature or using a vacuum chilling process. The staling rate was studied after partial baking and after the final baking. Vacuum chilled breads (VCBs) exhibited a higher moisture loss than conventionally chilled bread (CCB). A higher enthalpy of melting of amylopectin crystals was observed for VCB in comparison to CCB.

VCB had a negative effect on the texture of the bread. The hardness of the crumb of VCB was increased by 20% at the end of staling and the kinetics of staling was 10% faster for VCB in comparison to CCB. After 12 days of storage at 4 °C, a second and final baking was applied to the bread. The staling rate of VCB was almost two times that of CCB. The staling rate of CCB was unchanged in comparison to the staling rate after partial baking. Data on the enthalpy of melting of amylopectin showed that the same amount of amylopectin was formed at the end of staling for CCB after part baked process and after full baking process. Beside, the VCB showed a higher amount of recrystallized amylopectin (10%) at the end of the staling which followed the partial baking.

## 1. Introduction

Bread baking addresses different challenges in terms of quality. Each unit operation involved in the bread making procedure may play a role in the final quality of the bread. In the case of partially baked (which can eventually be frozen), the number of stages involved in the baking procedure is increased in comparison to direct bread making. In particular the bread has to be baked a second time after storage.

The refrigeration step after partial baking has not been investigated very much in the existing literature. Grenier (2000) and Grenier et al. (2002) have studied the impact of chilling conditions on moisture and on cooling rate of bread. A pan bread was used for

this study. Chilling time and water losses were assessed for selected air temperatures between 5 and 20 °C. Results showed that high air temperature increased chilling time and decreased water loss. Cooling rate was high at the beginning of the cooling and decreased with time during chilling due to intense evaporation–condensation in the crumb. A higher cooling rate was observed at surface than at center and was confirmed by a higher water loss at surface of the product. Monteau et al. (2004a, 2004b) studied the influence of water spray on bread during post baking chilling with the objectives of reducing mass loss and of increasing evaporative cooling.

Results obtained by Monteau et al., (2004a, 2004b) showed that post baking chilling with water spraying did not seem to significantly improve the chilling rate, but can help to limit water losses. The mathematical model developed for this study showed that the temperature gradient in the bread during chilling is modified when water is sprayed on the surface.

Vacuum cooling has been described in several recent publications (Sun and Zheng, 2006). Vacuum cooling can be applied to a wide range of products, in particular to porous products such as bread. Vacuum cooling consists in placing a food in a vessel whose pressure is decreased. The reduction of the pressure results in a lowering of the boiling temperature of water. Therefore, the reduced pressure enhances the evaporation of the water contained in food. This results in an efficient refrigeration of food, in particular

*Abbreviations:* CCB, conventionally cooled bread; E, Young modulus of the bread crumb (MPa);  $E_0$ , Young modulus of the bread crumb at initial time (MPa);  $E_{\infty}$ , Young modulus of the bread crumb at end of staling (MPa); VCB, vacuum cooled bread;  $\Delta H_0$ , melting enthalpy of amylopectin in the crumb at initial time (J/g<sub>dm</sub>);  $\Delta H_{\infty}$ , melting enthalpy of amylopectin in the crumb at end of staling (J/g<sub>dm</sub>); t, time (days);  $\tau$  or  $\tau'$ , time constant of first order model (days);  $\rho$ , density of the crumb (kg/m<sup>3</sup>);  $\varepsilon = \Delta L/L$ , strain of the sample during compression (dimensionless).

\* Corresponding author. ONIRIS, UMR 6144 GEPEA CNRS, Nantes F-44307, France. Tel.: +33 2 51 78 54 54; fax: +33 2 51 78 54 67.

E-mail address: alain.lebail@oniris-nantes.fr (A. Le-Bail).

porous food with the consequence of a certain loss in moisture which can hardly be avoided. Vacuum cooling is undeniably very well adapted to a porous matrix rich in water. Porous matrices are poorly conductive and address huge difficulties in terms of heat removal. Attempts to vacuum cool bread were made in the US in 1929 (Ovadia, 1996; Panschar, 1956). Many applications in the baking area have been done and are still used but the expected success doesn't seem to be fully obtained; this comes maybe because of the cost of the equipment and of the difficulty linked to moisture loss. APV baker of Burnley (UK) developed a modulated vacuum cooling system in 1975 based on the patent of Bradshaw (Bradshaw, 1975, 1976). APV vacuum chilling systems have been used by different companies; vacuum modulation permitted better control of the moisture loss. Other companies such as RF-SYSTEMS in Italy have developed a large vacuum cooler using a water ring pump. Water ring pumps can absorb gas containing moisture and particles but have the disadvantage of substantial water consumption. RF-SYSTEMS has for example equipped most of the Panettone industry in Italy. Semi continuous systems have been developed with a high production rate of up to 6 ton/h. The company Hortsmann in Germany has also developed vacuum cooling systems applied to the baking sector. They propose some specific solutions to reduce the moisture loss.

Vacuum cooling is fast. It reduces the cooling time of any bread from one or more hours to 2–4 min depending on the performance of the pumping system. It results in an expansion of the loaf. When specific gas is used to return to atmospheric pressure, (e.g. CO<sub>2</sub> or mixtures of CO<sub>2</sub> with N<sub>2</sub>), vacuum cooling permits injection of the gas at the core of the product and by the way to prolong the shelf life (with respects to molds growth). However, it dries the loaf more than conventional cooling. This is a critical issue for bakery products which are low profit foods. Recently, Primo-Martín et al. (2008) investigated the impact of different cooling processes including vacuum cooling on crust characteristics. It was observed that vacuum cooling resulted in rapid evaporative cooling which in turn yielded breads with lower moisture content in the crust than the air cooled breads. Both fracture behavior and sound emission of the crust were affected by vacuum cooling. As an advantage, Primo-Martín et al. (2008) showed that VCB (Vacuum Cooled Bread) had a better retention of crust crispness than CCB (Conventionally Cooled Bread). More recently Anonymous (2008) indicated that vacuum chilling delays the staling. The explanation proposed was that the gluten in the baked goods intensely gelatinizes during the cooling phase under vacuum. This slows down retrogradation and keeps rolls and bread fresher for a longer time.

Texture is maybe the most studied physical parameter of bread. Texture of the crumb, is linked to the mechanical properties of the material constituting the foam and to its structure (Liu and Scanlon, 2003). Baik and Chinachoti (2000) showed that the staling rate of bread with crust was faster than the staling of bread without crust. This phenomenon was attributed to the equilibration of moisture between the crust and the crumb. During storage, the crust traps moisture coming from the crumb, resulting in a dehydration of the crumb and a faster staling in the case of bread with crust. However, some of the water diffuses through the crust and some of the water trapped by the crust evaporated to the atmosphere.

The impact of vacuum cooling on bread staling has not been clearly evaluated in the existing literature. Some authors claimed that it may have an effect on the staling rate and on the texture of bread but there is no clear evidence about this matter. The objective of this study was to assess the impact of vacuum cooling on the staling rate of bread made from whole meal flour with a sourdough technology. Results on the kinetics of staling are presented based on texture analysis and on the melting energy of amylopectin, which recrystallizes during staling.

## 2. Materials and methods

### 2.1. Bread-making procedure

A sourdough has been provided by a local baker. The dough was made of whole meal flour. After mixing the sourdough with the fresh flour, the dough was left for rest and pre fermentation for 2 h. Then the dough was flattened and was cut as rectangular sections of 70 g each. The dough pieces were installed in a proofing cabinet at 23–25 °C, 80% R.H. for 3 h.

Baking was done in a static sole oven (MIWE Condo, Arnstein, Germany) at 250 °C for 10 min 200 ml of steam was injected at the beginning of baking. The breads were then cooled down either at ambient temperature (CCB = Conventionally Cooled Bread) or in a vacuum cooler (VCB = Vacuum Cooled Bread). After cooling down to room temperature, the breads were installed in a sealed plastic pouch and were stored in a refrigerated cabinet at 4 °C. This temperature was optimal for our recipe and baking procedure. It allowed the monitoring of the kinetics of staling over a 2 week period, which was convenient in terms of timing (e.g. 3 DSC runs were needed for each experimental point which makes one day of testing when considering the texture tests which were done on the same day). The cabinet used to store the bread was a domestic refrigeration unit equipped with a fan and a small heating element. An external temperature controller (EUROTHERM, France) was used to control the refrigeration unit. The temperature stability during storage was checked and was  $\pm 1$  °C. The storage temperature was adjusted at 4 °C in order to control the kinetics of staling. Indeed, it is well known that temperature influences the staling which is governed by the recrystallization of amylopectin, mainly that which has been gelatinized during baking (Gray and Bemiller, 2003). Amylose usually recrystallizes during cooling and during the first hours after baking. The second baking was done in the same oven at 220 °C for 15 min 200 ml of steam was injected at the beginning of baking. After the second baking, the breads were placed in a sealed plastic pouch and were stored once again at 5 °C.

Vacuum cooling was done in a prototype system developed in our laboratory (see Fig. 1). A 25 l glass flask is used and is connected to a vacuum pump through a moisture trap. The moisture trap was a heat exchanger connected to a refrigerated bath. A control panel allowed control of the pressure during vacuum cooling. Thermocouple passages were installed, making possible recording of the temperature during cooling. Temperatures in the bread were logged with K type thermocouples (0.3 mm diameter) connected to a data logger (SA 32 - AOIP - France).

### 2.2. Water content of the bread

The water content was determined by drying samples of crumb used for texture analysis. Pieces of crumb were weighted and were placed in a drying cabinet at 104 °C for 96 h. The mass of the samples was measured with a Mettler balance (0.01 g accuracy). 4 samples were considered and the values were averaged. A standard deviation was thus determined.

### 2.3. Analysis of the specific volume of the crumb

The specific volume of the bread crumb was measured by cutting a cylinder of crumb in a slice of known thickness (ca. 15 mm thick  $\times$  3 cm  $\times$  3 cm). Knowing the weight and the dimensions of the sample, the specific volume was calculated in cm<sup>3</sup>/g. Each sample tested for compression was used to determine the specific volume. Six samples were thus examined and the values were averaged.

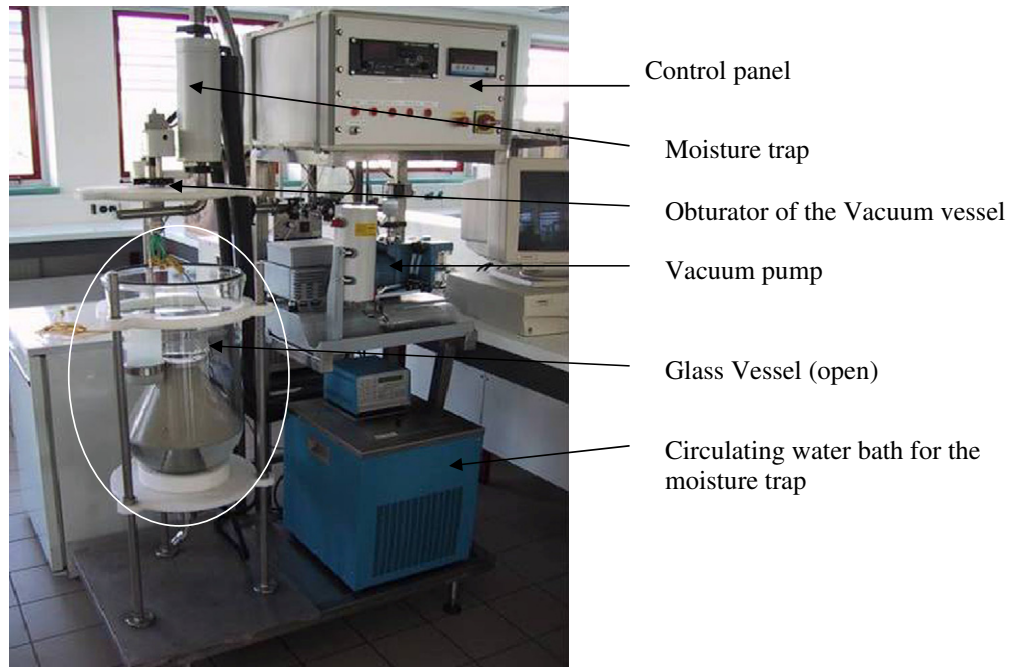


Fig. 1. Overview of the vacuum cooler used for the vacuum cooling tests.

#### 2.4. Analysis of the texture of bread crumb

Measurements were performed after 1 h equilibration at room temperature, the bread being still kept in its plastic pouch to prevent any condensation effect. The texture of bread was determined at day 0 at 20 °C by a compression test with a JJ LLOYD LR5K texturometer. For each measurement, a minimum of 6 slices of 15 mm were used for the compression tests. A cylindrical plunger of 20 mm diameter was used. The velocity of the plunger was 60 mm/min and the compression was done up to 40% deformation. The displacement was logged when the force was higher than 0.1 N. The linear section of the force–deformation plot was used to determine the Young modulus of the crumb. The Young modulus  $E$  in MPa is defined as proposed in equation (1) from the slope of the stress (Force/surface of the plunger) as a function of relative displacement or strain ( $\varepsilon = \Delta L/L$ ).

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \text{ (MPa)} \quad (1)$$

#### 2.5. Calorimetry

Samples were taken from the central section of the crumb. DSC tests were carried out with a PYRIS 6 DSC (PERKIN ELMER). 4 DSC pans were prepared to run 4 different DSC tests with crumb coming from the same sample. The remaining pieces of samples were weighed and the moisture was checked by drying tests in a drying cabinet at 104 °C for 24 h. The moisture of the piece of crumb used for the DSC test was determined separately; this is important to do due to the fact that the enthalpy of melting of amylopectin is given in Joules per gram of dry matter. Each DSC Pan contained ca. 50–70 mg of crumb. A Mettler Toledo balance (accuracy 0.01 mg) was used. The two first DSC runs were programmed as follow. The DSC temperature was equilibrated at 20 °C for 5 min. Then the sample was cooled down to –60 °C at 3 °C/min and was maintained at –60 °C for 10 min. Then a scan was performed from –60 °C to

100 °C with a heating rate of 3 °C/min. The two other runs were similar to the previous ones except that the scan was skipping the subzero phase (no scan down to –60 °C). The temperature scan was performed directly from 20 °C to 100 °C. The two first scans were used to determine the amount of freezable water and the melting enthalpy of amylopectin. Beside, the two additional scans provided two other values of the melting enthalpy of amylopectin. The melting enthalpy of amylopectin and of freezable water  $\Delta H$  was determined in Joules per gram of dry matter ( $J/g_{dm}$ ). The amount of freezable water was obtained by dividing the melting enthalpy of ice by the latent heat of melting of pure water. The results were expressed as grams of freezable water per gram of crumb on a dry matter basis ( $g_{water}/g_{dm}$ ).

Aging was done at 4 °C, breads being packed in sealed plastic pouches and installed in a temperature controlled cabinet. The temperature of 4 °C was chosen so that the kinetics of staling were completed within a 2 weeks time frame, permitting monitoring of the staling process under good conditions. Texture and DSC tests of baked crumb were done at day 0 and followed during staling with a minimum of 4 experimental points. First order kinetic models were used to model the evolution of the melting enthalpy of amylopectin  $\Delta H(t)$  (equation (2)) with  $\Delta H_0$  and  $\Delta H_\infty$  being the melting enthalpy at initial time and for long storage (time =  $\infty$ ). First order kinetics models derived from Avrami models (Avrami, 1940) are commonly used to fit crystallization data and were found to fit quite well our experimental data. A similar equation was used to model the hardening (from the Young modulus  $E(t)$ ) of the bread crumb (equation (3)) with  $E_0$  and  $E_\infty$  being the Young modulus at initial time and for long storage (time =  $\infty$ ). Characteristic times  $\tau'$  and  $\tau$  of equations (2) and (3) were used to compare the kinetics of the two phenomena, namely amylopectin retrogradation and crumb hardening.

$$\Delta H(t) = \Delta H_\infty + (\Delta H_0 - \Delta H_\infty) \cdot e^{-\left(\frac{t}{\tau'}\right)} \quad (2)$$

$$E(t) = E_\infty + (E_0 - E_\infty) \cdot e^{-\left(\frac{t}{\tau}\right)} \quad (3)$$

## 2.6. SEM imaging

The samples were observed with an environmental SEM at 15 kV (ZEISS). Environmental microscopy permits observation of the sample without any treatment that is usually done for most SEM protocols (Drying + gold plating). Observation of the sample was done from a “fresh” piece of crumb. The sample is placed on a temperature controlled sample holder. The temperature of the sample is adjusted as well as the partial vapor pressure of water above the sample to prevent dehydration.

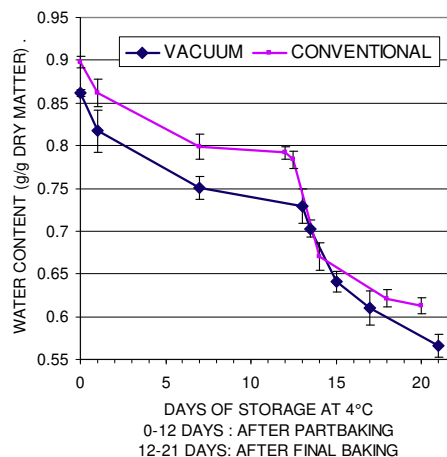
## 3. Results and discussion

Vacuum cooling is quick. This is clearly visible in Fig. 2-a. The temperatures shown in this graph are the mean values of 3 sensors installed in 3 different breads. Conventional cooling was done in still air at 20 °C. For vacuum cooling, time (2–3 min) was needed to connect the thermocouples, to close the vessel and to run the vacuum pump; this explains the small delay at the beginning of the plot. In Fig. 2-b, a focus is done on vacuum cooling of bread equipped with two sensors; one was located 7 mm below the surface of the bread and the other sensor was at the center of the bread. One can see that the two temperatures drop very quickly and at the same rate, demonstrating the great advantage of vacuum cooling in terms of the isotropic refrigeration effect.

The evolution of the moisture content of bread crumb is shown in Fig. 3 for VCB and for CCB. One can see that the VCB is less rich in water than the CCB. This is due to the fact that in the case of VCB, the bread is cooled only by evaporative cooling whereas for CCB, there is a mix of convective heat transfer and evaporative cooling. The initial difference in moisture remains almost unchanged during the first 12 days of staling (corresponding to a part baked bread with a very thin crust). Then, on day 12, the breads have been “fully” baked using our protocol presented in the Material and methods section. The discontinuity in moisture content which corresponds to the moisture loss during the second baking is embedded in between the two points before and after second baking in the plot. The decay of the moisture content after the first and the second baking was attributed to the re equilibration of moisture between the crust and crumb zones.

In our conditions, we didn’t face any specific crust problem. This may be attributed to the fact that during storage (until day 12), the moisture had time to re equilibrate between the crust and the crumb (both for CCB and VCB).

The color of the crust has not been measured in our tests. There was no significant big difference at first glance between the two cooling conditions. After the second baking, the breads were cooled

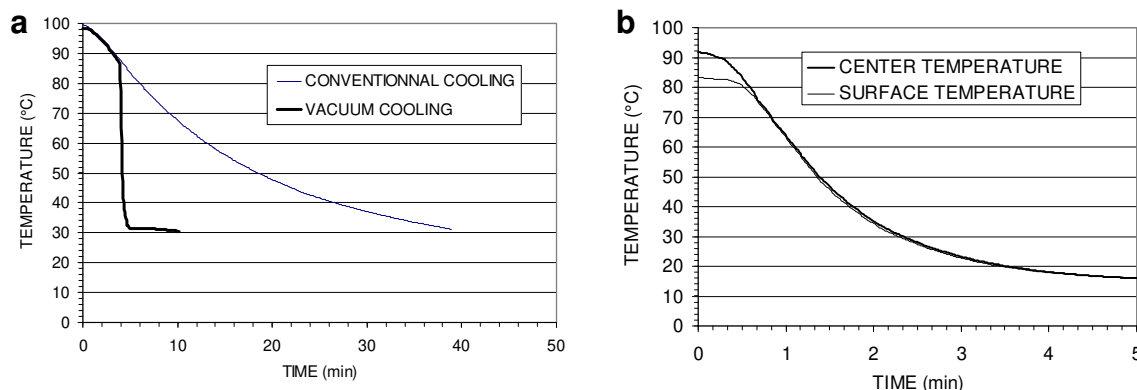


**Fig. 3.** Evolution of the moisture content of the bread crumb during staling. Values until day 12 are for part baked bread stored at 4 °C whereas the values after 12 days correspond to bread after the second baking.

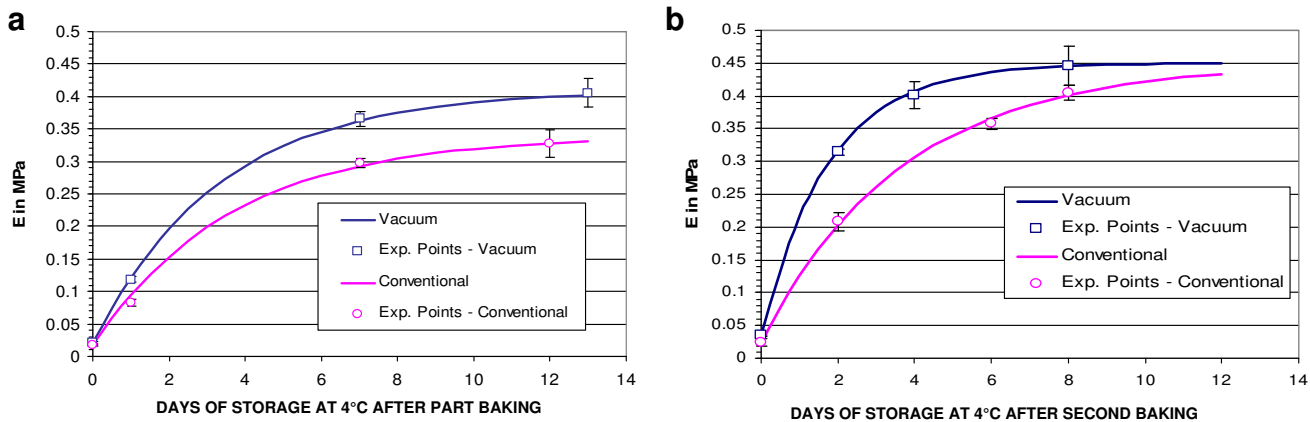
conventionally down to room temperature and were then placed in a storage cabinet at 4 °C (wrapped in a plastic pouch). One can see that, after the second baking, the difference in between the two types of bread was reduced. However, the CCB still contained more water than the VCB.

Kinetics of staling was assessed from the evolution of the texture of the crumb first. This was done after partial baking (from day 0 to day 12) and then after the second baking (from day 12 to day 21). In addition, the melting enthalpy of amylopectin crystals was determined by DSC with the same agenda. Results of texture are shown in Fig. 4-a and -b for texture (Young Modulus) after partial baking and after final baking respectively. Results of enthalpy of melting of amylopectin are shown in Fig. 5-a and -b after partial baking and after final baking respectively.

Regarding the Texture (Young modulus), it is clear that the VCB is harder than the CCB; this can be attributed to a higher moisture loss for VCB. After partial baking, the Young modulus of the two types of bread is increasing at a similar rate (the kinetic parameter  $\tau$  was 3.33 and 3.64 days for VCB and CCB respectively or a 10% difference). In turn, one can see in Fig. 5-a that the appearance of the amylopectin crystals (which is linked to increase of the melting enthalpy) occurs in advance with respect to the increase of the Young modulus during staling. At day 3 the enthalpy of melting has reached its maximum while the Young modulus is stabilized to its maximum value only at day 13 (and even then it seems to continue to increase slightly). Similar observations have been made by



**Fig. 2.** Evolution of the temperature during cooling. Left (2-a): Comparison between conventional air cooling and vacuum cooling. Right (2-b): Focus on vacuum cooling (15 mbar).



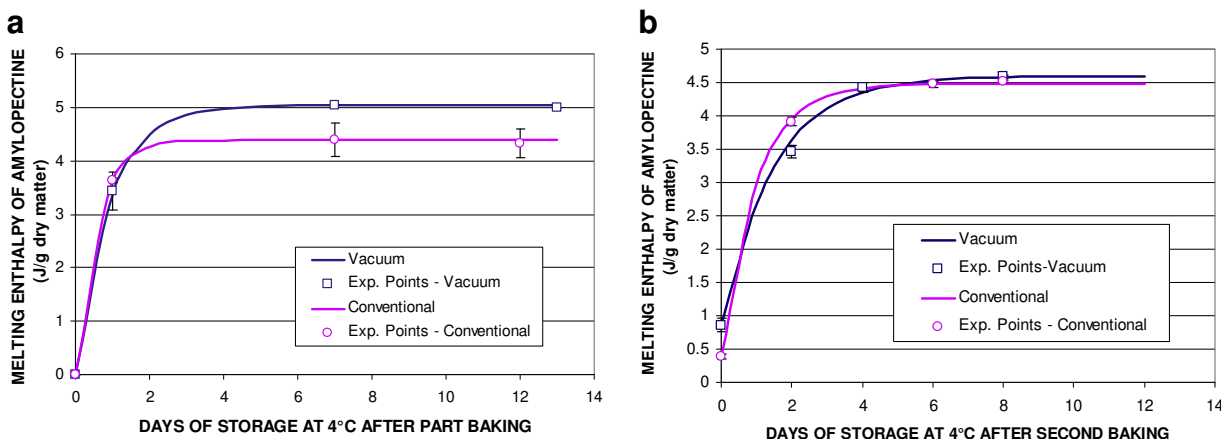
**Fig. 4.** Evolution of the texture of the crumb during staling of conventionally cooled bread and of vacuum cooled bread. Left (a) after partial baking and Right (b) after the second baking.

Le-Bail et al. (2009) with a white flour-soft wheat formulation. However, the difference in time between the rise in amylopectin enthalpy and texture of the crumb was smaller than in the present case. This could be attributed to the fact that in the present study, a flour rich in fiber associated to a sourdough formulation has been used; indeed, it is known by the technologists that such a combination tends to slow down the kinetic of staling in comparison to a “white flour” recipe using yeast as leavening agent. At the end of staling, there was a 20% difference in Young modulus (0.4 against 0.33). Beside, the enthalpy of melting started at zero and ends up at 4.4 and 5 J/g<sub>DM</sub>, for VCB and CCB, respectively making a 14% higher enthalpy of melting of amylopectin for VCB. The concept of rapid cooling of a polymer suspension such as a baked bread crumb may have some impact in terms of crystallization of the polymers. In the case of VCB, the very rapid cooling effect may result in a kind of “quenching”, which in turn could have resulted in a lower amount of crystallized polymers. Even though such a phenomena had happened for VCB, it is likely that during the storage at 4 °C, which is known to be a temperature at which staling rate is in the range of its maximum (Gray and Bemiller, 2003; Guilbot and Godon, 1984; Guinet and Godon, 1994), the crystallization of amylopectin has occurred anyway. This phenomenon and hypothesis could be explored by keeping the bread at lower temperature during staling (e.g. frozen storage). An adverse effect may have happened. The rapid cooling achieved with VCB may have resulted in placing the

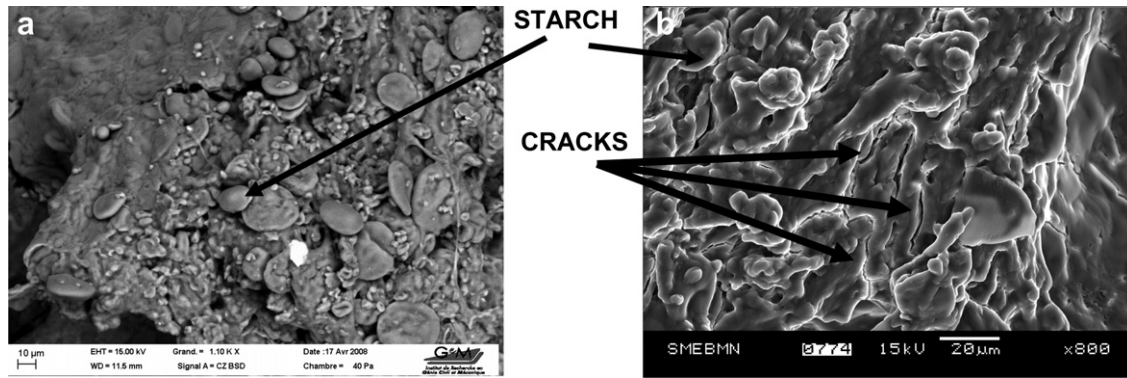
biopolymer in a supercooled state which has favored the formation of multiple nuclei. The situation would then be comparable to rapid freezing of food which is known to generate a higher number of finer ice crystals. The theory of nucleation says that a 1 °C supercooling results in a 10 fold higher nucleation rate (Mazur, 1976, 1984). During storage, the high number of nuclei may have in turn resulted in a higher amount of recrystallized amylopectin. This could explain the higher value of the enthalpy of melting of amylopectin at the end of staling for VCB.

It should be mentioned here that the rate of retrogradation of starch depends strongly on temperature and moisture content. Recrystallization of starch occurs between the glass transition temperature and melting temperature of the starch. The maximum rate of crystallization is around 0 °C according to Guilbot and Godon (1984), which is a temperature close to the storage temperature. One should distinguish the rate of crystal nucleation which is fastest at lower temperatures and the crystal growth rate, which has its maximum at higher temperatures. In addition, the recrystallization rate of starch depends on the water content, roughly increasing in the range 27–50% percent total moisture due to an increasingly effective mobility of the starch chains and decreasing at higher water content. Thus the rate is at a maximum at a water content of about 50%.

Regarding the staling after the second baking, one can see in Fig. 4-b that the VCB and the CCB start the staling with the same



**Fig. 5.** Evolution of the enthalpy of melting of amylopectin during staling of conventionally cooled bread and of vacuum cooled bread. Left (a) after partial baking and Right (b) after the second baking.



**Fig. 6.** SEM images of the crumb (environmental microscopy – the sample has been dried and gold plated). Observation is done from a “fresh” piece of crumb and the partial vapor pressure of water is adjusted above the sample to prevent dehydration. Left (a): conventional cooling - Right (b): vacuum cooling. One can see the cracks observed in the crumb of the sample which has been cooled using vacuum cooling. Starch granules are indicated with arrows.

value of Young modulus. A slight increase of the Young modulus is observed both for initial time and final time (end of staling) after the second staling due to the moisture lost by the bread. There is a larger difference in the Young modulus at the end of the staling after the partial baking (Fig. 4-a) than after the second baking (Fig. 4-b). This difference can be explained by the lower water content of the VCB in comparison with the CCB (see Fig. 3). The difference is smaller after the final baking due to a lower difference in moisture content (see Fig. 3). The CCB samples staled much more slowly than the VCB. In this case (after second baking), the time constant  $\tau$  of the kinetic model was 1.75 and 3.68 days for VCB and CCB respectively (against 3.33 and 3.64 days after partial baking). The staling rate of the CCB is thus almost the same after partial baking and final baking. One should pay attention to the fact that the value  $\tau$  is a kinetic parameter; when regarding the hardness of the crumb, the crumb was indeed harder after the final baking. VCB part baked bread staled this time approximately two times faster than the CCB (the difference was 10% after part baked process alone).

Regarding the enthalpy of melting at day 0 (just after final baking), one can also observe that the value is small and is relatively close to the value for freshly baked bread (for first part baked). This observation is very important. Indeed, the objective of the final baking of partially baked bread is double. On one hand, the formation of the crust is obviously the principle target. On the other hand, the thermal treatment applied to the bread permits to “refresh” the crumb and to reduce the “hardening damage” caused by amylopectin crystals which have trapped the water (which act as a plasticizer) thanks to a mass transfer phenomena from the gels and gluten network contained in the crumb. One can see that concerning this last point, the melting of amylopectin crystals was effectively done. Indeed, when looking at Fig. 5-b, one can see that the melting enthalpy is not zero (as it was for partially baked bread) but starts at a value between 0.5 and 1 J/g<sub>D.M.</sub>. Another very interesting result regarding this figure is that at the end of staling, the enthalpy of melting of amylopectin returns to the value which was observed for CCB, being for the former VCB as well as for the CCB (around 4.5 J/g<sub>D.M.</sub>). After the second baking step, the two types of bread attain very close moisture contents. Since the retrogradation rate is a function of the moisture content, it is not surprising that either bread type undergoes retrogradation at similar rates and to a similar extent. However, this result brings some credit to the assumption proposed earlier about the possible impact of a very rapid cooling on the nucleation rate of amylopectin nuclei.

Results on freezable water are in agreement with the observations of Le-Bail et al. (2009). The freezable water (calculated on

a dry mater basis) decreases during storage. The values decreased from 0.56 to 0.42 for CCB and from 0.53 to 0.35 for CCB and VCB respectively during the 12 days which elapsed after part baking. The specific volume of the crumb was not significantly different between CCB and VCB. Values between 2.77 and 3.03 cm<sup>3</sup>/g have been measured.

SEM pictures are shown in Fig. 6. One of the remarkable differences between CCB and VCB was the presence of cracks and crevasses in the crumb for VCB. This is perhaps due to the sudden pressure drop imposed by VCB. The sudden evaporation of water applied on a soft material (baked crumb) may in turn result in ebullition and possible micro bubble or porosity inside the walls and the material of the crumb. Further investigations are needed to assess if this was due to our efficient pumping system (15 mbar pressure was applied rapidly). It is likely that a better control of the pressure drop at the beginning of the vacuum cooling may reduce this structural problem.

#### 4. Conclusion

The impact of chilling condition on the final quality of bread has been investigated comparing conventionally cooled bread (CCB) and vacuum cooled bread (VCB). VCB is very quick and permits cooling down the bread within a few minutes instead of ca. 1 h for our conditions (70 g breads). The VCB and CCB have been applied to part bread. VCM showed a higher moisture loss than CCB. A higher enthalpy of melting of amylopectin crystals was observed for VCB in comparison to CCB at the end of staling.

The hardness of the crumb of VCB was increased by 20% at the end of staling and the kinetics of staling were 10% faster for VCB in comparison to CCB. After 12 days of storage at 4 °C, a second and final baking was applied to the bread. The staling rate of VCB was this time almost two times faster for VCB in comparison to CCB. The staling rate of CCB was almost unchanged in comparison to the staling rate after partial baking. The VCB showed a significantly higher amount of recrystallized amylopectin (roughly 10% more) at the end of the staling which followed the partial baking. In contrast, at the end of the staling which followed the final baking, the melting enthalpy of VCB returned to a value similar to the one observed for CCB. It is assumed that this phenomena is due to the quick vacuum cooling which may in turn favor the formation of numerous nuclei of amylopectin crystallites and resulting finally in a larger amount of recrystallized amylopectin.

Further investigation is needed to study more in depth the interactions between the cooling rate and the quality parameters of bread. In particular, X ray diffraction would give access to the crystalline

structures of the retrograded starch. Also, the kinetics of pressure drop and of depressurization for VCB could have some impact on the final quality of the bread and could therefore be optimized.

### Acknowledgments

This study was carried out with financial support from the European Commission, FP6, Thematic Area "Food Quality and Safety", FOOD-2006-36302 EU-FRESH BAKE. It does not necessarily reflect its views and in no way anticipates the Commission's future policy in this area. Luc GUIHARD, Christophe COUEDEL and Delphine QUEVEAU are gratefully acknowledged for their help.

### References

- Anonymous, 2008. *New Path. BAKING+BISCUIT* 4, 24–27.
- Avrami, M., 1940. Kinetics of phase change. II. Transformation-time relations for random distribution of nuclei. *Journal of Chemistry and Physics* 8, 212.
- Baik, M.-Y., Chinachoti, P., 2000. Moisture redistribution and phase transitions during bread staling. *Cereal Chemistry* 77, 484–488.
- Bradshaw, W., 1975. *Treatment of Foodstuffs UK*.
- Bradshaw, W., 1976. Modulated vacuum cooling of bakery products. *Bakers Digest* 50, 26–31.
- Gray, J.A., Bemiller, J.N., 2003. Bread staling: molecular basis and control. *Comprehensive Reviews in Food Science and Food Safety* 2, 1–21.
- Grenier, A., 2000. Etude du refroidissement d'un pain en sortie de cuisson. In: *Ecole Doctorale Thermique, Energetique et Matériaux*, p. 30. Nantes.
- Grenier, A., Monteau, J.-Y., Le-Bail, A., Hayert, M., 2002. Effect of external condition on the cooling rate of post baking bread chilling. *Journal of Food Engineering* 55, 19–24.
- Guilbot, A., Godon, B., 1984. Le pain rassis. *Cahier de Nutrition et de Diététique* 19, 171–181.
- Guinet, R., Godon, B., 1994. La Panification Française. In: *Techniques et Documentation - Lavoisier*.
- Le-Bail, A., Boumali, K., Jury, V., Ben-Aissa, F., 2009. Impact of the kinetic of baking on staling rate and on the mechanical properties of crumb and degassed crumb. *Journal of Cereal Science* 50, 235–240.
- Liu, Z., Scanlon, M.G., 2003. Predicting mechanical properties of bread crumb. *Food and Bioproducts Processing* 81, 224–238.
- Mazur, P., 1976. Mechanisms of injury and protection in cells and tissues at low temperature. In: *Les colloques de l'INSERM. Cryoimmunology*, pp. 37–60.
- Mazur, P., 1984. Freezing of living cells: mechanisms and implications. *American Physiological Society* 16, C125–C142.
- Monteau, J.-Y., Cournil, J.-F., Bransolle, P., Hamdami, N., Le-Bail, A., 2004a. Bread chilling with water spraying. In: Jong, P.d.V., Maykel (Eds.), *Foodsim 2004 – 3rd International Conference on Simulation in Food & Bio Industries*. Eurosis, Wageningen, NL, pp. 32–36.
- Monteau, J.Y., Cournil, J.F., Bransolle, P., Hamdami, N., Le-Bail, A., 2004b. Post baking bread chilling: evaluation of water pulverisation on bread surface to control weight loss and cooling rate. In: *12th ICC Cereal & Bread Congress. ICC International, Harrogate, England*.
- Ovadia, D.Z., 1996. Microwave pressure baking and vacuum cooling of bread. In: *Department of Grain Science & Industry, College of Agriculture. Kansas State University, Manhattan, Kansas*.
- Panschar, W.G., 1956. *Baking in America*, p. 122.
- Primo-Martín, C., de Beukelaer, H., Hamer, R.J., van Vliet, T., 2008. Fracture behaviour of bread crust: effect of bread cooling conditions. *Journal of Food Engineering* 89, 285–290.
- Sun, D.W., Zheng, L., 2006. Vacuum cooling technology for the agri-food industry: past, present and future. *Journal of Food Engineering* 77, 203–214.