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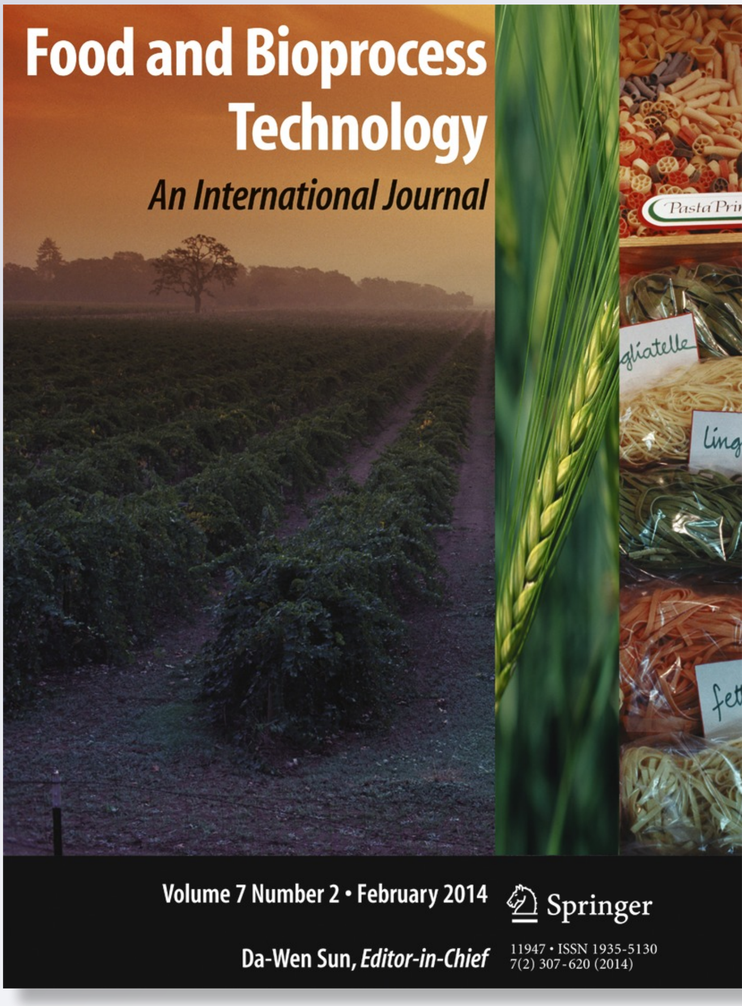

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ORIGINAL PAPER

Quality Attributes of Muffins: Effect of Baking Operative Conditions

María Micaela Ureta · Daniela F. Olivera · Viviana O. Salvadori

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Abstract Muffins are sweet baked products highly appreciated by consumers because of their soft texture and characteristic taste. The aim of this work was to study the influence of baking conditions on muffins' quality. Surface crust color was monitored during baking tests at oven temperatures ranging from 140 to 220 °C, and browning kinetics was modeled by means of a browning index, BI, which follows a logistic model; a joint analysis of core temperature profile and BI curve can assist in the prediction of baking time. Finally, weight loss, crust/crumb ratio, crumb and crust moisture content, porosity, crumb and global densities, and texture were measured in the already baked muffin. The water content in the crumb remains almost constant, while considerable dehydration occurs in the crust. Finally, the results showed that intermediate oven temperatures led to a more porous, aerated, and soft crumb, with intermediate textural properties.

Keywords Browning index · Moisture content · Crumb density · Porosity

Introduction

Sweet baked products in general, and muffins in particular, are highly appreciated by consumers because of their soft texture and characteristic taste. The principal ingredients of muffins—flour, sugar, fat, and egg—play an important role in the structure, appearance, and eating quality of the final product (Karaoglu and Kotancilar 2009; Martínez-Cervera et al. 2012).

The baking process itself is a decisive factor in producing high-quality baked goods. Baking is considered a simultaneous heat and mass transfer process, characterized by a rapid increase of the core temperature and the development of a dry surface crust. Also, the increase of the internal temperature is associated to several chemical reactions and physical changes, responsible for both the transformation of the cake batter into crumb and the product volume expansion. In consequence, baking process conditions—oven temperature, baking time, and oven humidity—strongly influence the development of all quality attributes (Hadiyanto et al. 2007).

From the different quality attributes, surface crust color is one of the critical quality characteristics, since its value directly affects initial consumer's acceptance (Mundt and Wedzicha 2007). Surface color is a consequence of browning reactions: combined sugars caramelization and Maillard reactions. When surface temperature exceeds 100 °C, browning reactions are activated and, therefore, the crust becomes darker (Broyart et al. 1998). Few researchers studied browning of different sweet baked goods: Broyart et al. (1998) proposed a kinetic model in order to predict lightness variation during cracker baking; Mundt and Wedzicha (2007) analyzed the effects of water activity and temperature on browning kinetics of biscuit baking.

Muffins are also characterized by a porous structure and a spongy texture. These attributes are measured, among others, by global density, crust/crumb ratio, moisture content (of crumb and crust), crumb porosity and density, and textural properties, which can all be influenced by operative conditions (Baik et al. 2000).

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Therefore, the aim of this work was to study the influence of baking conditions on muffins' quality. First, surface crust color was monitored during baking tests at oven temperatures ranging from 140 to 220 °C, and browning kinetics was modeled by means of a browning index, BI, representing in one variable the three parameters of the CIE L^*a^*b model. Finally, the previously mentioned parameters, related to structure and texture, were measured in the baked muffin. The results obtained for the different tested oven temperatures were then analyzed.

Materials and Methods

Batter Preparation

The muffin batter was prepared from a ready to bake dry premix, Satin Cake Premix (Puratos S.A., Argentina). It consists of a powder mixture of several dry ingredients: wheat flour, sugar, starch, gluten, chemical leavening agents, salt, emulsifying agents, and flavor compounds. The batter recipe was formulated with 250 g premix, 50 g fresh margarine, 100 g milk, and 60 g whole fresh eggs, which left a batter composition of 46.2 % of carbohydrates, 5.3 % of proteins, 14.0 % of fat, and 34.4 % of water.

All ingredients were mixed for 5 min at a constant speed of 240 rpm in a home multifunction food processor (Rowenta Universo 700, France); mixing time was enough to achieve a homogeneous batter. Each batch of batter was used to fill 10 individual disposable aluminum molds (47 mm diameter, 50 mm height).

Baking Tests

Baking experiments were carried out in a convective batch-type oven (Multiequip HCE-3/300, Argentina), with the dimensions of the oven chamber being 0.42 m (width)× 0.35 m (height)×0.4 m (depth). It was equipped with electrical resistances, which provide ambient temperatures of up to 300 °C, and also a fan installed on the back wall, which propelled the air, at a fixed, single air velocity of 2.8 m/s (this value was measured with a multifunction measuring instrument TESTO 435 equipped with a vane probe; TESTO, Germany).

In order to evaluate the influence of oven temperature in baking performance, five series of experimental runs were performed, setting the nominal oven temperature equal to 140, 160, 180, 200, and 220 °C, respectively. During the baking tests, the oven ambient temperature was measured using T-type thermocouples (Omega, USA) connected to a data logger (Keithley DASTC, USA) and incorporated to a PC. Three removable trays can be located simultaneously inside the oven, but only the one located at the middle level was used; five samples (molds with batter) were placed on this tray in each baking test.

The oven was preheated during several minutes until it reached the preset temperature, and then the molds were placed inside it. After baking and prior to performing the different analyses, samples were cooled for several hours at room temperature. Additional baking tests were carried out to estimate the heat transfer rate, using a flux heat sensor (Omega, HFS4) attached to the muffin surface.

Product Characterization During Baking

Temperature Profile

Muffin core temperature was recorded during baking tests, using the previously mentioned T-type thermocouples (Omega, USA) connected to a data logger (Keithley DASTC, USA). These thermocouples were inserted inside the batter, in a vertical position, fixed to the mold before baking. Three replicates were performed for each baking condition.

Moisture Content

Moisture content was measured in two different regions of the muffin: central crumb and upper crust, at three intermediate times during the baking test. The crust, very thin in the initial baking stage, was carefully separated using a scalpel. Only the lower oven temperature condition was monitored through this variable. Water content values were determined by drying approximately 3–5 g of sample in a stove at 103 °C, until constant weight was achieved. Moisture content was expressed in wet basis. Also, moisture content of unbaked batter and both zones of the final product were measured. Four replicates were made for each tested condition.

Kinetic of Crust Color Development

Surface color of muffins, represented by the CIE $L^*a^*b^*$ model (L^*—lightness, a^*—redness, b^*—yellowness), was measured using a MINOLTA CR-300 tristimulus colorimeter (Osaka, Japan). Surface color evolution was measured nine times for each of the five oven temperatures studied in this work. Due to the experimental difficulties of monitoring color continuously, partial baking experiments were designed, as suggested by Broyart et al. (1998). The most relevant phases were observed as follows: initial batter color, early formation of crust, several intermediate values, and a final crust color representing a burned product. At these selected baking times, the samples were removed from the oven, and surface color was measured and finally discarded. Reported values for each time and oven temperature condition correspond to the average of 15 measurements.

With the aim of analyzing the evolution of surface browning, a browning kinetic model is used, defining a BI (Eq. 1). The BI represents the purity of brown color when nonenzymatic browning takes place (Buera et al. 1986) and its definition takes into account the three parameters of the CIE $L^*a^*b^*$ model:

$$\mathrm{BI} = \frac{[100(\mathrm{x} - 0.31)]}{0.172} \quad (1)$$

where

$$x = \frac{(a^* + 1.75L^*)}{(5.645L^* + a^* - 3.012b^*)} \quad (2)$$

Although this index has been developed to represent browning of liquid model systems, recently, it has been satisfactorily used to report browning variation of sweet baked products, such as muffins (Yilmazer et al. 2011) and cookies (Kemerli et al. 2011).

Analysis of Muffin Attributes at the End of Baking

Weight Loss, Crust/Crumb Ratio, and Moisture Content

Weight loss, WL, was calculated as the percentage difference between initial and final product weight (wet basis), W_i and W_f, respectively, according to Eq. 3:

$$\mathrm{WL}(\%) = \frac{\mathrm{W_i} - \mathrm{W_f}}{\mathrm{W_i}} \times 100 \quad (3)$$

Crust/crumb ratio was calculated according to Le-Bail et al. (2011): the samples were removed from the oven and cooled for a few minutes. The crust was separated from the crumb using a scalpel, considering the crust as the dried and brown surface located at the upper zone of the muffin (MohdJusoh et al. 2009). Crust to crumb ratio was expressed as the mass ratio on wet basis. Also, the moisture content of both fractions in the completely baked sample was determined according the methodology previously described. Four replicates were made for each tested condition.

Muffin Structure

Porosity, ϕ, was defined as the ratio between number of pores and area. It was measured by image analysis, according to the following procedure: a baked sample was cut through its cross-section and images of each half were taken with a Samsung ST60 digital camera (Samsung, Indonesia), with a resolution of 3,264×2,448 (8 M). The images were converted first from RGB to gray images, and then into binary ones, using the Image Processing Toolbox (MatLab, USA), then the holes, representing the pores (from 0.2 to 35 mm^2), were transformed into black sections. The binary images were processed with an image editor (Microsoft Picture Manager, USA), visualizing a randomly selected normalized crumb area of 2.80 cm^2, which allows counting the number of black sections. The results were expressed in cells per square centimeter.

Global density, ρ_g, was measured as the ratio between the weight of a whole sample and its volume, measured by the rapeseed displacement method (Method 10-05, AACC 2000).

Finally, crumb density, ρ_c, was determined from crumb cylinders cut from the muffin. The crumb cylinder was weighed and its volume was calculated from its height and diameter, measured with a caliper.

Texture Characterization

In order to evaluate the textural characteristics of the baked product, a compression test was performed using a TA.XT2i Texture Analyzer (Stable Micro Systems, UK), equipped with a 75-mm-diameter aluminum probe (P/75). Cylinders of muffin crumb, 2.65 cm diameter and 1 cm height, were tested after removing the upper and lower crust ends. The test speed was 1 mm/s and the strain was 25 % of the total height. The maximum force $F_{25\ \%}$ was a firmness indicator of the cake crumb.

Statistical Analysis

The data was subjected to analysis of variance. Comparison of means was conducted using Fisher's least significant difference test, with 5 % significance level.

Results and Discussion

Baking Tests

Figure 1 shows the experimental histories of oven temperature measured during the baking tests. As it is detailed in Table 1, in all the tested conditions, the average oven temperature is higher than the nominal value (which is indicated on the oven control panel). The heat transfer coefficient, determined by the heat flux sensor, was equal to 30 $\mathrm{Wm^{-2}\ °C^{-1}}$.

Product Characterization During Baking

Temperature Profile

Muffin baking is considered a simultaneous heat and mass transfer process, characterized by a rapid increase of core temperature and the development of a dry surface crust. Also, the increase of internal temperature is associated to

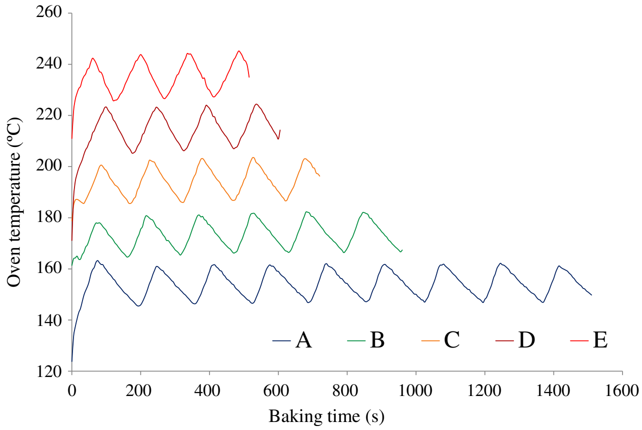

Fig. 1 Oven temperature

several chemical reactions and physical phenomena, which are responsible for the transformation of the cake batter into crumb and the product volume expansion.

In this sense, Fig. 2 shows the baking curves, representing the muffin core temperature vs. baking time, for the five tested operative conditions. At low oven temperatures (conditions A and B), the initial phase becomes rather unstable, with a fast temperature rise until 35 °C, followed by changes of the slope of the curve core temperature vs. time. According to our direct observations, this change in the slope represents an "initial" phase of the baking process, in which the sample, which still presents a batter consistency, starts acquiring a round shape on its surface and increasing its volume. This particular change of the slope of the baking curve is not observed at higher oven temperatures.

After that, two periods similar to those described by Lostie et al. (2002) are clearly noticed: a heating period, in which the temperature rises almost linearly before reaching a plateau, and a final one, with constant core temperature, which corresponds to the growing of the dehydrated crust.

From the analysis of the baking curves slope during the heating period (core temperature from 35 to 85 °C), heating velocities seemed to depend on oven temperature, being 17, 25, 26, 27, and 37 °C/min for conditions A, B, C, D, and E, respectively, this being a sign of an incipient crust.

Finally, all baking curves reach a plateau, characterized by core temperature stabilization around 100 °C. The period

Table 1 Baking tests: average measured oven temperature

Test	Oven temperature (°C)	
	Nominal	Measured
A	140	154.00±5.08
B	160	173.12±5.15
C	180	194.00±5.53
D	200	213.72±7.75
E	220	234.95±6.19

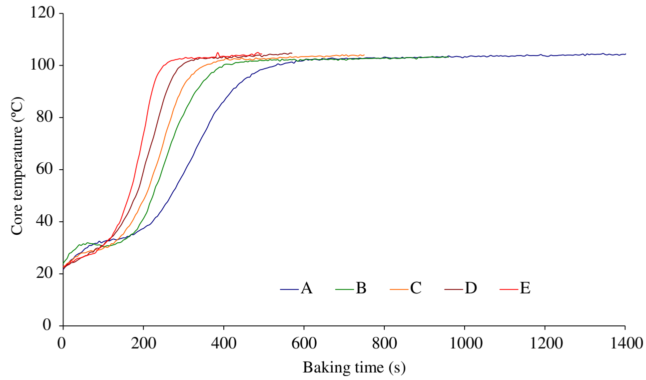

Fig. 2 Baking curves at different conditions

coincides with crust growth and has been observed in different sweet baked products: sponge cake (Lostie et al. 2002; Fehaili et al. 2010), cup cakes (Sakin et al. 2007), and muffins (Yilmazer et al. 2011).

Moisture Content

Figure 3 shows the variation of water content in the muffin during baking. The behavior of the two regions can be perfectly distinguished: the inner zone (crumb) maintains the initial moisture content of the unbaked batter, with only a slight decrease observed at the end of the process. On the other hand, the upper region of the muffin experienced dehydration during the whole baking duration, showed by a significant decrease of its water content. In this way, the crust prevents further dehydration of the inner zones, acting as a barrier to mass transfer towards the oven ambient temperature, as it was verified in other baked products (Purlis and Salvadori 2009a).

Kinetic of Crust Color Development

As it was previously mentioned, a BI was defined in order to consider the three color parameters of the CIE $L^*a^*b^*$ model at a time. From literature review, we have found that Zanoni et al. (1995), who studied bread baking, modeled the surface crust browning kinetics by adopting the color difference ΔE

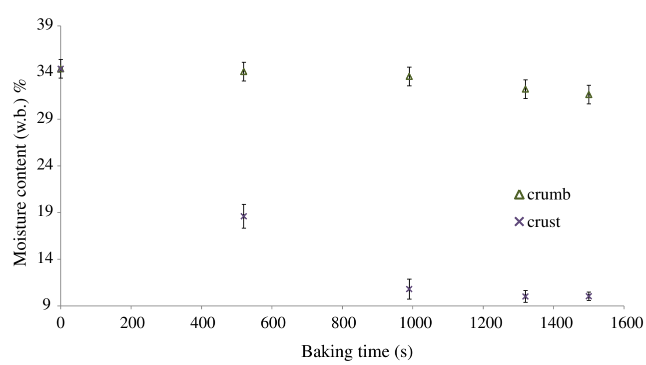

Fig. 3 Moisture content variation during baking

(measured with initial dough color as the reference value) as the BI. The model tended asymptomatically to a value equal to 52, which corresponded to a burned product. Recently, Chhanwal et al. (2011) used this browning kinetics as a quality parameter in their mathematical model of bread baking optimization. Purlis and Salvadori (2009b) also reported a first-order kinetics of browning based on lightness variation of bread crust.

Related to sweet baked products, Yilmazer et al. (2011) and Kemerli et al. (2011) used the BI defined by Eq. 1 to report browning of muffins and cookies. The authors found that the oven characteristics (steam assisted vs. convective type) affect browning values. Apart from these results, no other models of browning kinetics of muffins or similar products were found in specialized literature.

Figure 4 shows the measured variation of the surface BI with baking time for the different oven temperatures tested in this work. These results reveal that an increase in oven temperature has a significant effect on color development rate.

The shape of BI variation is similar, regardless of oven temperature: the initial value of the batter is approximately 28, then the sample presents an initial period of induction (whose length depends on oven temperature) where the color change is minimum and hardly noticeable, and finally, the BI augments gradually until reaching asymptotically a final value close to 160, which represents a totally burned product. The BI vs. time curves are sigmoid, with the best fit obtained by applying the logistic model stated in Eq. 4:

$$BI = BI_o + \frac{BI_{max} - BI_o}{1 + e^{-k(t - t_{1/2})}} \quad (4)$$

where BI is the browning index measured at time t, BI_o is the initial browning index (t=0), k is the browning rate constant (per second), BI_{max} is the maximum browning index, and $t_{1/2}$ is the time (in seconds) when half of the maximum browning index is reached.

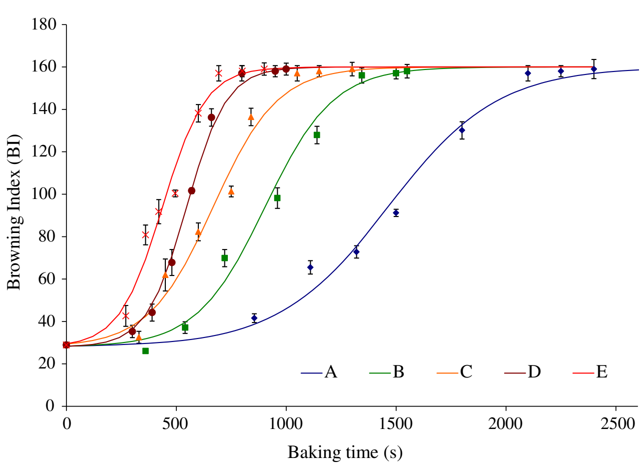

Fig. 4 BI (*symbols* experimental, *lines* Eq. 4) at different oven temperatures

This model was reported to describe nonenzymatic browning of other food systems different from baked products: isothermal and dynamic heating of apple juice concentrates (Vaikousi et al. 2008) and isothermal and dynamic heating of honey (Vaikousi et al. 2009). The logistic model was the most appropriate among the five different primary models—zero-order, first-order, parabolic, Weibull, and logistic—that were tested.

Model parameters are presented in Table 2; predicted BI values are also shown in Fig. 4 (solid lines). As expected, as oven temperature increases, the kinetic constant k increases and $t_{1/2}$ decreases.

To complete this study, Eq. 4 was used to adjust the browning kinetics of other sweet baked products from experimental data reported in literature: vanilla cakes (Baik et al. 2000), muffins (Yilmazer et al. 2011), and cookies (Kemerli et al. 2011). Table 3 informs the obtained kinetics parameters, as well as the coefficient of determination, R^2. These results confirm that the logistic model proposed in Eq. 4 can be applied to represent the browning kinetics of baked products. Both parameters k and $t_{1/2}$ depend on product characteristics (formulation, size) and baking conditions (oven temperature, heat transfer coefficient).

Surface crust color is an important quality attribute, being frequently used to characterize the end of the baking process (AitAmeur et al. 2007; Chevallier et al. 2000; Mundt and Wedzicha 2007). From a technological point of view, a joint analysis of core temperature profile and BI curve can assist in the prediction of baking time. The end of the baking process is considered by several researchers as the time in which the core temperature reaches 95–98 °C (Le-Bail et al. 2009; Olszewski 2006). Nevertheless, as Le-Bail et al. (2009) indicate in their studies on bread baking, reaching such temperature at the core correspond to partial baking of bread. At these times, the product has not yet acquired the desirable quality characteristics, such as surface color, crumb and crust texture, and humidity, among others.

As an example, the muffins baked at oven condition A reach the target value of 100 °C after 600 s of baking. From the results of Fig. 4, predicted crust color at this baking time is extremely light, and the product cannot be considered a

Table 2 Fitting parameters of the BI model, Eq. 4

Test	$t_{1/2}$ (s)	k (10^3; s^{-1})	R^2
A	1462.67	4.00	0.997
B	903.84	6.45	0.993
C	667.71	6.84	0.997
D	546.74	11.10	0.995
E	434.59	10.23	0.995

Table 3 Fitting parameters of the BI model, applied to other baked products (data from bibliography)

Reference	Product	$t_{1/2}$ (s)	k (10^3; s^{-1})	BI_{max}	R^2
Baik et al. (2000)	Cake	121.14	27.3	113	0.917
Yilmazer et al. (2011)	Muffin	1,673.60	2.09	157	0.990
Kemerli et al. (2011)	Cookie	1,184.72	2.91	116	0.988

An initial value of BI_o=28 was assumed

good product from a quality point of view. Similar results are obtained by analyzing the remaining operative conditions.

Muffin Quality Attributes at the End of Baking

For the following assays, totally baked muffins were used, considering the surface BI of the samples close to 100. In all cases, process time ensures that the core temperature had reached the plateau value.

Weight Loss, Crust/Crumb Ratio, and Moisture Content

The main mass transfer characteristics associated to baking include an evaporation front moving from the surface towards the product core. The evaporation front divides the product into two zones: the crumb (inner zone, humid) and the crust (outer zone, dehydrated).

WL, evaluated according to Eq. 3, is a measure of the yield of the batter and, hence, global yield of the whole baking process. The experimental results detailed in Table 4 indicate that WL drops as oven temperature increases. Due to the small size of the samples, oven temperature increase produces a significant decrease of baking time and, in consequence, the available time for water evaporation is low. WL values measured in this work ranged from 12 to 15 %, similar values were determined by Martínez-Cervera et al. (2012) for a similar product.

On the contrary, a decay is observed in the crust/crumb ratio. Again, higher oven temperatures result in lower process times and, in consequence, thinner crust and lower crust/crumb ratio are obtained.

From the results presented in Table 4, it is easily noticeable that the moisture content of the crumb is not significantly affected by oven temperature, with an average value of 31.61 %, only a slight difference with the moisture content of the batter (34 %) is observed. As it was previously discussed, it is evidence that considerable dehydration occurs in the surface crust, which allows the crumb to maintain its humidity. Regarding crust moisture content (Table 4), higher oven temperatures seem to produce a more humid crust. This behavior could also be ascribed to shorter baking process time.

Table 4 Moisture characteristics of baked muffin

Test	WL (%, wet basis)	Crust/crumb ratio (wet basis)	Crumb moisture (%, wet basis)	Crust moisture (%, wet basis)
A	14.65±0.73a	0.21±0.020a	31.64±0.49a	10.03±0.90a
B	14.21±0.66a	0.16±0.004b	31.95±0.35a	10.75±1.20ab
C	14.33±0.54a	0.15±0.013c	31.40±0.75a	11.35±1.18b
D	13.46±0.53b	0.16±0.009b	31.36±0.50a	11.46±1.06b
E	12.89±0.47c	0.14±0.010d	31.70±0.36a	13.17±0.37c

Data are expressed as the mean ± standard deviation. Values with the same letter are not significantly different (P>0.05)

Porous Structure

Cake batter is a complex fat-in-water emulsion composed of bubbles as the discontinuous phase and of egg–sugar–water–fat mixture as the continuous phase in which flour particles are dispersed (Shelke et al. 1990). As it was previously mentioned, during the first period of baking, the batter turns into a porous structure, the crumb. The air bubbles incorporated into the batter during mixing are transformed into pores entrapped in the crumb structure (Martínez-Cervera et al. 2012).

From the results presented in Table 5, we can appreciate that, even though global and crumb densities together with porosity characterize the aeration of the cake and the cake sponginess, the behavior of these parameters with oven temperature differs from one another.

Porosity, which depends on the number and size of pores, is higher at conditions C and D. Figure 5 shows muffin images (conventional photographs and binary images) from samples used in these analyses. From these images, it can be seen that low oven temperature produces a more homogeneous pore development with a size area smaller than 11 mm^2. On the contrary, higher temperatures lead to larger pores, and the muffin surface also presents a less round and uniform shape.

From the results detailed in Table 5, both global and crumb densities present lower values at conditions A, B, and C and higher values at the higher oven temperatures.

Table 5 Structure parameters of baked muffin

Test	ϕ (cells/cm^2)	ρ_g (kg/m^3)	ρ_c (kg/m^3)	$F_{25\ \%}$ (N)
A	9.14±0.54a	490±30a	440±30a	6.46±0.50a
B	11.20±0.59b	500±35a	490±10b	8.06±1.60a
C	12.64±0.61c	510±20a	470±10ab	6.52±0.55a
D	12.90±0.95c	570±30b	510±10b	5.03±0.65b
E	11.40±0.54b	620±40b	580±20c	4.70±0.88b

Data are expressed as the mean ± standard deviation. Values with the same letter are not significantly different (P>0.05)

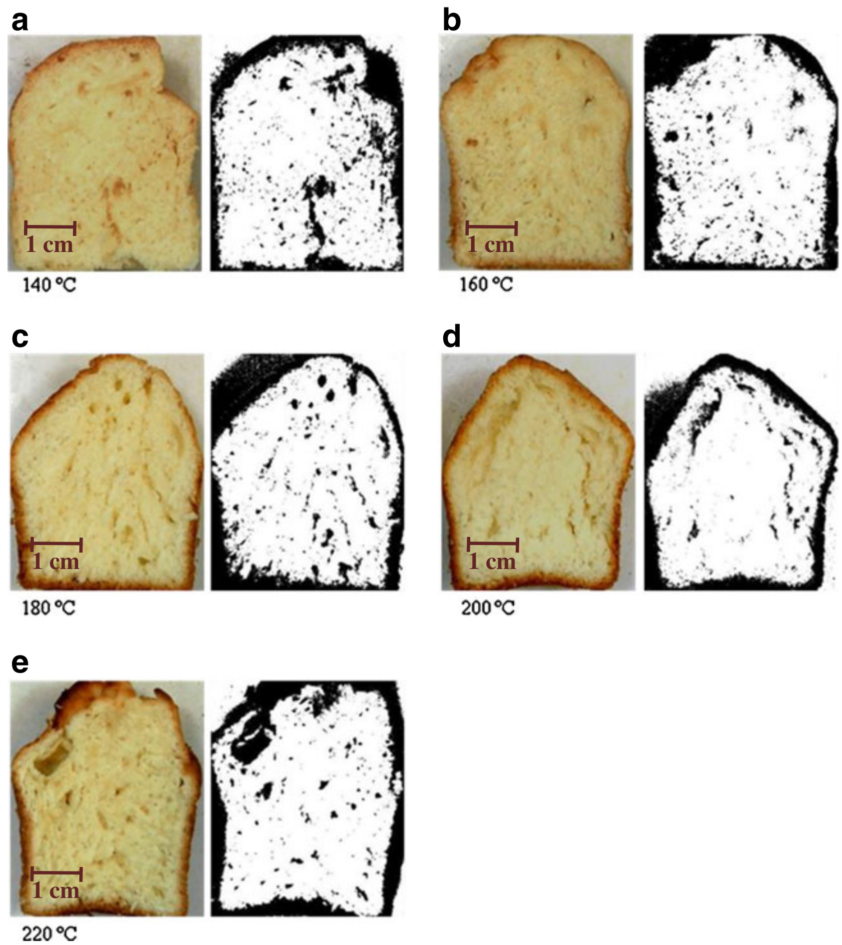

Fig. 5 Photographs and binary images of muffin cross-sectional area at different oven temperatures

In consequence, taking into account these previously mentioned quality attributes, oven temperatures in the range of 180–200 °C lead to a more porous, aerated, and soft crumb, with these quality characteristics being highly appreciated by consumers (Ureta et al. 2011a).

Texture Characterization

The cellular structure of food materials, in both macro (porosity and density) and micro (cell wall thickness, cell diameter, and their distributions) scales, also influences mechanical properties (Sozer et al. 2011).

In previous work (Ureta et al. 2011b), the best mechanical test to differentiate crumb firmness in this product was found to be compression test. The results shown in Table 5 indicate that, at lower values of oven temperatures, the crumb is firmer; on the contrary, the firmness decreases significantly when high oven temperature is used. This fact can be explained by the presence of bigger pores (see Fig. 5) which generate a weak porous structure. An easily deformable structure is a negative feature; it means that the product crumbles easily and loses its typical shape.

Conclusions

In this work, the influence of oven temperature on quality characteristics of muffins was analyzed. Two periods can be distinguished in the core temperature curve: a heating period, in which the temperature rises almost linearly before reaching a plateau, and a final phase, which corresponds to the growing of the dehydrated crust. At the end of baking, internal temperature remains constant at approximately 100 °C.

Browning kinetics was modeled by means of the BI. A logistic model accurately adjusts experimental values of BI vs. time, for an initial value BI_o=28 to an end value BI_{max}=160, which corresponds to the batter and a burned product, respectively. Both the half time $t_{1/2}$ and the browning rate constant k depend on oven temperature. A joint analysis of core temperature profile and BI curve can assist in the prediction of baking time.

The water content in the crumb remains almost constant, while considerable dehydration occurs in the crust. Higher oven temperatures result in lower process times; in consequence, thinner crust, lower crust/crumb ratio, and more humid crust are obtained.

Finally, several parameters related to muffin structure and texture were evaluated. The results showed that intermediate oven temperatures lead to a more porous, aerated, and soft crumb, with intermediate textural properties.

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