

Effects of Temperature and Mechanical Input on Semisweet Biscuit (Cookie) Quality and Dough Characteristics¹

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ABSTRACT

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The effects of specific mechanical energy (SME) and dough temperature at the end of mixing (T_f) on semisweet biscuit dough characteristics and biscuit quality were studied using an experimental mixer fitted with monitoring devices. The fluid circulating in the double jacket of the mixing bowl was regulated at variable temperatures and mixed dough samples were prepared at T_f of 23, 30, and 37°C for three levels of SME input (20, 60 and 120 kJ/kg). Correlation analysis showed that semisweet biscuit length and thickness were independent quality parameters, influenced respectively by the T_f of dough and SME. Biscuit thickness and

volume increased with SME input, but SME had no significant influence on the physicochemical characteristics of the dough. Biscuit length was related to the density and stickiness of the dough and to rheological behavior as assessed by fundamental and empirical measurements. A rise in dough temperature >35°C induced a dramatic increase in viscoelastic properties, leading to biscuit shrinkage. The increase of dough density with T_f seemed to be related to the melting of solid fat in the dough recipe. Melting of fat during mixing could also be a source of viscoelastic changes in the dough at T_f .

Mixing is a key stage in semisweet biscuit making. In the case of the French biscuit *Petit-Beurre*, energy input during dough mixing was found to control biscuit quality (Contamine et al 1995). As in breadmaking, mixing has three main functions: blending of the recipe ingredients, creation of oriented protein structures by the effects of shear, and air inclusion (Bloksma 1990). The viscoelastic properties of dough, related to the extent of the gluten network, determine dough behavior during sheeting and final biscuit quality (Wade 1988a), the latter being a matter of industrial concern and including regularity in biscuit length, thickness, and density. For semisweet biscuit dough, gluten network development must be limited so that the dough is extensible enough to be easily sheeted but not too elastic to prevent biscuit shrinkage after cutting and baking (Contamine et al 1995).

The quality of biscuit and bread products is controlled by wheat flour composition and mixing variables such as mixer design, mixing time and speed, and water content (Kilborn and Tipples 1972, Olewnick and Kulp 1984, Contamine et al 1995). Wade (1988b) emphasized the critical importance of energy input and, more specifically, the mechanical energy supplied during mixing or the final temperature reached by the dough (T_f) on consistency and subsequent dimensional quality parameters of the biscuits such as weight and thickness. With the semisweet biscuit *Petit-Beurre*, we earlier identified a specific mechanical energy (SME) threshold of 60 kJ/kg, beyond which biscuit length suddenly decreased (Contamine et al 1995). During mixing, the SME imparted to the dough is partially converted into heat by frictional forces. This viscous dissipation of SME increases dough temperature, thus T_f is strongly related to the SME imparted to the dough (Contamine et al 1995).

The aim of this work was to ascertain the respective influence of SME and T_f on changes in dough and biscuit characteristics. Mixing conditions were modified from our previous work (Contamine et al 1995) to dissociate these two variables. The temperature of the fluid circulating in the double jacket of the mixing bowl was

adjusted to obtain different T_f in doughs with similar SME input. The specific effects of mixing variables (i.e., SME, mixing speed, mixing time, and T_f) on biscuit quality parameters (length, thickness, and density) were determined using a balanced experimental design. Dough characteristics including rheological behavior, stickiness, density, and extractability of the lipid content by hexane were also investigated and related to mixing variables and biscuit quality. Physicochemical events occurring during dough mixing and responsible for the final biscuit quality are discussed.

MATERIALS AND METHODS

A soft wheat flour of biscuit-making quality was provided by Grands Moulins de Paris (France). Protein content (10.2% flour db) was determined by the Kjeldahl method ($N \times 5.7$) (Approved Method 46-10, AACC 2000). Damaged starch content (7.3%, AACC units) was measured by amperometry (SD4, Chopin). Flour water absorption capacity (53.9%) was ascertained by Brabender Farinograph (AACC Method 54-21). Alveograph measurements were obtained according to AACC Method 54-30A ($W = 142$ J/g, $G = 21.4$, $P = 50$ mm, $P/L = 0.54$). Total pentosan (1.88% db) and water-soluble pentosan (0.51% db) levels were obtained by the Douglas colorimetric method (Rouau and Surget 1994).

The experimental biscuit mixer (De Vuurslag, Roosendaal, The Netherlands) was of horizontal type with a uniaxial arm and variable speed (0–250 rpm). Mixing capacity was 6 kg of dough. A torque sensor (Beta N-1350, 100 daN) perpendicular to the floating motor axis was used to measure mechanical power consumption. Data were relayed to a data acquisition system (AOIP SAM 80) linked to personal computer. The amount of SME absorbed by the dough (J/kg) was calculated as:

$$SME = C \times \omega \times t / M_d \quad (1)$$

where C is the average torque (N/m), ω is the angular velocity (rad/sec), t is the mixing time (sec), and M_d is the weight of dough (kg). Dough temperature was continuously recorded by a thermistance (Betatherm, 10K3MCD1) held on the surface of the arm and connected to a rotating electronic contact. For temperature regulation, the mixer was fitted with a double jacket which circulated a thermostatically controlled water and propylene glycol mix.

To predict T_f , mixing tests were performed for 12 min at mixing speeds of 60–160 rpm with the mixing vessel at different temperatures of regulation (T_{reg}) to establish:

$$N = 58.76 + 1.0232 \times SME - 0.6733 \times T_f \quad R^2 = 0.98 \quad (2a)$$

$$T_{reg} = -7.2462 - 0.1901 \times SME + 1.3413 \times T_f \quad R^2 = 0.98 \quad (2b)$$

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where N is the mixing speed (rpm), SME is expressed in kJ/kg, and T_f in °C.

These equations were used to estimate the correct T_{reg} and N after 12 min of mixing to obtain the required combination of T_f (23 and 37°C) with SME (20 and 120 kJ/kg) (Table I). To test the influence of T_f , mixing speed, and mixing time as independent variables, the combinations of T_{reg} and N previously estimated for 12 min of mixing were retained for 8 min of mixing. Two T_f levels (23 and 37°C) were successfully obtained (23 ± 1 and $36 \pm 2^\circ\text{C}$) for both mixing times (8 and 12 min) and speeds (55–60 and 150–160 rpm). SME levels (≈ 20 and ≈ 120 kJ/kg) showed larger deviations owing to mixing time accordingly to Equation 1 (Table I).

Two additional conditions were tested. First, duplicate estimates of T_{reg} and N were made using Equation 2 to obtain a dough at 12 min, 30°C T_f , and 60 kJ/kg. Next, the same T_{reg} value was used in combination with intermediate levels of N and t (105 rpm and 10 min) to obtain a dough at 30°C T_f . For relatively similar SME input (≈ 20 and ≈ 120 kJ/kg), the T_f of dough samples were quite unlike those obtained when the fluid in the double jacket circulated at a constant temperature of 27.5°C (Fig. 1). In our experimental design, T_f were no longer correlated to SME input. This allowed us to analyze biscuit quality parameters and dough characteristics as a function of two sets of noncorrelated variables, either SME, T_f , and mixing time or mixing speed, T_f , and mixing time.

Baking Test

The dough recipe (French biscuit, *Petit-Beurre*) based on a wet flour weight (water content 15% db) was 17.7% fat (copra and palm blend), 35% sugar, 19.6% water, and 2.4% leavening agent (sodium bicarbonate). All recipe ingredients were tempered for 24 hr at 25°C before mixing. Dough properties (stickiness, consistency) were measured after mixing. Approximately 20 g of dough was immediately frozen in liquid nitrogen and kept at -18°C for further analysis (density, extraction of fat with hexane). After resting for 30 min at 25°C, the dough was sheeted to a thickness of 2 mm with a pilot-scale sheeter (R-Tech, Wigan, UK) and punched out manually with a rectangular cutter (70 × 58 mm). The biscuits were baked at 250°C for 5.5 min in a domestic oven (Arthur Martin, Conni-

vence, France). Reproducibility of the test was assayed with five replicates (N 105 rpm, T_{reg} 22°C, mixing time 12 min) using a flour of biscuit-making grade provided by Danone. Relative standard deviations (RSD) were 1, 0.1, 2, 0.8, and 5.9%, respectively, for biscuit length, width, thickness, and weight and volume (measured with a volumeter filled with 0.2-mm glass beads).

Physicochemical Analysis

Lipid content extractable by hexane. The lipid content of dough was extracted according to Contamine et al (1995). To track hexane diffusion within the dough, Oil Red O (Sigma), a hexane- and fat-soluble dye was mixed with two dough samples regulated at 105 rpm for 12 min at T_f 22.4 and 39.4°C, respectively.

Determination of dough stickiness. Immediately after mixing, the dough was enclosed in a polyethylene bag and stored at 25°C in a water bath for 15 min. The dough sample was then shaped to 12 mm in thickness and 64 mm in diameter in a cylindrical mold by manual compression with a steel cylinder. The cylindrical Plexiglas tester (25 mm diameter) of the TA.XT2 texture analyzer (Stable MicroSystems) was applied three times on different spots of the dough for 4 sec at a force of 100 g and withdrawn at 10 mm/sec. Measurements were made in triplicate. Stickiness was recorded as the average of the withdrawal peak areas (g/sec) units (10–20% RSD).

Determination of dough density. The volume of water displaced by a dough sample of known mass (1.5–2 g) was evaluated with a Hubbard pycnometer. The density value was the mean of at least six measurements. Repeatability (<1.75% RSD) and reproducibility (<1.9% RSD) of the method were considered satisfactory.

TABLE I
Experimental Mixing Conditions^a

| t (min) | N (rpm) | T_{reg} (°C) | SME (kJ/kg) | T_f (°C) |
|-----------|-----------|----------------|-------------|------------|
| 12 | 60 | 20.3 | 19.5 | 23.4 |
| 12 | 55 | 41.2 | 24.6 | 37.8 |
| 12 | 160 | -3.2 | 134.2 | 24.2 |
| 12 | 150 | 22.8 | 119.6 | 38.8 |
| 8 | 60 | 20.5 | 14.9 | 22.7 |
| 8 | 55 | 41.7 | 14.7 | 35.2 |
| 8 | 160 | -3.2 | 92.7 | 22.5 |
| 8 | 150 | 22.0 | 81.0 | 34.9 |
| 12 | 105 | 22.5 | 61.1 | 30.0 |
| 12 | 105 | 21.7 | 55.2 | 29.9 |
| 10 | 105 | 22.8 | 44.4 | 28.4 |

^a N and t represent mixing speed and mixing time. T_{reg} , SME, and T_f represent temperature of regulating fluid, specific mechanical energy, and final dough temperature.

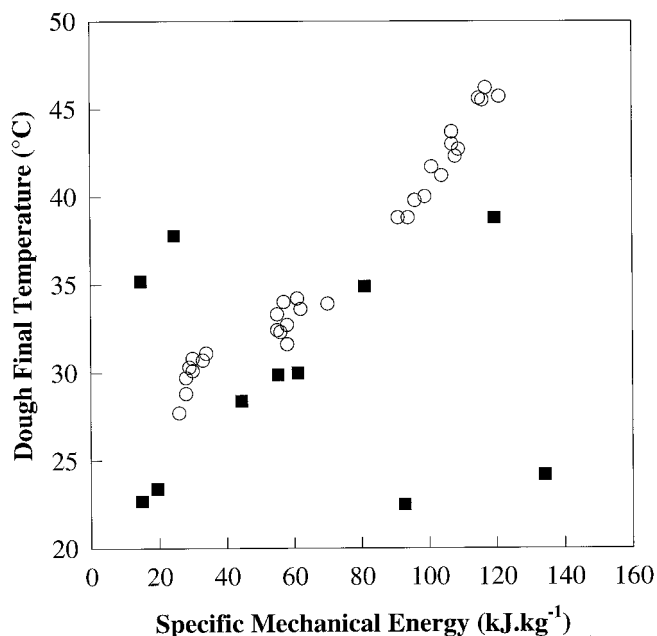


Fig. 1. Relationship between specific mechanical energy imparted during mixing with final dough temperature. Variable temp. of regulation of the double jacket (Table I) (■). Constant temp. of regulation (27.5°C) (○).

TABLE II
Correlation Matrix Relating Dough and Biscuit Parameters and Mixing Variables^a

| Mixing Variables | Dough Parameters | | | | Biscuit Parameters | | | |
|------------------|------------------|--------------|-------------------|---------|--------------------|-----------|---------|----------|
| | SRAWM | Extr. Lipids | Stickiness | Density | Length | Thickness | Volume | Density |
| N | ns ^b | ns | 0.51 [†] | -0.55* | 0.58* | 0.56* | 0.72** | -0.82*** |
| t | ns | ns | ns | ns | ns | 0.71** | 0.50 | ns |
| T_f | 0.81*** | -0.70** | -0.70** | 0.68** | 0.74** | ns | ns | ns |
| SME | ns | -0.59* | ns | ns | ns | 0.72** | 0.86*** | -0.91*** |

^a N and t represent mixing speed and mixing time. T_f and SME represent final dough temperature and specific mechanical energy. Dough extrusion time measured using a Simon research water absorption meter (SRWAM); dough lipids extractable by hexane (Extr. Lipids).

^b †, *, **, *** = Significant correlation at $P < 0.1, 0.05, 0.01,$ and $0.001,$ respectively; ns = not significant.

Rheological Measurements

Measurements at large deformations. A dough sample (40 g) was introduced into the cylindrical die (9.5 mm diameter) of a SRWAM (Simon research water absorption meter, Henry Simon Ltd., Stockport, UK) regulated at 28°C with a water jacket. After a 5-min rest, a plunger (3,830 g) was placed on top of the dough piece. The time taken for the plunger to travel 4 mm was recorded. This empirical method is widely used in the biscuit industry. The flow in the system undergoes shear and elongational deformations and is strongly influenced by dough and die wall contact conditions.

Measurements at small deformations. Rheological measurements were made with a dynamic spectrometer (RMS 800, Rheometrics, Piscataway, NJ), consisting of two coaxial grooved parallel plates 30 mm in diameter. The top plate was oscillated at a defined angular strain and frequency; torque was measured on the bottom plate. Frequency sweep within a range of 0.1–100 rad/sec was performed by applying a 0.2% strain (within the limit of the linear domain of the sample) according to Charun et al (1997).

Fat Ingredient Solid-to-Liquid Ratio Measurement

Solid and liquid contents of fat used in the dough recipe were ascertained by nuclear magnetic resonance (NMR) measurement at temperatures of 0–45°C according to Desarzens et al (1978).

Statistical Analysis

Data were analyzed for linear correlation coefficients and variance, linear, quadratic, and multiple regression (Stalab and Statgraphics software), where T_f , mixing speed, and mixing time or T_f , SME, and mixing time were sources of variation. To compare all mixing variables on an equal numerical basis, dough and biscuit characteristics were analyzed using centered and reduced variables.

RESULTS

Correlation coefficients between mixing variables and dough and biscuit parameters are listed in Table II. Three groups of dough and biscuit characteristics were clearly delimited according

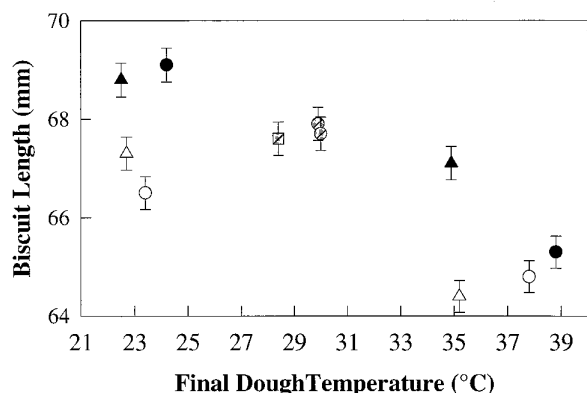


Fig. 2. Relationship between final dough temperature and biscuit length. Mixing speed: 55–60 rpm (white symbol), 105 rpm (striped symbol), 150–160 rpm (black symbol). Mixing time: 8 min (Δ), 10 min (□), 12 min (○).

to contrasting dependence on mixing variables. The first group comprised parameters strongly correlated to T_f : SRWAM extrusion time, dough lipid yield extractable by hexane, dough stickiness, dough density, and biscuit length. Conversely, T_f did not account for biscuit thickness, volume, and density variations, which were correlated to mixing speed and SME. Dough lipid yield extractable by hexane was the sole parameter correlated to both T_f and SME. Biscuit width and weight did not correlate to any variable of the mixing process. The range of variation for these quality parameters was within the standard deviation.

Effect of Mixing Variables on Biscuit Quality Parameters

Biscuit length. Biscuit length fluctuated at 64.4–69.1 mm, depending on T_f (Fig. 2). This variable was the main determinant of biscuit length and exerted a negative influence (Eq. 3 in Table III). Variance analysis showed that biscuit length was positively influenced by mixing speed and was independent of mixing time and SME, though mixing speed is involved in SME calculation (Eq. 1).

Biscuit thickness. Figure 3 shows that biscuit thickness varied at 5.1–6.2 mm and was influenced mainly by SME and mixing time. Thickness also exhibited small positive changes related to T_f . Analysis of variance and subsequent stepwise multiple regression led to a model of good predictive capacity (Eq. 4, $R^2 = 0.90$, Table III), confirming the role of mixing time.

Biscuit volume. Biscuit volume varied at 17.7–20.5 cm³. Variance analysis and multiple regression showed that it increased with SME input (Eq. 5, Table III). The influence of T_f was smaller and not highly significant ($P = 0.1$). Predictive models of biscuit thickness and volume were similar. This was to be expected

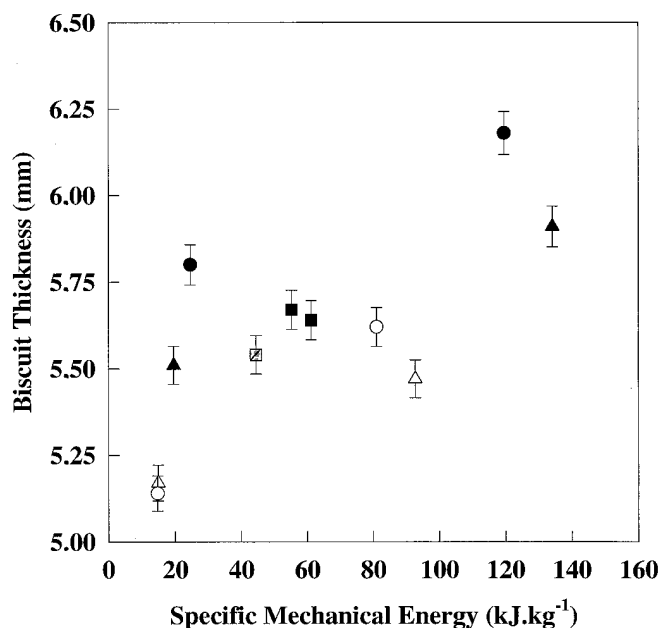


Fig. 3. Relationship between specific mechanical energy and biscuit thickness. Mixing time: 8 min (white symbol), 10 min (striped symbol), 12 min (black symbol). Final dough temperature: 20–25°C (Δ), 28–35°C (□), 35–40°C (○).

TABLE III
Predicting Models for Biscuit Quality Parameters^a

| Equation | Biscuit Quality Parameter | Model ^b | R^2 |
|----------|------------------------------|--|-------|
| 3 | Length (mm) | $67.0 - 1.07 \times T_f^{***} + 0.8 \times N^{***}$ | 0.80 |
| 4 | Thickness (mm) | $5.6 + 0.09 \times T_f^{**} + 0.17 \times SME^{*****} + 0.15 \times t^{***}$ | 0.90 |
| 5 | Volume (cm ³) | $17.7 + 0.23 \times T_f^* + 0.65 \times SME^{*****}$ | 0.78 |
| 6 | Density (g/cm ³) | $0.43 - 0.018 \times SME^{*****}$ | 0.80 |

^a N , t , T_f , and SME represent mixing speed, mixing time, final dough temperature, and specific mechanical energy, respectively. Variance analysis and multiple regression performed using reduced and centered variables.

^b *, **, ***, and **** = Significantly variable at $P < 0.1$, < 0.005 , < 0.0005 and < 0.0001 , respectively.

because the volume is the product of length, width, and thickness, the latter exhibiting the largest coefficient of variation (5.33 vs. 2.2% for biscuit length).

Biscuit density. Biscuit density decreased strongly (0.462–0.394 g/mL) when SME increased (Eq. 6, Table III). Variance analysis showed that SME ($P < 0.0001$) was better than mixing speed ($P < 0.0005$) for predicting biscuit density, though both were strong influences.

Effect of Mixing Variables on Rheological Behavior of Dough

Dough consistency evaluated by SRWAM extrusion time increased sharply and nonlinearly in connection with T_f according to Eq. 7 (Table IV). An antagonistic (negative) linear effect of mixing speed was noticeable. The occurrence of a positive interacting term ($N \times T_f$) illustrated the fact that, at the lowest T_f , a rise in mixing speed led to a decrease in extrusion time (Fig. 4).

The rheological behavior of the dough in terms of linear domain and evolution of the storage (G') and loss (G'') moduli with angular frequency and shear strain was similar to that depicted in Con-

tamine et al (1995, figures 5 and 6). Linear behavior was observed only for strain $\leq 0.3\%$, and mechanical spectra were characteristic of a weak physical gel with G' superior to G'' for the whole frequency range investigated. Statistical analysis of the results obtained at an angular velocity of 0.1 rad/sec, representative of the range investigated, revealed that only T_f affected modulus G' (Eq. 8, $R^2 = 0.95$, Table IV). An increase in T_f resulted in higher G' and also modified the frequency dependence of moduli (Fig. 5). Temperature rise tended to decrease the frequency sweep dependence of the moduli while increasing the values. As a consequence of moduli variations, the loss tangent ($\tan \delta = G''/G'$) decreased when T_f and mixing speed increased (Eq. 9, Table IV).

Effect of Mixing Variables on Dough Quality Parameters

Dough stickiness. Sticky dough tends to adhere to the metal parts of machines during sheeting or cutting. This kind of trouble was obvious when the withdrawal areas measured by the implemented method were >16 g/sec. Stickiness notably decreased when T_f increased (Eq. 10, Table V). Conversely, for a given T_f ,

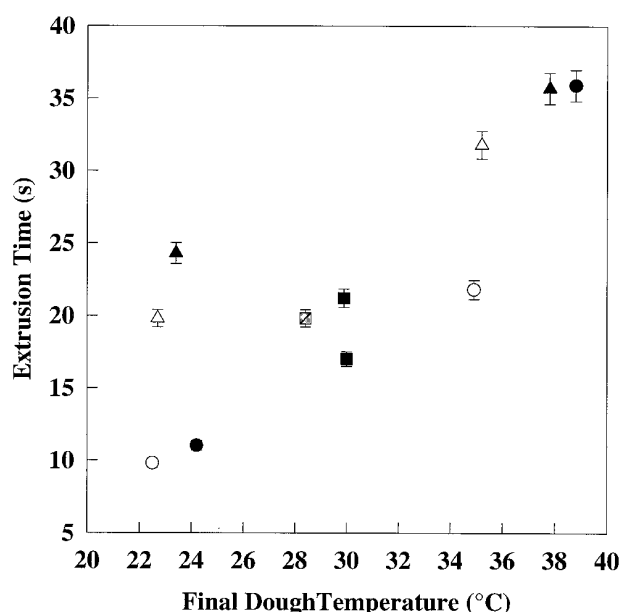


Fig. 4. Relationship between final dough temperature and dough extrusion time. Mixing time: 8 min (white symbol), 10 min (striped symbol), 12 min (black symbol). Mixing speed: 55–60 rpm (Δ), 105 rpm (\square), 150–160 rpm (\circ).

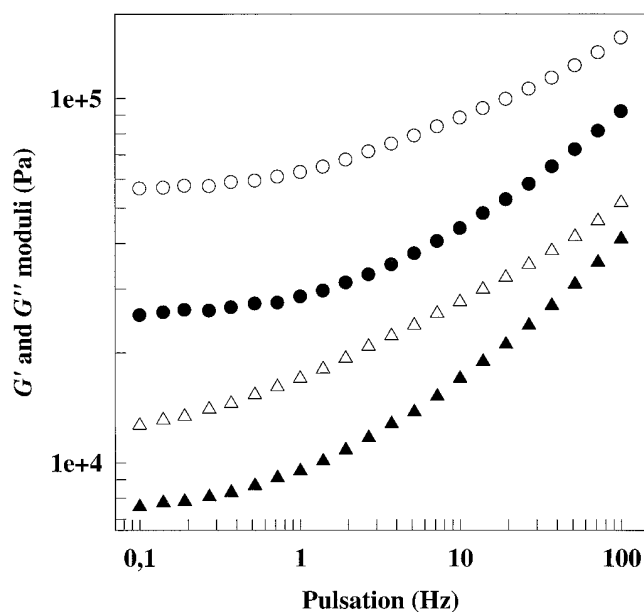


Fig. 5. Effect of final dough temperature on the evolution of storage modulus (G') and loss modulus (G'') with pulsation. Modulus: G' (white symbol), G'' (black symbol). Dough mixed at: 120 kJ/kg and 20.8°C (Δ), 120 kJ/kg and 37.2°C (\circ).

TABLE IV
Predicting Models for Some Dough Rheological Parameters^a

| Equation | Rheological Parameter | Model ^b | R^2 |
|----------|--------------------------------|--|-------|
| 7 | SRWAM extrusion time (sec) | $17.0 + 3.97 \times T_f^{2***} + 4.94 \times T_f^{****} - 3.51 \times N^{***} + 1.68 (N \times T_f)^*$ | 0.77 |
| 8 | Storage modulus G' (Pa) | $34,838 + 16,763 \times T_f^{****}$ | 0.95 |
| 9 | Loss tangent ($\tan \delta$) | $0.55 - 0.069 \times T_f^{****} - 0.021 \times N^*$ | 0.84 |

^a Dough extrusion time measured using a Simon research water absorption meter (SRWAM); N and T_f represent mixing speed and final dough temperature, respectively. Variance analysis and multilinear regression performed using reduced and centered variables. Storage modulus (Pa) and $\tan \delta$ predicted at 0.1 rad/sec.

^b *, **, ***, and **** = Significantly variable at $P < 0.1$, < 0.05 , < 0.01 , and < 0.001 respectively.

TABLE V
Predicting Models for Some Physicochemical Dough Characteristics^a

| Equation | Dough Characteristic | Model ^b | R^2 |
|----------|------------------------------------|---|-------|
| 10 | Dough stickiness (g/sec) | $12.9 - 2.9 \times T_f^{****} + 2 \times N^{**} - 1.5 \times (N \times T_f)^{**}$ | 0.83 |
| 11 | Dough density (g/cm ³) | $1.2 + 0.021 \times T_f^{***} - 0.017 \times N^{**}$ | 0.66 |
| 12 | Extractable lipid (%) ^c | $78.7 - 16.1 \times T_f^{2***} - 16.1 \times T_f^{****} - 6.5 \times N^{**}$ | 0.85 |

^a N and T_f represent mixing speed and final dough temperature, respectively. Variance analysis and multilinear regression performed using reduced and centered variables.

^b **, ***, and **** = Significantly variable at $P < 0.05$, < 0.01 , and < 0.001 , respectively.

^c % Lipid content of dough recipe.

stickiness increased significantly with mixing speed. Predictive equation of dough stickiness included the interacting term ($N \times T_f$) as a significant factor. In practice, stickiness was encountered when mixing speed was >100 rpm and T_f was $22\text{--}29^\circ\text{C}$. In fact, it was obvious that doughs were never sticky when T_f was $>30^\circ\text{C}$.

Dough density. Mixing speed and dough T_f exerted negative and positive effects, respectively, on dough density (Eq. 11, Table V). The linear model accounted for $<70\%$ of the total variation. During mixing, air is continuously entrapped and released from the dough; when entrapped, it is stabilized inside bubbles in the dough. The lack of accuracy in the predictive model might then reflect the complex determinism of dough density. The positive influence of T_f indicated that the number or volume of air bubbles in the dough decreased when the temperature increased. The effect of high mixing speed could be mean more efficient incorporation of air into dough.

Dough lipids extractable by hexane. Lipid content (flour lipids and recipe fat) extractable from dough by hexane decreased when T_f and N increased (Eq. 12, Table V). Equation 12 shows that T_f was again the main contributory variable. The evolution of extractable fat in relation to T_f was strongly nonlinear (Fig. 6) and revealed by the quadratic term in Eq. 12 (Table V). Extractable fat content decreased notably when T_f was $>35^\circ\text{C}$ and was lowest at high mixing speed.

During lipid extraction by hexane with a slow rotating motion, dough pieces were not disrupted but stuck together and constituted a ball. To track hexane dispersal throughout the dough ball, a lipid stain, Oil Red O, was added to the solvent. Two dough samples mixed at 59 kJ/kg and at different T_{reg} to give $T_f = 22.4$ and 39.4°C were extracted with the stained solvent. For the dough mixed at 39.4°C , only the surface of the ball was stained at the end of extraction. So a lower extractable lipid yield at $T_f > 35^\circ\text{C}$ was related to a failure in hexane percolation inside the dough ball. The sample mixed at $T_f 22.4^\circ\text{C}$ was deeply stained. Decrease in fat extraction yield ($58\text{--}68\%$) observed for doughs mixed at low T_f ($22\text{--}24^\circ\text{C}$) when SME increased would not seem to be due to a physical impediment of hexane percolation.

DISCUSSION

In our experimental procedure, there was no correlation ($r = 0.03$) between biscuit thickness and length, which were influenced by different mixing variables (Table II). This contrasts with the data

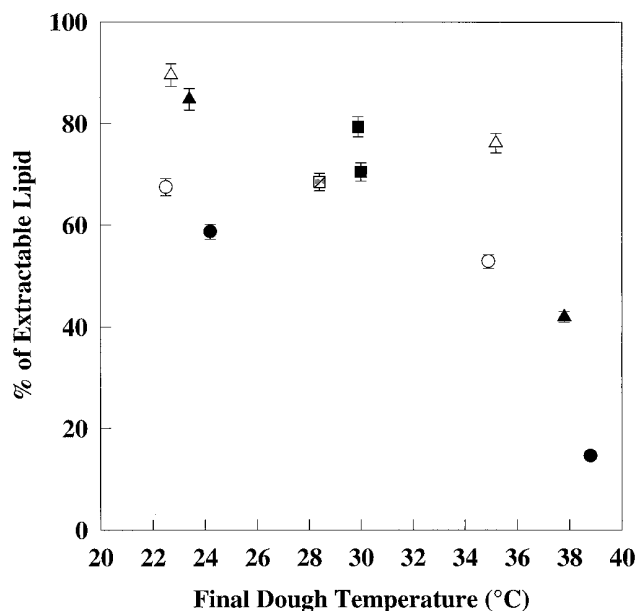


Fig. 6. Relationship between final dough temperature and extractable fat (% dough recipe fat). Mixing time: 8 min (white symbol), 10 min (striped symbol), 12 min (black symbol). Mixing speed: 55–60 rpm (Δ), 105 rpm (\square), 150–160 rpm (\circ).

of Contamine et al (1995) showing that in a standard mixing process (mixing bowl regulated at 27.5°C), both thickness and length increased with SME. Obviously, with these mixing conditions, biscuit thickness and length were interrelated because SME and T_f increased concurrently (Fig. 1). So the positive effect of mixing speed on biscuit length might be attributed to the shear stress contribution rather than to the SME input. Given these results, there should be a reconsideration of the decrease in biscuit length when SME input exceeds a threshold value of 60 kJ/kg (Contamine et al 1995). In standard mixing conditions ($T_{\text{reg}} 27.5^\circ\text{C}$), when SME is >60 kJ/kg, T_f rises to $>35^\circ\text{C}$ (Contamine et al 1995, figures 1 and 2). Beyond this temperature threshold, biscuit shrinkage was observed even when dough was mixed at 187 rpm because the positive effect of mixing speed was hidden by the negative effect of temperature (Eq. 3, Table III).

Effects of Dough Temperature

Dough temperature influenced several characteristics of dough and biscuit, which are correlated in a way that may or may not be causal. The relationship between biscuit length and dough viscoelasticity is obviously causal: biscuit shrinkage arises from the elastic recovery of dough after sheeting and cutting.

Predicting models for dough consistency (evaluated by SRWAM extrusion time) and dough stickiness are rather similar and we are tempted to make a causal connection between these highly correlated parameters ($r = -0.92$). It is well established that both surface forces and bulk viscoelastic behavior play critical roles in the performance of pressure-sensitive adhesives (Dale et al 1989). According to Heddleson et al (1993), flour-dough tack behavior is analogous to that of pressure-sensitive adhesives, and tack ceases completely when G' reaches the Dahlquist criterion 10^5 Pa (1 Hz). When T_f rose from 20.8 to 37.2°C , the G' of biscuit dough increased from 0.24×10^5 Pa to 0.80×10^5 Pa (at 6 rad/sec = 1 Hz, Fig. 5) and fell within the range where wheat dough stickiness reportedly decreased (Heddleson et al 1993).

The rheological properties of wheat doughs are mainly influenced by the protein composition of wheat gluten (MacRitchie 1992; Sharma et al 1993; Hou et al 1996a,b). According to Ross-Murphy (1995), the plateau zone observed at intermediate frequencies for the G' modulus (≈ 1 rad/sec) is consistent with a transient entangled network structure in which polymeric chains are linked together by hydrogen bonds and hydrophobic interactions. Rise of dough T_f might increase the number of cross-links between gluten polymeric

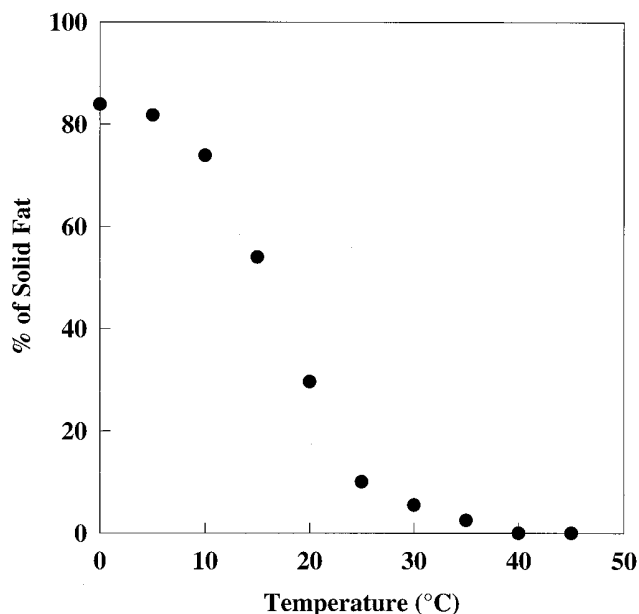


Fig. 7. Melting curve of recipe fat (blend of copra and palm fats).

chains and their lifetime. A rise in temperature could therefore strengthen the elastic behavior of dough. As in other natural or synthetic polymers, the rheological behavior of wheat gluten depends on temperature and plasticizer content (Levine and Slade 1990, Kalichevsky et al 1992). Because of its water content, the gluten of biscuit dough is obviously in a rubbery state for the temperature range investigated (Slade et al 1989). The rheological behavior of moistened gluten was sensitive to thermal denaturation. According to Tsiami et al (1997), aggregation of wet gluten proteins occurs at temperatures >40 – 50°C , leading to an increase in the gluten G' . Schofield et al (1983) demonstrated that wheat protein polymerization occurred when wet gluten was heated at 55 – 75°C . However, these temperature ranges are above our experimental values. It seems unlikely that such events occur as low as 32°C for a complex blend like biscuit dough as against $>40^{\circ}\text{C}$ for pure gluten.

A rise in dough temperature also influenced density. Figure 7 shows that the range of T_f studied overlapped that of fat melting. So when T_f is $>35^{\circ}\text{C}$, almost no fat crystals should remain. Brooker (1993) demonstrated that triglyceride crystals in bread dough and cake batter stabilized air bubble interfaces. A similar mechanism might occur in semisweet biscuit dough. In this respect, an increase in mixing speed might contribute to better spatial distribution of fat crystals (Breitschuh and Windhab 1997) and, hence, better stabilization of air bubbles and lower dough density. Conversely, fat melting at $>35^{\circ}\text{C}$ would cause air bubbles to collapse, resulting in higher dough density.

The melting of fat crystals thus seems to be the main physicochemical event occurring at 25 – 40°C that could be causally connected to structural changes in dough induced by T_f . We may suppose that during mixing, at a molecular level, gluten proteins interact mainly with fat crystals rather than together, thus decreasing the density of protein chain entanglement. This hypothesis is supported by the reduction in yield of extractable dough lipids observed as SME increases in dough mixed at low temperature. As reported for bread dough mixing (Frazier et al 1981, Chung 1986), lipid-protein interactions could occur in biscuit-dough mixing. As crystals melt, these interactions would be suppressed as liquid fat is entrapped in the dough matrix as droplets stabilized by polar wheat lipids (Le Roux et al 1990). Consequently, connectivity between protein chains would increase, leading to a higher G' . This hypothesis will need to be confirmed by studying the effects on biscuit length of the nature and physical state of the recipe fat ingredient.

Effect of Mixing Speed

Variance analyses showed that biscuit length, dough extrusion time, stickiness, density, and extractable fat were influenced by mixing speed rather than SME. For these parameters, the disruptive effect of shear stress caused by mixing speed prevailed over the distributive action associated with SME. The higher the speed, the greater the disruption and the lower the elasticity of dough. In this respect, dough extrusion time decreased when mixing speed increased. Nevertheless, a decrease in elasticity with increased mixing speed was not really disclosed by dynamic tests. The G' and G'' remained unchanged and increase in the loss tangent (i.e., dough elasticity) was related to a rise in either dough temperature or mixing speed. This result is inconsistent with the opposing effects of mixing speed and dough temperature on biscuit length. The discrepancy between fundamental and empirical rheological results emphasizes the complex behavior of biscuit dough. The behavior of gluten in small and large deformations differs according to its structural nature. Shear and elongational properties are also different. The effect of mixing speed on extrusion time (SWRAM) and biscuit length seems to indicate a change in elongational properties that would be less visible on oscillatory shear measurements.

Effect of SME on Biscuit Thickness

SME was the main contributory variable in biscuit thickness and related parameters (i.e., volume and density). According to our results, biscuit thickness is not related to the rheological behavior of

dough either at small or large deformations. As mixing time influences biscuit thickness, some slow physicochemical change might be involved in determining this quality parameter. As proposed for cookie spreading (Doescher et al 1987), biscuit thickness is probably the result of a combination of the rate of dough expansion by chemical leavening agents and differences in setting time. Both phenomena are governed by changes in dough temperature and water content during baking. More relevant information should be obtained by studying the rheological behavior of dough through thermo-mechanical analysis, as recently done by Chevalier et al (1998).

CONCLUSIONS

Our study demonstrated that semisweet biscuit length and thickness are influenced by different mixing variables, respectively identified as dough temperature at the end of mixing (T_f) and specific mechanical energy (SME) imparted to dough. The T_f contributed to an increase in the storage modulus (G') and hence the elastic behavior of dough, whereby dough stickiness and biscuit length decreased. A rise in dough temperature is likely to induce melting of fat crystals. Consequently, interactions between protein chains and fat crystals would be suppressed and dough elasticity increased. Dough density also rose, suggesting that fat crystals stabilized air bubble interfaces in semisweet biscuit doughs, probably according to a mechanism like that demonstrated by Brooker (1993) for cake batters.

SME imparted to the dough did not affect rheological properties but contributed to greater biscuit thickness, maybe by some physicochemical change in the dough yet to be identified.

When SME and T_f are not correlated, biscuit length and thickness appear to be independent quality parameters, so mixing conditions can be selected to control them separately. Conversely, in standard mixing conditions (i.e., for a given temperature of regulation), mixing speed, SME and T_f are strongly correlated. This is why the positive influence of mixing speed on biscuit length was hidden by the rise in dough temperature and not detected in our previous study (Contamine et al 1995).

The control of T_f (by regulation of the mixing bowl, liquid nitrogen spraying, or preliminary cooling of the ingredients) would successfully shift the relationship between T_f and SME input so the targeted combination of biscuit length and density could be obtained.

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