Determining Wheat Dough Mixing Characteristics from Power Consumption Profile of a Conventional Mixer

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ABSTRACT

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A Hobart mixer with a pin-type attachment was used to mix soft wheat flour dough. Power consumption profiles were measured continuously during mixing for 20 min using a current transducer and a data logging system. Experimental variables were quantity of flour (500, 1,000, and 1,500 g of dry wheat flour), water content (43, 45, and 47%, wb), and mixer speed setting (low, medium, and high). The power consumption profiles were evaluated by moving average and spectral analysis. Peaks in the power consumption profiles were located to determine the optimal mixing time. The optimal mixing times were then compared with storage and viscous moduli measured using a dynamic rheometer to assure the maximum strength of wheat dough at the optimal mixing time. Tolerance was determined using the signal amplitude and phase angle data from spectral analysis. Optimal mixing times of various doughs at medium speed ranged from 510 to 850 sec; low and high flour quantities required longer mixing times than medium quantity of flour. The optimal mixing time increased when the moisture content was lowered. Tolerance was affected by mixing speed and moisture content of flour

Because short fermentation baking has been developed by employing dough mixing, the mixing operation is considered as a process to facilitate structure development and ingredient homogenization. During mixing, the dough develops a protein network in which air bubbles are incorporated, and it becomes a soft and shiny viscoelastic material. Work input and mixing intensity are two critical factors for optimal dough development (Finney 1985; MacRitchie 1985). The work input is defined as the energy required to mix the dough to peak height in a development curve that is above a critical minimum value. The mixing intensity, the rate at which the dough is mixed, should also be above a minimum critical value.

Many researchers use empirical mixers such as the farinograph and mixograph to evaluate wheat flour and baking properties (AACC 2000). The factors measured using a farinograph are water absorption, dough development time, stability, and softness; the factors measured using a mixograph are mixing time, maximum resistance, and tolerance (Walker and Hazelton 1996). Zounis and Quail (1997) reported that the optimal mixing times predicted using two empirical dough mixers (such as farinograph and mixograph) and an 100-g capacity pin-type dough mixer were similar. Mixograph and the pin mixer results were similar because the pin configuration is used for kneaders. Mani et al (1992) examined farinograph, mixograph, and Krups and Hobart mixers to test breadmaking performance. The bread quality was similar at the optimum dough mixing regardless of mixer type. However, the optimum mixing times were different depending on the flour composition, mixer type, and bread formula. Optimal mixing time predicted based on dynamic rheological tests was in good agreement with the farinograph results but were 1 min shorter than the mixograph results because the mixograph usually generates more vigorous mixing action than farinograph.

To evaluate dough mixing properties, mechanical parameters such as mixer speed, mixing bowl capacity, and mixer geometry must be precisely controlled. Consequently, most published investigations have been performed using farinograph or mixograph for baking test because these empirical dough mixers have been developed to control the testing conditions well. However, such mixers can only accommodate small samples. The measurements could not be translated directly to evaluate baking quality nor do they correspond with results obtained using other mixers (Walker and Hazelton 1996; Graybosch et al 1999). The information for scale-up is not obtained to simulate the commercial mixers because the specially designed kneaders are used (Zounis and Quail 1997).

Voise et al (1966; 1969; 1970a,b; 1974) used a torque transducer incorporating a strain gauge and developed different recordable micromixer designs. They were able to record the torque at the mixing bowl electronically and analyzed the data in a manner similar to the typical farinograph data. They established that use of electronic recorder is a practical procedure to record dough development. But their work was limited to research and quality control purposes and they did not attempt to control dough mixing in large scale. Modification of mixing device was required, which may not be feasible for various large-scale mixers.

Conventional dough mixers such as a mixer with a dough hook or a spiral blade are commonly used in the industry. Most industries rely on the experience of their operators to determine the optimal mixing. Consequently, the baked product quality is controlled empirically, especially when the composition of flour mix is changed or a new mixing machine is introduced, etc. Conventional mixers are preferable to measure dough quality because they allow scale up. However they are not considered suitable because of the noisy signals or complicated modifications necessary (Anderssen et al 1996). At present, data logging techniques and data analysis procedures have been developed extensively to filter noisy signals and extract meaningful results, even in on-line mode with simple equipment such as an induction ammeter. Furthermore, such measurements do not require any physical modification and can be used by simply attaching to the power cable of the mixing equipment to record signals proportional to power consumption during mixing.

Our goal was to use a conventional mixer to monitor the dough mixing process with an induction ammeter and a data logger and develop procedures to analyze the power consumption profiles and define some useful measures of dough quality for the purpose of dough mixing control. The specific objectives of this study were to 1) evaluate wheat dough mixing characteristics using a conventional mixer; 2) analyze the mixer power consumption profile using moving average and spectral analysis techniques; 3) identify the critical factors such as peak mixing time and tolerance to evaluate the mixing properties; 4) determine the effects of mixing speed, flour quantity, and moisture content; 5) correlate the critical mixing factors with viscoelastic properties of wheat dough during the mixing time.

MATERIALS AND METHODS

Soft wheat flour (Wingold pastry, Bay State Milling Co., Quincy, MA) was mixed with various amounts of water to prepare doughs with 43, 45, and 47% moisture content. This flour was chosen

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because softer wheat flours tend to accentuate the variation during the dough development with fewer noisy signals (Khatkar et al 1996). A conventional mixer (model A-120, Hobart, Columbus, OH) with a three-prong pin-type attachment (National Mfg. Co., Lincoln, NE) was used. The mixer had three speed settings: low (106 rpm for agitator and 61 rpm for attachment), medium (196 rpm for agitator and 113 rpm for attachment), and high (358 rpm for agitator, 205 rpm for attachment). An inductive current transformer (model CTL-113005, Omega Eng. Inc., Stamford, CT), a current-to-voltage transducer (model CCT-04, Omega), and a data logger (model HP 34970A, Hewlett-Packard Co., Palo Alto, CA) were used to record power consumption profiles during mixing. The data logger was set to record voltage signals corresponding to the circuit currents at a rate of 27 points/sec, which is sufficient to collect more than four points/cycle at the highest mixer speed setting. Although the data logging speed does not significantly affect mixer power consumption profile (Hazelton and Walker 1995), our sampling speed was adequate to describe the data fairly well. The experimental parameters were: mixer speed (low, medium, and high), flour quantity (500, 1,000 g, and 1,500 g), and flour moisture content (43, 45, and 47%). The experiments were performed in a single-factor design with three replicates.

Two noise-reduction techniques employed S-Plus (MathSoft, Cambridge, MA): moving average analysis and spectral analysis. The moving average analysis was used to smooth raw profiles by averaging every 100 points. The spectral analysis was employed at selected frequencies based on some preliminary tests. Complex demodulation was used for analyzing nonstationary time responses by estimating the instantaneous amplitude and phase angle of a given harmonic component at the center frequency of 0.016 Hz. Then the amplitudes were smoothed with a least-square approximation to a low pass filter with a pass frequency of 0.05 Hz and a stop frequency of 0.1 Hz. The data analysis was performed off-line but can be performed on-line with appropriate programming.

In addition, rheological properties of dough during mixing were also measured using a controlled stress dynamic rheometer (model

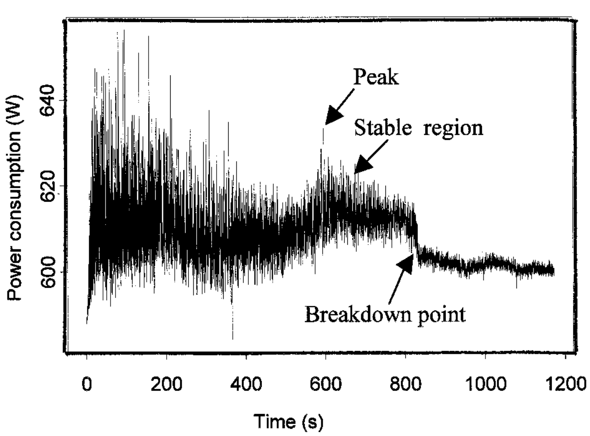

Fig. 1. Typical power consumption profile during mixing of wheat flour dough (500 g of flour, 45% moisture, and medium mixing speed).

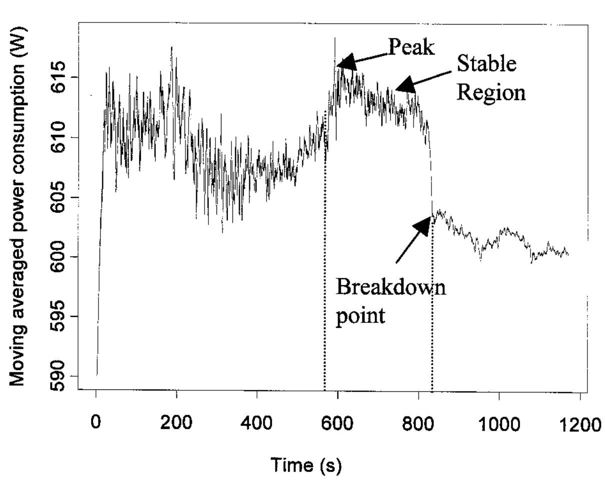

Fig. 2. Moving averaged power consumption profile during mixing of wheat flour dough (500 g of flour, 45% moisture, and medium mixing speed).

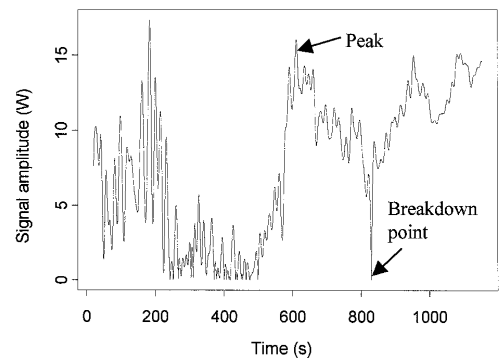

Fig. 3. Amplitude of mixing profile for wheat flour dough (500 g of flour, 45% moisture, and medium mixing speed).

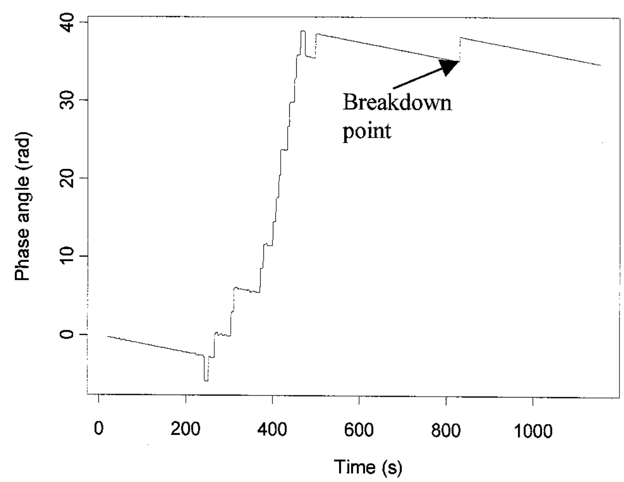

Fig. 4. Phase angle of mixing profile for wheat flour dough (500 g of flour, 45% moisture, and medium mixing speed).

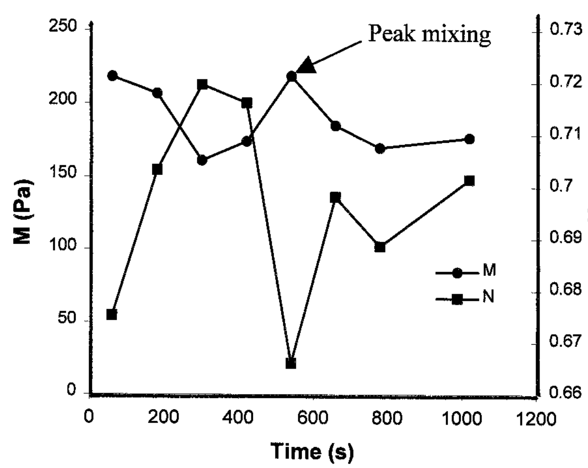

Fig. 5. Change in power law parameters (*M* and *N*) for dough (500 g of flour, 45% moisture, and medium mixing speed) in nonlinear viscoelastic range (strains 0.005–0.2) during mixing. $G' = M \bullet \gamma^{-N}$.

CVO, Bohlin Reologi AB, Sjöbo, Sweden). Dough (2 g) was sampled every 2 min while the dough was being mixed. Stress sweep tests >1 to 200 Pa (corresponding strains were 0.001 to 0.2) were performed at 1 Hz frequency in parallel plate configuration. A sample thickness of 2 mm was used and the sample edge was coated with petroleum jelly to prevent drying during the test. Sandpaper (grit 100, Rockler, Medina, MN) was attached to the parallel plate surfaces to prevent slipping. Based on Safari-Ardi and Phan-Thien (1998) and Mani et al (1992), strain levels for the dynamic tests were 0.008–0.2. It was determined that the extra harmonic components were not >10% of the first harmonic for the experimental condition, and the resulting oscillation was sinusoidal without severe shape distortion.

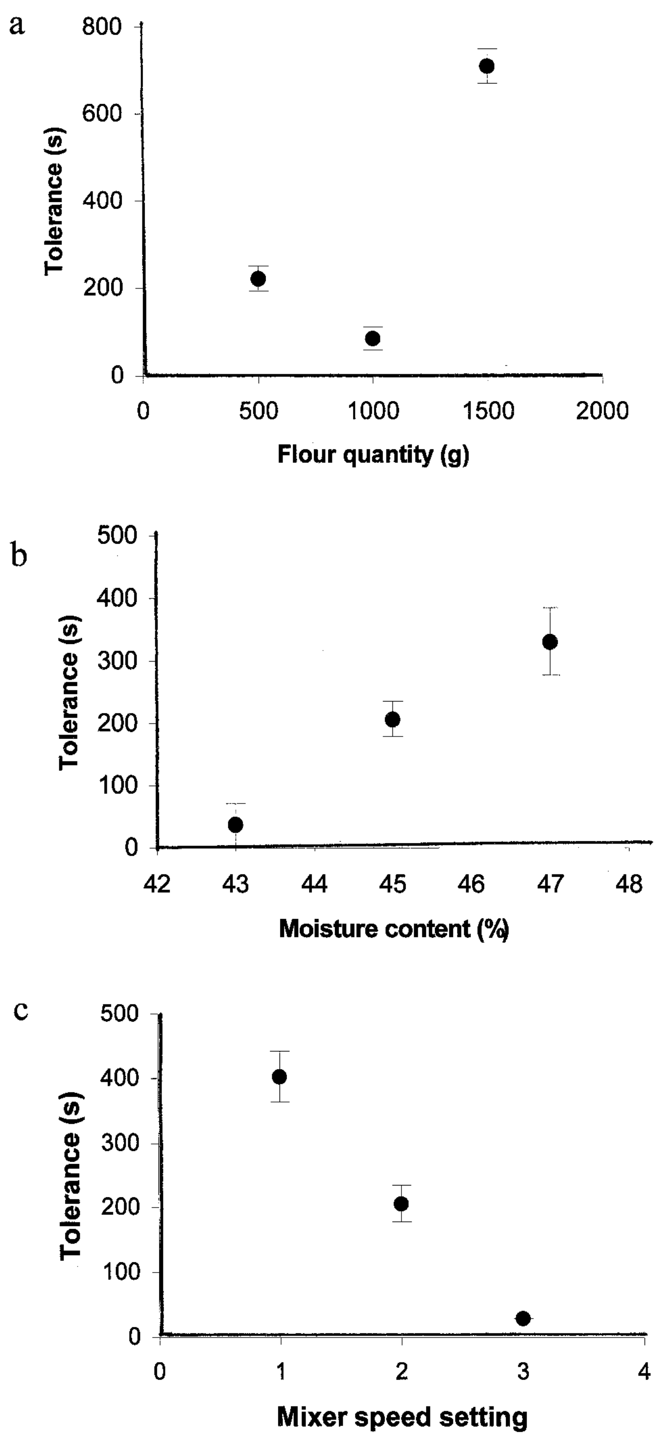

Fig. 6. Mixing time determined by different methods as a function of **a,** flour quantity (45% moisture, medium speed); **b,** moisture content (500 g flour, medium speed); and **c,** mixer speeds 1–3 (low, medium, and high) (500 g of flour, 45% moisture).

RESULTS AND DISCUSSION

Moving Average Analysis

A typical wheat flour dough mixing profile obtained using the conventional mixer is presented in Fig. 1. The beginning part of the profile consists of sharply varying peaks and valleys. The signals became stable and formed a peak, then dropped suddenly and flattened out. The region with sudden drop and flattening-out signals represents complete breakdown of dough structure due to overmixing. The profile has too many sharply varying signals and it is difficult to accurately obtain the peak mixing time and breakdown time. Therefore, the moving average technique was employed to smooth the raw profile. In the moving averaged power consumption profile (Fig. 2), the peak, stable region, and breakdown point are more easily distinguishable as compared with Fig. 1. The peak mixing time identified corresponded to the peak power consumption at 600 sec. Similarly, the breakdown point was identified where there was a sudden and steep drop in the averaged signal at ≈820 sec.

Spectral Analysis

Amplitude data of the power consumption profile, generated by spectral analysis are presented in Fig. 3. It is a more robust technique to extract the signal profile with specific frequency responses. With low frequency signals (0.016 Hz), the peak mixing time can be easily identified in this figure at 600 sec after a period of low amplitude region where the protein networks gradually build up. There is a sharp decline in amplitude at the breakdown point at ≈820 sec. The spectral analysis amplifies low frequency signals in the overmixed region (past the breakdown point) and produces several peaks. This is because the demodulation of the signal was based on 0.016 Hz that is very slow and tends to pick up low frequency signals well. This could be avoided by looking at the phase angle profiles of the signals that show step changes. This can help to determine major events during dough mixing (Fig. 4). The early step changes at 250 and 410 sec represent ingredient homogenization and were not considered here because they do not relate to the protein network formation and breakdown. The last step change at ≈820 sec corresponds to a breakdown point observed in the raw and averaged mixing profile. The phase angle profile is not helpful in identifying the peak mixing time because it is not an event associated with maximum power consumption, but rather a sudden drop followed by a period of fairly stable power consumption. Therefore, the spectral analysis of the power consumption profile can be used to identify the peak mixing time from the signal amplitude data and the breakdown point from the signal phase angle data.

Dynamic Rheometer Data

The elastic moduli versus strain data from the dynamic rheological tests were fitted (R^2 = 0.99) to a power law model ($G' = M{\bullet}\gamma^{N}$) using the data obtained at strains $0.008 \leq \gamma \leq 0.2$. This strain level, though not considered to be in the linear region, was selected based on recommendations of Safari-Ardi and Phan-Thien (1998) and Mani et al (1992). They reported that dynamic tests at $\gamma \leq 0.003$ are not helpful in distinguishing the type of wheat flour dough; but, at $\gamma = 0.2$, weak and strong flour dough samples can be distinguished. Mani et al (1992) reported the problems in evaluating dynamic rheological properties at $\gamma = 0.008$ over mixing time. A high value of the power-law model parameter M represents a high modulus at a given strain value, which can be interpreted as the dough having a strong network structure. A small N value would mean that the modulus changes little with strain. Therefore, we would expect higher M and smaller N values when dough becomes stronger. The plot of M and N versus time (Fig. 5) shows a clear peak and valley, respectively, at ≈540 sec. Because the sampling was done every 2 min, the true peak value may be 480–660 sec. This range includes the peak mixing time (≈600 sec) identified by the moving average and spectral analyses. It suggested that the maximum dough development occurs at 480 and 660 sec and moving average and spectral analysis determined it as 600 sec with good agreement. The trends of the viscous modulus (G'') data were similar to those of the storage modulus data and are not shown. However, unlike power consumption measurement, dynamic viscoelastic analysis can not be performed on-line, and the dough sampling can not be done more frequently than 1 min. The optimum mixing time can be in minutes. These are major disadvantages compared to the power consumption measurement.

The G' data we obtained over $0.001 \le \gamma \le 0.003$ (the generally accepted linear viscoelastic range) did not show any significant events corresponding to stages in dough development, as was the case with Safari-Ardi and Phan-Thien (1998).

Peak Mixing Time

The effects of flour quantity, moisture content, and mixer speed on the peak mixing time are presented in Fig. 6. The data obtained by moving average analysis, amplitude data from spectral analysis, and dynamic rheometry are all presented. The peak mixing times estimated based on all three techniques were higher when a small amount of flour (500 g) was used (Fig. 6a). When 1,000-g samples were used, the peak mixing times were shorter, and they subsequently flatten out for 1,500-g samples. This may be due to overloading of mixer that causes partial mixing. The peak value for the dough prepared with 500 g of flour determined from dynamic rheometry data deviated substantially from the others. This could be due to sample drying during mixing. Small loads of flour during mixing tend to dry faster than larger loads because of increased exposure to the surroundings. Because the dynamic tests are more susceptible to sample conditions, no clear trend of dynamic rheological properties was observed even for higher flour quantities.

Overall, the quantity of flour used in preparing the dough may not have a significant effect on the optimal mixing time except when the partial mixing occurs (Fig. 6a). The effect of moisture content is presented in Fig. 6b. The peak times determined from all techniques decreased with increasing moisture content. Water, which acts as a plasticizer (Kumagai et al 2000), may cause weaker protein network formation by softening structure.

The effect of mixer speed on peak time prediction (Fig. 6c) shows that the peak mixing time is slightly longer at the medium speed than at either low or high speed. The data at speed 1 (slow speed) may not be reliable because the data from three techniques were not consistent due to insufficient mixing power as previously reported.

Tolerance

Tolerance can be described as the duration over which the dough is expected to be stable during mixing after optimal mixing time. Long tolerance would mean that dough mixing is not sensitively affected by slight miscalculations of dough development or optimal mixing time. Therefore, for a certain quality of dough, the manufacturer must seek the operational conditions that would result in an adequate tolerance. The tolerance is directly obtained from mixograph data and is similar to dough stability determined from farinograph data. For practical purposes, we can define tolerance as the duration between peak mixing time and breakdown point. Therefore, the spectral analysis facilitates easy determination of tolerance based on the signal amplitude (peak mixing time) signal and phase angle data (breakdown point). The tolerance can also be determined from raw or moving averaged power consumption profiles. However, they require graphical determination with operator assistance and are not readily amenable for automatic data analysis and process control.

In Fig. 7, the tolerance times of the doughs studied were plotted against quantity of flour used for mixing, dough moisture, and mixer operating speed. The minimum tolerance was obtained when 1,000 g of flour samples were used. When low (500 g) or high (1,500 g) flour quantities were used, the tolerance increased (Fig. 7a). Changing the flour quantity to obtain longer tolerance is not a good option because the minimum tolerance obtained (≈100 sec) is generally sufficient to control the mixing operation. The tolerance is linearly related to dough moisture content (Fig. 7b) and it appears that tolerance can be adjusted by changing the dough moisture content. However, it is not a practical option because the dough moisture content is dictated by the required end product quality. Mixer opera-

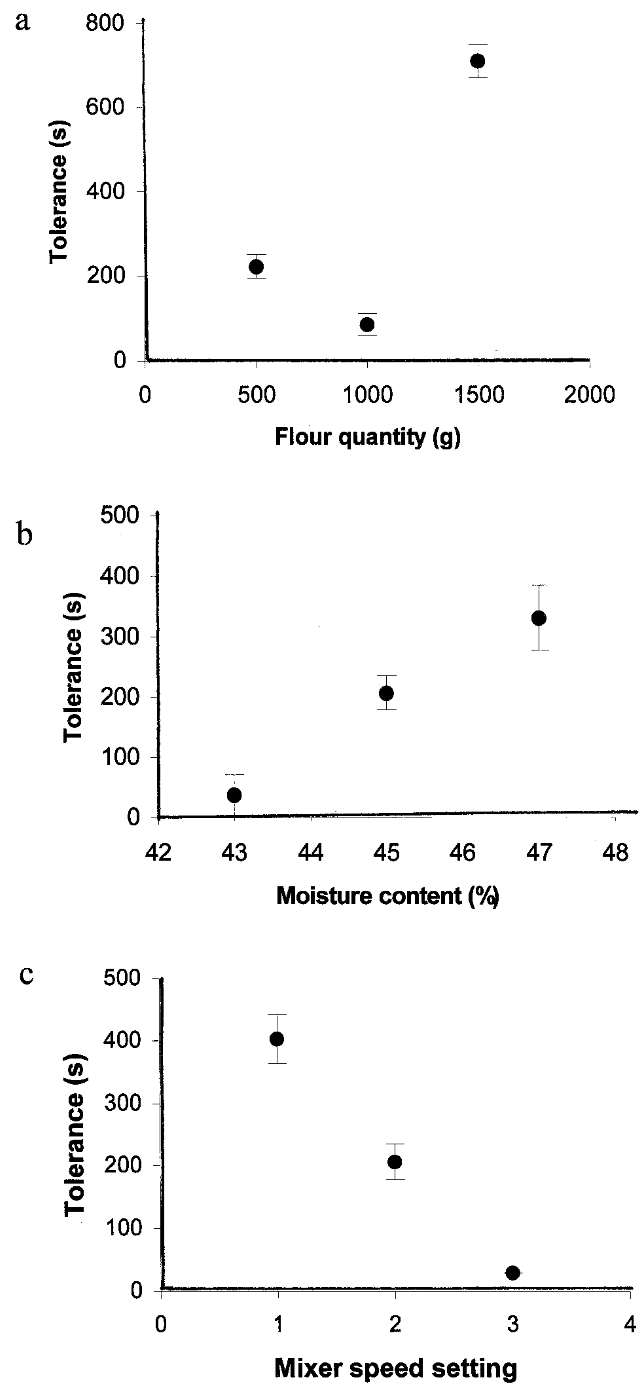

Fig. 7. Tolerance (difference of peak mixing times from amplitude and phase angle profiles) as a function of **a,** flour quantity (45% moisture, medium speed); **b,** moisture content (500 g of flour, medium speed), and **c,** mixer speeds 1–3 (low), medium, and high) (500 g of flour, 45% moisture).

ting speed is linearly related to inverse of tolerance in a wide range of ≈25–400 sec (Fig. 7c). Therefore, mixing speed offers a real choice in controlling the required tolerance. Based on this, dough-mixing speed can be optimized. Slower speed would be favorable to increase tolerance but need to be above the minimum required for good mixing.

It should be noted that, mixing attachment, the geometry of mixing bowl, and mixing action also affect the peak mixing time and tolerance time and should be investigated in future research. Improved shear detecting sensor (stress transducer) of Dealy and Soong (1984), easily attachable to mixing bowls, can be used to determine less noisy stress and time profiles during dough mixing. New design for mixing paddles may also provide more stable signals than what we have recorded. Because the intensity of mixing is important to develop the optimum condition of bread dough, the speed of mixing should be well controlled. Several steps of mixing speed may be beneficial over constant mixing speed widely used today. We have described some possibility of moving toward automatic control of dough mixing. With some robust noise filtering protocol, a control algorithm can be developed for on-line determination of peak mixing time and tolerance. A programmable logic controller can be utilized to design a stand-alone automatic, batch dough mixer, or a household automatic breadmaking machine.

CONCLUSIONS

Power consumption profiles of a conventional dough mixer were measured during mixing and evaluated by moving average and spectral analyses. Peak mixing times were determined from the peaks of the moving averaged power consumption profiles and amplitude profiles from spectral analysis and were compatible with the optimum mixing time from dynamic rheological tests. Tolerance was calculated based on the signal amplitude and phase angle data. Optimum mixing times of various dough samples at medium speed were 510–850 sec. A clear maximum peak was not observed at lower speeds due to insufficient mixing intensity. Low and high flour quantities required longer mixing times than medium quantity flour. Optimum mixing time increased when the moisture content was lowered to 43–47%. Tolerance was critically affected by mixing speed and moisture content of flour. The results indicate that direct measurement of mixer power consumption profile during dough mixing can be used to determine some critical wheat flour dough mixing characteristics.

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