Journal of the Science of Food and Agriculture *J Sci Food Agric* **85**:2194–2202 (2005)
DOI: 10.1002/jsfa.2237

Dough aeration and rheology: Part 2. Effects of flour type, mixing speed and total work input on aeration and rheology of bread dough

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Abstract: The aeration and rheological properties of bread doughs prepared from strong and weak flours at various mixing speeds and work inputs in a high-speed laboratory-scale mixer were investigated. Dough aeration was quantified in terms of gas-free dough density and gas void fraction using density measurements, while dough rheology was characterized in terms of the strain hardening index, failure strain and failure stress under large biaxial extensional deformation using the SMS Dough Inflation System. Increasing mixing speed had little effect on the gas-free dough density but increased the void fraction of gas occluded in dough. As mixing progressed, the gas-free dough density initially increased, more dramatically for the weak than the strong flour, before reaching a plateau at approximately 30 kJ kg^{-1} energy input. The gas content tended to increase over the range of work inputs tested. For both flours, the strain hardening index, failure strain and failure stress increased with work input initially, followed by a decrease. The absolute values were all higher for the strong flour, while maximum values and the work input at which the maximum occurred depended on the mixing speed. These results show that both aeration and rheological characteristics of dough are dependent on both the total work input and the work input rate. The results also demonstrate the facility of the Dough Inflation System to describe the mechanical development of dough rheology over the course of high-speed mixing.

Keywords: bread dough mixing; aeration; rheology; Dough Inflation System

ABBREVIATIONS

CBP	Chorleywood Bread Process
DIS	Dough Inflation System
DIS-PDD	Dough Inflation System point of peak dough development
TSE	total specific energy

INTRODUCTION

Dough rheology and aeration are closely related because the changes in dough rheology during development affect both the incorporation of gas bubbles and their ability subsequently to evolve into gas cells in the baked loaf. The aeration and rheological properties of dough at the end of mixing have a direct effect on the gas cell structure in the baked loaf. This is especially true in no-time processes such as the Chorleywood Bread Process (CBP) because doughs are fully developed in the mixer itself and punching is eliminated while moulding is performed before significant yeast activity occurs. Rheological studies of dough abound in the bread literature, while aeration studies have surfaced from time to time and are currently prominent, with several new measurement and evaluation techniques emerging in the last decade. However dough rheology and aeration are seldom studied together.

Rheological measurements for bread dough are broadly classified into empirical and fundamental techniques.[1] The empirical methods provide useful information and are widely accepted for flour characterization and quality control. The fundamental methods provide better-defined experimental conditions of stress and strain which allow results to be interpreted in fundamental units.[2,3] The Dobraszczyk–Roberts Dough Inflation System (DIS), for example, is a recently introduced fundamental dough rheology test that measures stress and strain relationships based on the inflation of a sheet of dough.[4,5] The deformations involved in biaxial extension tests are relevant to the type of deformation of the dough around an expanding gas bubble during proving and baking.[6–8] Dobraszczyk and Morgenstern[1] and Kokelaar *et al*[9] advised that biaxial extension tests were more relevant to breadmaking quality than small strain dynamic measurements.

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(*Received 4 August 2004; revised version received 8 December 2004; accepted 27 January 2005*)

Designed using the Alveograph concept, the DIS has so far been used principally for comparing flour quality.[4,8,10] It is designed to operate at constant volumetric air flow rates which vary between 10 and 2000 ml min^{-1}, corresponding to maximum strain rates of $0.001-0.2\,\text{s}^{-1}$; the lower limit approaches rates of baking expansion,[4] unlike the Alveograph that operates at strain rates in the range of $0.1-1\,\text{s}^{-1}$, which are at least 100-fold higher than those occurring in actual baking processes.[11] The assumptions currently employed to derive strain hardening parameters using the DIS have been criticised by Charalambides *et al*[12,13] and, more recently, the facility to inflate doughs at an approximately constant strain rate has been introduced,[10] arguably improving the validity of the analysis whereby rheological parameters are derived (see Appendix). The constant strain rate is achieved (approximately) through an algorithm in the software that exponentially increases the rate of travel of the piston that drives the inflation. Newberry *et al*[14] used the same approach in their studies of uniaxial elongation of doughs.

Dough rheology measurements using the DIS have been analysed and interpreted in various ways previously. Dobraszczyk and Roberts[4] and Dobraszczyk[8] described the stress–strain curves using the power law relationship

$$\alpha = k\varepsilon'' \tag{1}$$

and Dobraszczyk *et al*[10] used the exponential equation

$$\sigma = k\mathrm{e}^{n\varepsilon} \tag{2}$$

where σ is the stress and ε the Hencky strain. The latter was found to match experimental data well. The coefficient, k, might be understood as relating to dough viscosity, while the index, n, is considered a measure of the degree of strain hardening. Their proposed Considère instability criterion gives a relationship between the strain hardening index, n, and the critical strain, $\varepsilon_{\text{crit}}$, beyond which instability occurs, such that for a power law relationship $n = \varepsilon_{\text{crit}}$. For the exponential equation, the analogous derivation does not yield a clear relationship between n and $\varepsilon_{\text{crit}}$, and this relationship is therefore still the subject of consideration (Dobraszczyk, personal communication; Dobraszczyk *et al*[15]). Both equations, however, imply that a higher value of n (greater strain hardening) gives a greater strain at which instability occurs, and hence greater bubble failure strains and ultimately greater loaf volumes. Results from the DIS can also be reported in terms of the measured pressure *versus* drum distance (distance moved by the piston), to give traces similar to those recorded by the Alveograph.

Since the application of larger strains through biaxial extension in dough rheology testing is relevant to the breadmaking process, the DIS, which has not been used previously to investigate mechanical dough development, is applied in the current work to measure rheological properties of dough related to the CBP. Aeration characteristics are also investigated using dough density measurements. This paper investigates the aeration and rheological characteristics of doughs mixed to various work input levels at three mixing speeds and under three headspace pressures using commercial flours.

MATERIALS AND METHODS

Dough preparation and experimental design

A factorial design experiment incorporating two flour types, three levels of mixing speed, six levels of work input, and three levels of mixing pressure ($2 \times 3 \times 6 \times 3$) was performed. Doughs from the strong flour, President White, and weak flour, Soft Patent, were mixed in the Tweedy 1 mixer using the system described in Part 1 of this series[16] at three mixing speeds, low, medium and high, ranging from about 40 to 70 rad s^{-1}, and at three headspace pressures, high vacuum (0.07 or 0.17 bar absolute), atmospheric (1 bar) and high pressure (2 bar). The work input levels were 10, 20, 30, 40, 50 and 60 kJ kg^{-1} (however, results were obtained for only the first four levels for the low speed, as the dough failed to mix properly beyond a work input of 40 kJ kg^{-1}). Flour characteristics and dough formulation were as described previously.[16]

Dough aeration

Dough density, ρ, was measured by weighing dough samples in air and immersed in xylene using a double cup system as described by Campbell *et al*[17] and Chiotellis and Campbell.[18] Six samples were obtained from each mixing trial and the average density calculated. The gas-free dough density, ρ_{gf}, was obtained by extrapolating the graph of dough density *versus* mixing pressure, P, back to zero absolute pressure and fitting a regression line to find the intercept:[19,20]

$$\rho = \rho_{\text{gf}} - sP \tag{3}$$

where s is the slope of graph. The gas void fraction, α_{P}, at pressure P is then expressed as:

$$\alpha_{\text{P}} = 1 - \frac{\rho_{\text{P}}}{\rho_{\text{gf}}} = \frac{sP}{\rho_{\text{gf}}} \tag{4}$$

Error bars (±1 standard deviation) were calculated following Campbell *et al.*[19]

Dough rheology

Dough rheology was measured using the SMS Texture Analyser $\text{TA.XT}_{\textit{plus.}}$ (Stable Microsystems, Godalming, UK) with the Dobraszczyk–Roberts Dough Inflation System attached.[5] These measurements were performed on the doughs mixed at atmospheric pressure only, and were carried out at room temperature. Approximately 300 g of dough was taken from the mixer and rolled flat to a thickness of 8 mm using a roller mechanism. Five 55 mm diameter circular samples were cut from this sheet using a pastry cutter and pressed for 30 s into holders to form sheets with a nominal thickness of 2.67 mm and a ring diameter of 55 mm. Excess dough extruded through holes in the ring. The samples and apparatus surfaces were coated with paraffin oil (Fisher Scientific, Loughborough, UK) to prevent moisture loss and dough surface drying. The five discs were compressed in turn, then stacked up in holders to prevent moisture loss and rested for 30 min, to allow relaxation of stresses, prior to testing. Each disc, in turn, was slotted into the nozzle on the platform of the DIS and inflated at a constant strain rate of 0.1 s^{-1}. The test stopped automatically when a break or rupture of dough bubble was detected. Two sets of measurements were performed for each mixing trial.

From the pressure, volume and time data recorded at 10 pps (points per second) during the inflation, stress and strain data were calculated as described in the Appendix. An exponential curve, $\sigma = k\varepsilon^{n\varepsilon}$, was fitted to the stress–strain curves using Microsoft Excel's solver function and minimising the sum of the squares of the normalised errors to find the coefficient k and index n. The failure strain and failure stress were determined from the bubble failure point, *ie* when the dough bubble material failed to sustain the inflation and ruptured. The reported rheological parameters of dough, k, n, failure strain and failure stress, were averaged from ten dough samples (consisting of five samples from each of two replicate runs). Error bars appearing in the graphs are the standard deviation of the mean of the ten samples, *ie* the standard error. Using the constant strain rate inflation approach resulted in some bubbles not rupturing by the time the limit of travel of the DIS's piston was reached; this new facility would benefit from a longer piston chamber. (Note: as a result of these findings and those of other workers, a longer piston chamber is now available from Stable Microsystems.) Inflated dough bubbles that did not rupture were also included in the reported results; thus some of the larger failure strains and stresses reported are underestimates.

The aeration and rheological data were statistically analysed using analysis of variance (ANOVA) or the generalised linear model of analysis of variance (GLM ANOVA) for the effect of mixer speed and work input levels. The NCSS 2000 v2.00 statistical package (NCSS Statistical Software, Kaysville, Utah, USA) was used for all calculations and the sample size for GLM ANOVA was 3 × 4 (mixing speed × work input).

RESULTS AND DISCUSSION

Gas-free dough density and gas void fraction

Figure 1 shows an example of a graph of dough density *versus* mixing pressure, extrapolated to zero absolute pressure to find the gas-free dough density. This set of results is from doughs from both the strong and weak flours mixed at low speed up to 10 kJ kg^{-1} of work input. The gas void fraction at atmospheric pressure (1 bar) for the strong flour dough (4.4%) is higher than that for the weak flour dough (3.5%). This is in contrast to the trend usually observed, where weak flour doughs give greater aeration, owing to the low work input level selected for illustration.

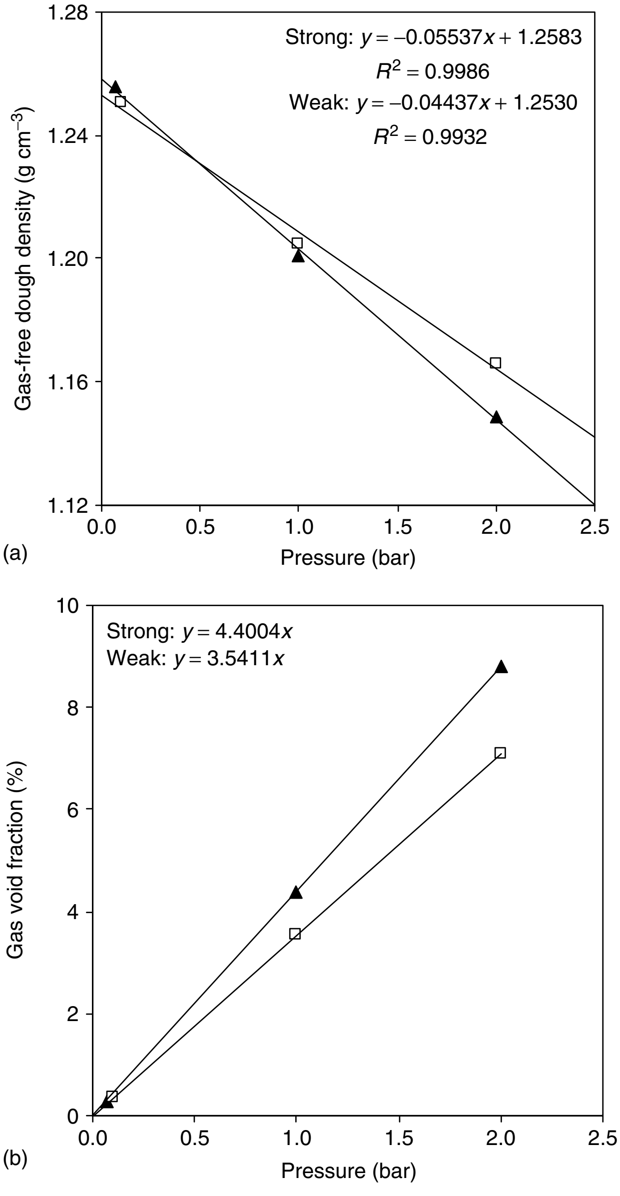

Figure 1. Determining (a) gas-free dough density and (b) gas void fraction of doughs mixed at low speed up to 10 kJ kg^{-1} for strong (▲) and weak (□) flour doughs.

Figure 2 illustrates the gas-free density of doughs mixed to various levels of work input at three speeds. The work input factor ($P < 0.05$ for strong flour and $P < 0.001$ for weak) gave a more significant effect than the mixing speed factor ($P < 0.3$ for strong and $P < 0.7$ for weak) on the gas-free dough densities. Work input levels affected the gas-free dough density for both flours, more significantly (indeed, quite dramatically) for the weak flour at low levels of work input. This demonstrates that the gas-free dough density is not simply a function of the dough

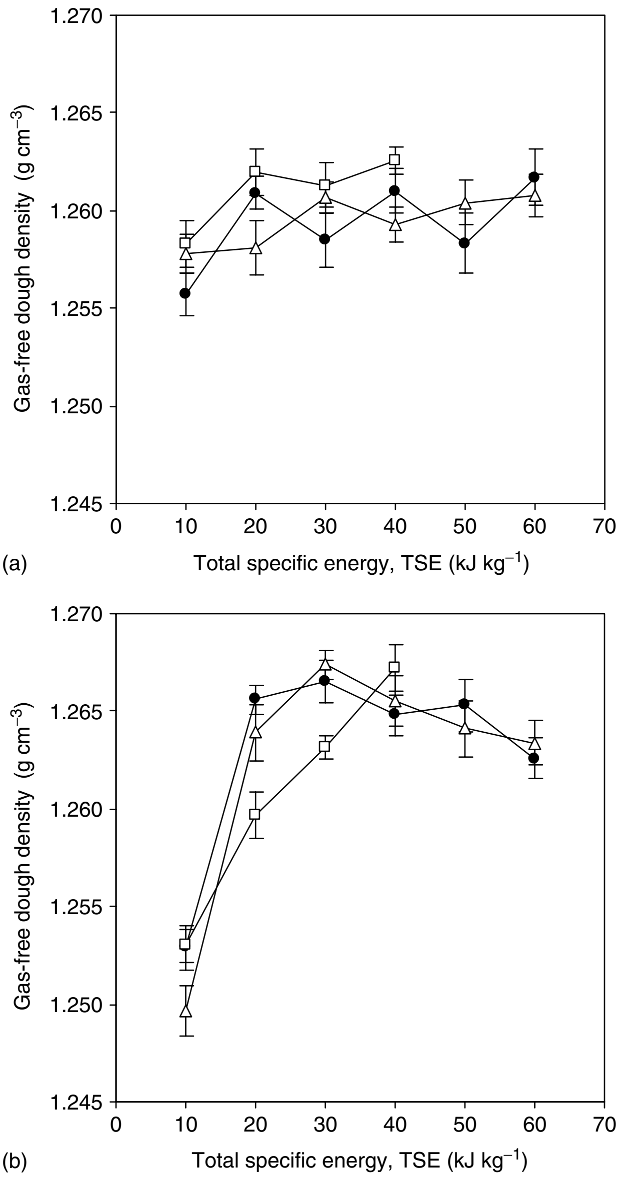

Figure 2. Gas-free dough density at low (□), medium (●) and high (△) mixing speeds and at various work inputs for (a) strong and (b) weak flour doughs.

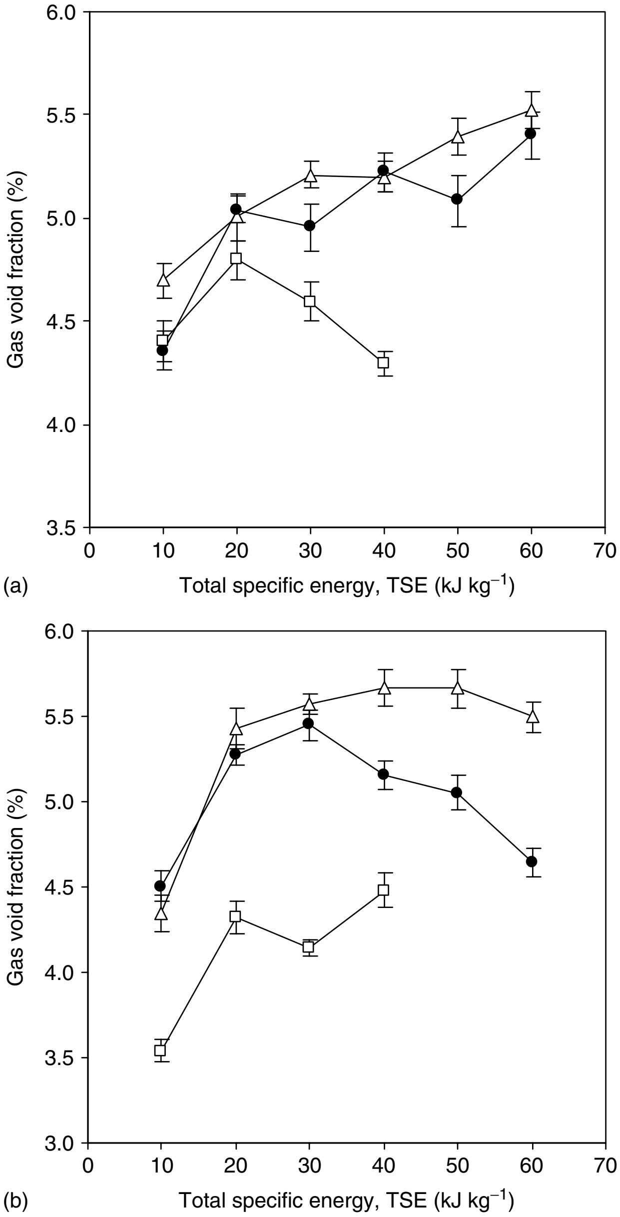

Figure 3. Gas void fraction at low (□), medium (●) and high (△) mixing speeds and at various work inputs for (a) strong and (b) weak flour doughs.

formulation, but depends also on the dough's shear history. Note that calculations of void fraction are sensitive to the gas-free dough density assumed: a 0.5% increase in the gas-free dough density typically corresponds to about a 10% increase in the calculated void fraction.

Figure 3 shows that both work input level and mixing speed affected the gas void fraction at atmospheric pressure in doughs. The results suggest a progressive occlusion of air up to a peak, followed by a decreased ability to incorporate and retain air, with the work input at the peak dependent on both mixing speed and flour type, in agreement with Baker and Mize[21] and Junge *et al.*[22] Mixing at faster speeds gave greater aeration, in agreement with previous workers.[17–19,23] Both factors, the mixing speed ($P <$ 0.05 for strong flour and $P < 0.0003$ for weak) and work input ($P < 0.2$ for strong and $P < 0.003$ for weak) gave more significant effects on the gas void fraction in weak flour doughs than in strong flour doughs. In the case of the strong flour mixed at medium and high speeds, the maximum aeration had apparently not been achieved after 60 kJ kg^{-1} of work input.

Dough rheological parameters

Figure 4(a) shows a typical pressure *versus* drum distance trace of an inflating bubble from doughs mixed at low speed up to a work input of 10 kJ kg^{-1}. The strong flour displayed a higher peak pressure and further drum distance before bubble rupture occurred. The corresponding stress–strain data in Fig 4(b), calculated following the approach detailed in the Appendix, shows a considerable increase in stress with strain. This curvature up to failure

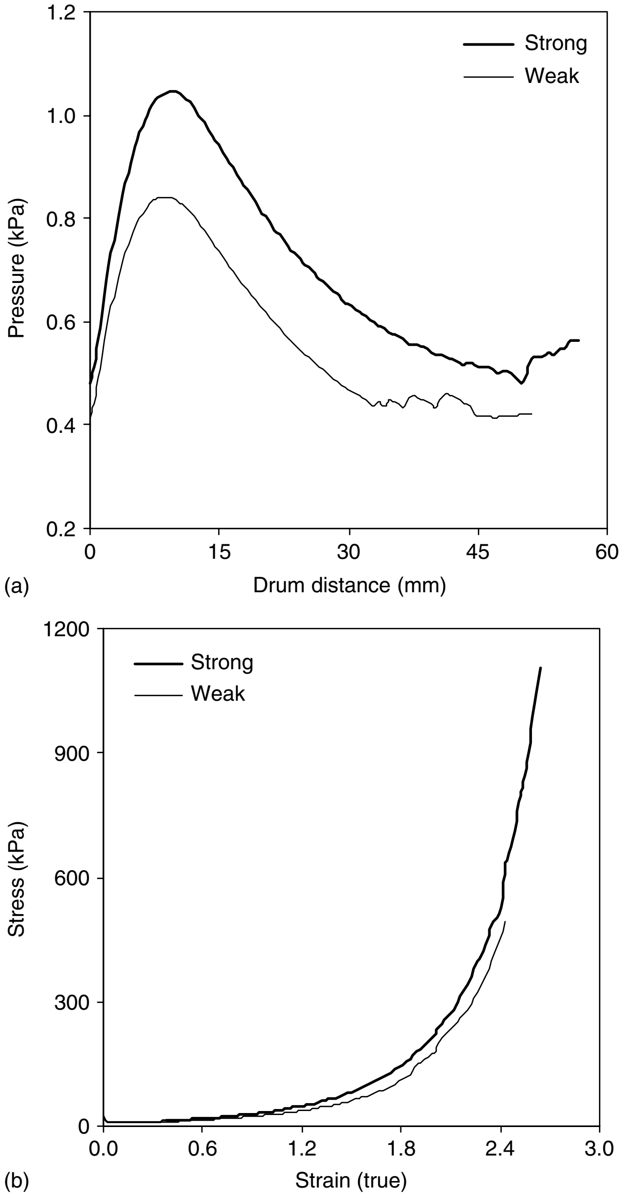

Figure 4. (a) Pressure *versus* drum distance plots of inflating dough bubbles; and (b) their corresponding stress *versus* strain plots, for doughs mixed at low speed to a work input of 10 kJ kg^{-1}.

indicates an increased shear modulus and a clear strain hardening effect within the walls of the inflating dough bubble. The stress–strain curves were fitted with the exponential equation (Eqn (2)) to obtain the coefficient k and index n, while the failure strain and stress were identified from the point at which bubble rupture or failure was detected.

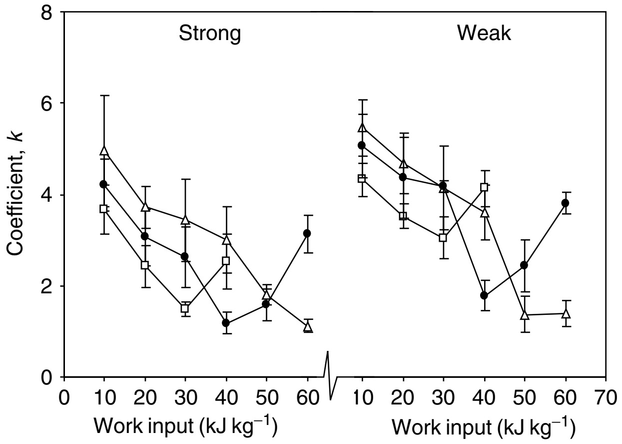

Figure 5. Coefficient of strong and weak flour doughs mixed at low (□), medium (●) and high (△) speeds.

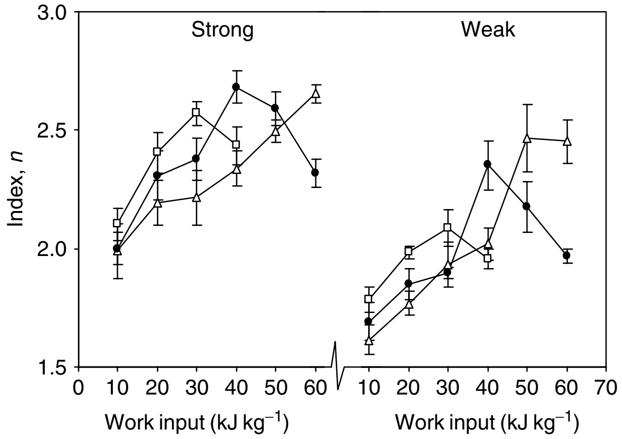

Figure 6. Strain hardening index of strong and weak flour doughs mixed at low (□), medium (●) and high (△) speeds.

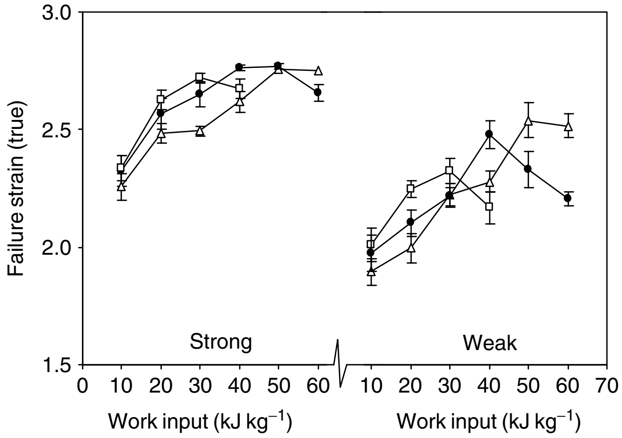

Figure 7. Failure strain of strong and weak flour doughs mixed at low (□), medium (●) and high (△) speeds.

Figures 5–8 show how the four rheological parameters varied with work input and mixing speed for the two flours. Figure 5 shows that k first decreased and then increased with work input for both flours. Doughs mixed at low speed turned at lower work inputs. Figure 6 shows the opposite trend for n, which first increased and then decreased with increasing work input. Again, the turn occurred at lower work inputs when mixing at low speed. The value of k at the minimum point was higher when mixing at low speed and, correspondingly, the value of n at the maximum point was lower. Strong flour doughs consistently showed lower k and higher n values at all mixing speeds when compared with the weak flour doughs. The parameters k and n are clearly correlated, essentially as a result of the equation fitting procedure, but n is more readily and relevantly interpreted as indicating strain hardening behaviour.[4,8,10] The results indicate that

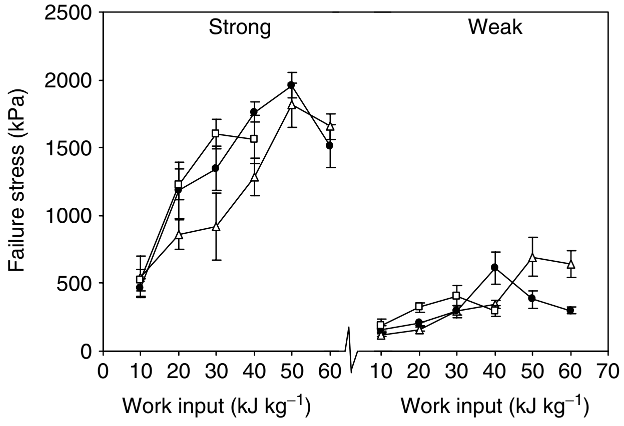

Figure 8. Failure stress of strong and weak flour doughs mixed at low (□), medium (●) and high (△) speeds.

the strain hardening property of dough increases as mixing progresses, up to a maximum, then deteriorates as the dough becomes overmixed. The turning point is reached at higher work inputs when mixing is carried out at faster speeds, and the maximum degree of strain hardening achieved is higher at greater speeds.

Wilson *et al*[24] concluded that mechanical dough development can take place over a wide range of mixing speeds; however, the above results suggest that optimum rheological properties for bubble stability are affected quite strongly by both work input and mixing speed. This may reflect the sensitivity of the laboratory-scale mixer compared with those used in industry; Wilson *et al*[25] noted that the industrial-scale mixer they studied was less sensitive to changes in work input optima than their laboratory mixer, making it more tolerant of different flours, which is an advantage in industry.

The above results suggest that loaves baked from doughs mixed to the point of maximum strain hardening would have the greatest volume and/or finest crumb structure. Loaves were not baked in this work; however, the failure strains and stresses were measured, and these have been demonstrated previously (along with strain hardening index) to correlate with loaf volume.[10] Figures 7 and 8 show that both the failure strain and failure stress increased and then decreased with work input, in strong correlation with the pattern of strain hardening development in Fig 6. This conjecture on the relation to baking performance would also be strengthened if measurements were made at lower strain rates and higher temperatures, conditions more similar to those achieved during proof and baking. However, the current results demonstrate the potential for applying dough inflation measurements to describe mechanical dough development and relate it to baking performance.

Figure 9 confirms that the strain hardening index and the strain at bubble failure are highly correlated, in agreement with the results of Dobraszczyk *et al*,[8,10] and shows that failure tended to occur at a strain value slightly larger than the value of n. As noted above, when using the exponential equation to describe the stress–strain data, the relationship between $\varepsilon_{\mathrm{crit}}$ and n is not clear, but these results suggest that the relationship may be $\varepsilon_{\mathrm{crit}} = n$, with failure occurring once the strain is slightly beyond the critical strain for stability. The current variations in strain hardening and bubble failure were generated by varying the mixing process applied to constant dough formulations, in contrast to Dobraszczyk and coworkers' results which were obtained for doughs prepared from different flours. The current results therefore complement these earlier results and strengthen the confidence that a sound relationship between $\varepsilon_{\mathrm{crit}}$ and n can be established, and that it will allow prediction of the effects of processing as well as of formulation factors.

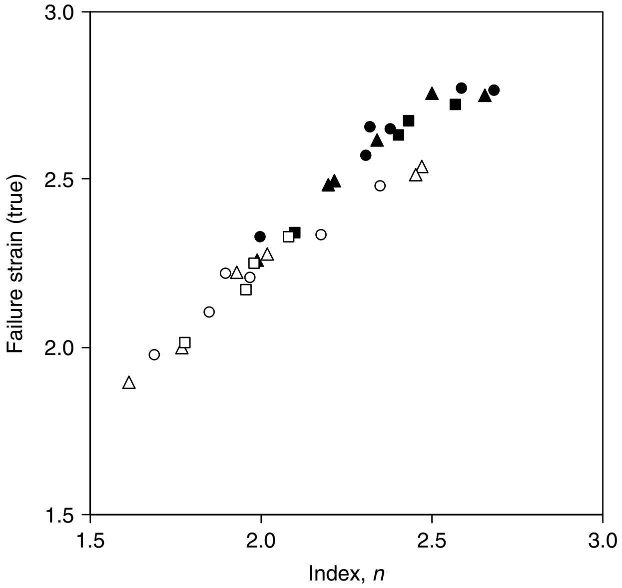

Figure 9. Failure strain *versus* strain hardening index of strong (filled symbols) and weak flour (empty symbols) doughs mixed at three mixing speeds: low (■, □), medium (●, ○) and high (▲, △).

The above results are also consistent with the findings of several workers who measured the response of dough rheology and baking properties to mixer speed, and found that the point of optimum dough development moved to larger work inputs, and achieved higher degrees of development, when doughs were mixed at faster speeds.[26,27] However, Fig 8 of Frazier *et al*[26] implies a greater magnitude of the rheological parameter (compressive stress relaxation time) with increasing mixing speed at all work inputs. In contrast, the current results indicate a more complex overlapping relationship. For illustration, from Fig 6, delivering 30 kJ kg^{-1} at the low speed gives a greater strain hardening index than delivering the same work input at the medium or high speed. However, at the higher speeds a greater strain hardening index is ultimately achievable, but at the cost of more work. This pattern is consistent for all four rheological parameters measured and for both flours. The unexpected observation that mixing at low speed gave higher values of strain hardening index, failure strain and failure stress than mixing at higher speeds to the same (low) work input might be explained by considering the aeration data. From Fig 3, the gas void fraction in the dough was lower at lower mixing speeds. Previous work (Campbell *et al*[28]) and the results presented in Part 3 of this series[29] indicate that lower gas contents result in higher values of these parameters. Thus the apparent high values of n, failure strain and failure stress in the doughs mixed to low work inputs at low speed may simply reflect the lower gas contents of these doughs. According to this view, at higher work inputs the underlying rheology of the developing gluten then dominates over the aeration effect, such that high-speed mixing ultimately delivers greater strain hardening and bubble stability, despite the higher gas content. Part 3 of this series[29] considers the consequences of aeration of the dough on its measured rheology further.

The results also suggest that it is possible to define a Dough Inflation System point of peak dough development (DIS-PDD). The DIS-PDD mixing time describes the point at which the gluten network is optimally defined for maximum bubble stability during subsequent proving and baking. (As noted above, measurements made at lower strain rates and higher temperatures are likely to give a better correlation with baking performance; the DIS-PDD should preferably be based on measurements made under these conditions.) This is more relevant than the point of peak resistance to mixing obtained from torque traces,[16] although less easy to measure. Figure 10 shows the total work input at DIS-PDD *versus* work input at peak torque for the current study. The DIS-PDD appears to show a slight correlation with the peak torque, but occurs at a work input at least 65% greater than that given by the peak torque.

Alava *et al*[30] introduced a dough mixing time based on the changing patterns of the near infrared (NIR) spectrum of the dough measured by a diode array system. This mixing time, based on a non-invasive, on-line approach, is considerably easier to measure than the DIS-PDD mixing time described above; however, parallel studies of the two mixing times would throw mutual light on the physico-chemical phenomena underlying each and their relevance to baking performance.

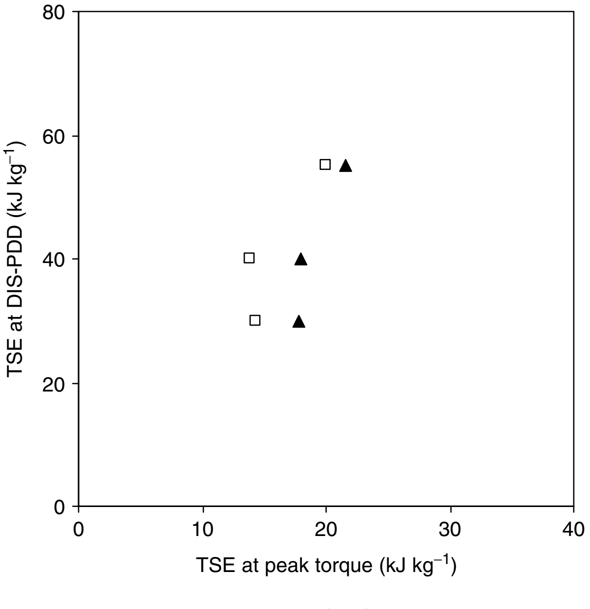

Figure 10. Total specific energy input (TSE) at DIS-PDD *versus* that at peak torque for strong (▲) and weak (□) flour doughs.

CONCLUSIONS

Mixer blade speed and work input displayed clear effects on aeration of dough during mixing, for doughs prepared from both weak and strong flours. Mixing speed had little effect on the gas-free dough density, but increasing the mixing speed increased the void fraction of gas occluded into the dough. Work input clearly affected both the gas-free dough density and the gas content. The gas-free dough density initially increased, more dramatically for the weak than the strong flour, before approaching a plateau. The gas content tended to increase over the range of work inputs investigated.

Dough rheological characteristics measured using the Dough Inflation System depended strongly on both the work input and the rate of work input. The strain hardening behaviour of the dough, the failure strain and the failure stress increased with work input initially, followed by a decrease, with the change occurring at lower work inputs for slower mixing speeds. The strong flour displayed higher absolute values for these parameters than the weak flour, while the maximum values in each case were higher at faster mixing speeds. The results indicate that the optimum mixing speed and work input can be defined in terms of the rheological development of the dough as described by the Dough Inflation System, but that allowance for the effects of aeration on the measured dough rheology must be made.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Satake Corporation of Japan for support in establishing the activities of the SCGPE, and University Putra Malaysia for financial support to NL Chin's course at UMIST, and thank Dr Peter Martin for valuable comments on the manuscript.

APPENDIX

The rheological properties from the DIS data were calculated directly from the time t pressure P and air volume V following Anon.[31] The equations were derived by Bloksma[32] and verified by Launay and Buré[33] and Launay *et al*[34] based on the geometry of the dough bubble shown in Fig A1. The air volumetric

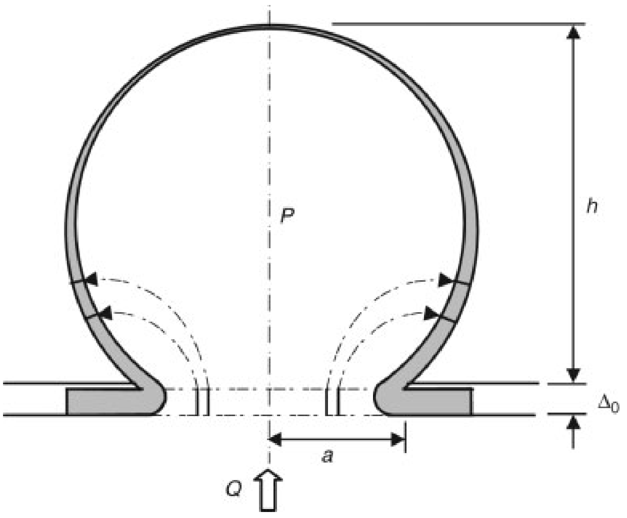

Figure A1. Cross-section of an inflating dough bubble.

flow rate Q and the drum distance D were calculated as follow:

$$Q = \frac{V_i - V_{i-1}}{t_i - t_{i-1}} \tag{A1}$$

$$D = t \times 5.5\,\text{mm}\,\text{s}^{-1} \tag{A2}$$

The bubble height, h, was calculated using the scaled volume SV and inversion length IL:

$$SV = \frac{3}{\pi}V \tag{A3}$$

$$IL = \left(SV + \sqrt{a^6 + SV^2}\right)^{\frac{1}{3}} \tag{A4}$$

$$h = IL - \frac{a^2}{IL} \tag{A5}$$

where a is the initial sample radius (27.5 mm) and h is the bubble height.

The stress σ, Hencky strain ε, strain (linear) e and strain rate $\dot{\varepsilon}$ were calculated as follows:

$$\sigma = \frac{P}{4}\frac{(a^2 + h^2)^3}{h\Delta_0 a^4} \tag{A6}$$

$$\varepsilon = \ln\left(1 + \frac{h^2}{a^2}\right) \tag{A7}$$

$$e = \exp\varepsilon - 1 \tag{A8}$$

$$\dot{\varepsilon} = \frac{4h\dfrac{\mathrm{d}V}{\mathrm{d}t}}{(h^2 + a^2)\pi} \tag{A9}$$

where Δ_0 is the initial sample thickness (2.67 mm), P is the pressure, σ is the stress, ε is the strain (true) or Hencky strain, e is the strain (linear) or engineering strain, and $\dot{\varepsilon}$ is the strain rate.

The failure stress was the maximum value of stress, and its corresponding Hencky strain value was taken as the failure strain.

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