

## THE PHYSICS OF BAKING: RHEOLOGICAL AND POLYMER MOLECULAR STRUCTURE-FUNCTION RELATIONSHIPS IN BREADMAKING

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Molecular size and structure of the gluten polymers that make up the major structural components of wheat are related to their rheological properties *via* modern polymer rheology concepts. Interactions between polymer chain entanglements and branching are seen to be the key mechanisms determining the rheology of HMW polymers. Recent work confirms the observation that dynamic shear plateau modulus is essentially independent of variations in MW amongst wheat varieties of varying baking performance and is not related to variations in baking performance, and that it is not the size of the soluble glutenin polymers, but the structural and rheological properties of the insoluble polymer fraction that are mainly responsible for variations in baking performance.

The rheological properties of gas cell walls in bread doughs are considered to be important in relation to their stability and gas retention during proof and baking, in particular their extensional strain hardening properties. Large deformation rheological properties of gas cell walls were measured using biaxial extension for a number of doughs of varying breadmaking quality at constant strain rate and elevated temperatures in the range 25°C to 60°C. Strain hardening and failure strain of cell walls were both seen to decrease with temperature, with cell walls in good breadmaking doughs remaining stable and retaining their strain hardening properties to higher temperatures (60°C), whilst the cell walls of poor breadmaking doughs became unstable at lower temperatures (45°C to 50°C) and had lower strain hardening. Strain hardening measured at 50°C gave good correlations with baking volume, with the best correlations achieved between those rheological measurements and baking tests which used similar mixing conditions. As predicted by the Considere failure criterion, a strain hardening value of 1 defines a region below which gas cell walls become unstable, and discriminates well between the baking quality of a range of commercial flour blends of varying quality. This indicates that the stability of gas cell walls during baking is strongly related to their strain hardening properties, and that extensional rheological measurements can be used as predictors of baking quality.

### INTRODUCTION

#### Dough rheology – its relationships with quality and gluten polymer structure

Within the Cereal Science community, there is a widespread conviction that the rheological properties of dough are related to baking quality of the final baked bread, mainly due to a long tradition of subjective manual assessments of dough rheology prior to baking: for example, the practice amongst bakers of kneading and stretching the dough by hand to assess its quality. Although this is a very subjective method of measuring rheology, it gives an indication of the sort of rheological measurements that should be made in order to predict baking performance.

Gluten is the major protein in wheat flour doughs, responsible for their unique viscoelastic behaviour and their ability to retain gas during proof and baking. Gluten proteins comprise a highly polydisperse system of polymers, classically divided into two groups based on their extractability in alcohols: gliadins and glutenins. The gliadins are single-chain polypeptides with molecular weight (MW) ranging from  $2 \times 10^4$  to  $7 \times 10^4$ , whilst the glutenins are multiple-chain polymeric proteins in which individual polypeptides are thought to be linked into a network by intermolecular disulphide and hydrogen bonds

to give a wide MWD [Carceller & Aussenac, 2001] ranging between  $10^5$  to well beyond  $10^8$ . It is only recently that it has been possible to measure and quantify the high MW glutenin polymers known to be responsible for variations in breadmaking quality using techniques such as dynamic light scattering [Wahlund *et al.*, 1996; Stevenson & Preston, 1996; Egorov *et al.*, 1998; Southan & MacRitchie, 1999], and their conformation and structure by techniques such as x-ray and electron scattering [Thomson *et al.*, 1999], NMR [Alberti *et al.*, 2002a, b], FTIR spectroscopy [Feeney *et al.*, 2003], hydrodynamic studies in solution [Field *et al.*, 1987], and AFM [Humphris *et al.*, 2000]. These show that gluten has a bimodal MW distribution which roughly parallels the classical division based on solubility into gliadins and glutenins. Individual glutenin molecules in solution have an extended rod-like structure *ca.* 50–60 nm in length made up of a regular spiral structure, termed  $\beta$ -spirals [Shewry *et al.*, 2002], and the secondary polymer structure is an entangled polymer network where the glutenin molecules are linked by intermolecular disulphide and hydrogen bonds, and are also branched, with a spacing between branch points occurring every 40–50 nm [Humphris *et al.*, 2000].

It is now widely accepted that gluten proteins are responsible for variations in baking quality, and in particular it is the insoluble fraction of the HMW glutenin

polymer, which is best related to differences in dough strength and baking quality amongst different wheat varieties [MacRitchie & Lafiandra, 1997; Weegels *et al.*, 1996]. However, the exact molecular mechanisms responsible for this variation still remain unclear, largely because information about the molecular size and structure of this fraction is inaccessible by conventional polymer size characterization techniques such as GPC and SE-HPLC due to its insolubility. Therefore other techniques sensitive to changes in polymer MWD and structure are necessary.

One such technique is rheology, which is increasingly being used as a sensitive indicator of changes in the structure of HMW polymers. It has long been recognized that the key mechanisms determining the rheology of HMW polymer melts and concentrated solutions arise from physical structural interactions between polymer molecules [Doi & Edwards, 1986; Ferry, 1980] and that much of the rheological behaviour of these polymers is independent of their chemistry. This is in contrast to the currently accepted position in the cereals literature, which assumes that the chemical structure of the HMW glutenin polymers is directly related to the rheology of bread doughs and to their baking quality. Recent work has shown that the elongational rheology of HMW polymer melts and concentrated solutions is a sensitive indicator of changes in secondary molecular structure, small increases in the size of the highest end of the MW distribution, and the presence of long chain branching (LCB) [Wagner *et al.*, 2000; Munstedt *et al.*, 1998]. The most significant property is elongational strain hardening (the non-linear rapid increase in stiffness or viscosity with increasing Hencky strain) which is highly sensitive to the degree of entanglement and LCB of the polymer. For example, LCB has been shown to explain the radically different behaviour of branched and linear polymers. Polymer melts which show no LCB, such as High Density Polyethylene (HDPE) show no extensional strain hardening, whilst branched polymers such as LDPE (Low Density Polyethylene), exhibit pronounced strain hardening [Kurzbeck *et al.*, 1999]. The presence of chain branches is important in giving rise to strain hardening, which is a necessary property for stability of polymers undergoing large deformation. Since gluten polymer has been shown to have a branched structure [Humphris *et al.*, 2000], it is expected that this structure will result in strain hardening in doughs, and will contribute strongly to its resistance to extension and bubble wall stability under large deformation. Therefore, it is very likely that it is the secondary structure of the HMW glutenin polymer network, in particular the degree of branching and number of entanglements, that determines the rheological properties of dough rather than the chemical structure of the primary polymer units (called glutenin sub-units in the cereals literature).

Modern polymer physical models relate the molecular size and structure of polymers to their rheological properties and end-use performance. The pom-pom model, recently proposed by McLeish and Larson [1998] describes the rheological behaviour of HMW branched polymer melts. This class of polymers is envisaged as a relatively flexible HMW backbone to which are attached a number of branches (pom-poms) radiating out from either end of the backbone. This model accurately predicts, for the first time, the well-known phenomenon of strain hardening under

uniaxial and planar extensional flow and strain softening (shear thinning) in shear seen in branched HMW polymer melts (Figure 1a) and in gluten (Figure 1b). The branches entangle with the surrounding polymers and stretching of the flexible backbone between entanglements produces strain hardening. Predictions of this model have shown that the number of branches and the distance between entanglements have the most effect on strain hardening.

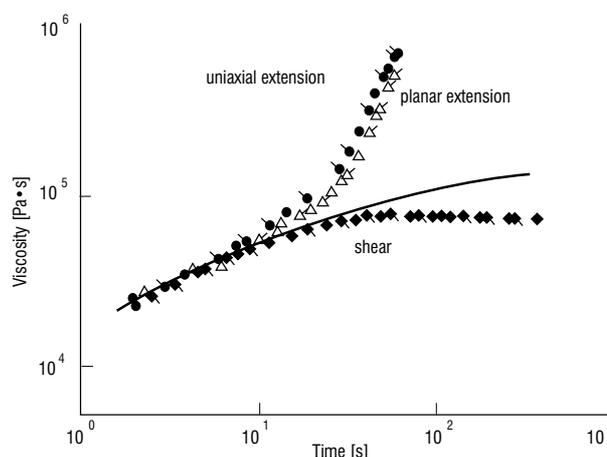


FIGURE 1a. Shear and extensional viscosity of LDPE (low density polyethylene) at 125°C at constant strain rate ( $0.05 \text{ s}^{-1}$ ). [MacLeish & Larson, 1998].

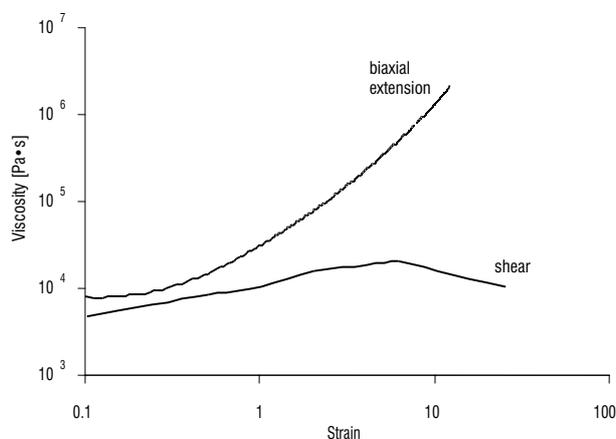


FIGURE 1b. Large deformation shear and biaxial extensional viscosities vs. strain for dough at constant strain rate ( $0.1 \text{ s}^{-1}$ ).

Rheological measurements are increasingly being used as rapid, sensitive indicators of changes in polymer molecular structure and end-use quality traits and, since gluten can be viewed as an entangled polymer melt or concentrated solution, an understanding of the rheological properties of gluten in relation to its molecular structure and its functional behaviour during the whole breadmaking process would therefore be highly desirable in relation to understanding the physical mechanisms responsible for variations in breadmaking quality. It is the aim of this paper to show that extensional rheological properties of doughs at elevated temperatures ( $50^\circ\text{C}$ ) are sensitive indicators of changes in the secondary structure of the gluten polymer and can be used as predictors of baking quality.

### Dough rheology and bubble wall stability during proof and baking quality

Baking is about the growth and stability of bubbles: their size, distribution, growth and failure during the baking process will have a major impact on the final quality of the bread, both in terms of its appearance (texture) and final volume [Dobraszczyk *et al.*, 2001]. Breadmaking is about aeration and controlling the gas phase throughout the baking process. The essential stages of the breadmaking process are mixing, proving and baking: each of these stages involves aeration. During mixing, small bubbles are incorporated into the dough, and these bubbles provide the nucleation sites for subsequent inflation by diffusion of carbon dioxide gas produced by yeast fermentation from the surrounding dough into the bubbles during proving. During proof the bubbles slowly expand, giving rise to a large increase in volume, and coalescence or rupture of adjacent bubble walls leads to the cessation of expansion and the typical open sponge-like structure we know as bread. Thus, the integrity of the cell wall structure surrounding the bubbles is extremely important in relation to gas cell stabilisation and gas retention during proving and baking, and to the final structure and volume of the baked product. During proof and baking it is the growth and stability of gas bubbles within the dough that determines the expansion of the dough, and therefore the ultimate volume and texture of the bread. It is thought that the limit of expansion is related directly to the stability of these bubble walls, due to coalescence and the eventual loss of gas on bubble rupture. The rheological properties of the bubble walls will therefore be important in maintaining stability against premature failure during baking, and also in relation to gas cell stabilisation and gas retention during proving and baking, and thus to the final structure and volume of the baked product [Dobraszczyk *et al.*, 2001; Kokelaar *et al.*, 1996].

Hence, baking may in reality be governed by failure processes: the failure of the bubble walls at large deformations. It is increasingly being recognised in the polymer literature that extensional strain hardening is essential for stability in large deformation processing situations, such as blow moulding, fibre drawing or stretching and in foam formation, where the deformation is essentially biaxial extension around the expanding gas cells, and that the strain hardening is closely linked to the secondary structure of the polymer.

The relevant deformation conditions around an expanding gas cell during proof and baking are biaxial extension, large extensional strain, low strain rate and elevated temperatures [Dobraszczyk *et al.*, 2003; 1997]. Any rheological tests which seek to relate to baking performance should therefore be performed under conditions similar to those of baking expansion, such as large strain biaxial extension and low strain rates. Methods such as bubble inflation and lubricated compression potentially offer the most appropriate method for measuring rheological properties of doughs. The major advantage of these tests is that the deformation closely resembles practical conditions experienced by the cell walls around the expanding gas cells within the dough during proof and oven rise, *i.e.* large deformation biaxial extension, and can be carried out at the low strain rates and elevated temperatures relevant to baking [Dobraszczyk *et al.*, 2003].

The failure of gas cell walls in doughs has been shown to be directly related to the elongational strain hardening properties of the dough measured under large deformation biaxial extension [Dobraszczyk *et al.*, 1997, 2003; Dobraszczyk & Roberts, 1994] (Figure 2). Strain hardening is shown as an increase in the slope of the true stress-strain curve with increasing Hencky strain, giving rise to the typical J-shaped stress-strain curve observed for highly extensible materials (Figure 3). Strain hardening in doughs is thought to arise mainly from entanglement coupling of the larger glutenin molecules which gives rise to the high viscosities observed at large strains [Singh & MacRitchie, 2001]. Under extensional flow, entangled polymers exhibit strain hardening which is enhanced for polymers with a broad MW distribution, particularly a bimodal distribution [Watanabe, 1999] and branching [Wagner *et al.*, 2000]. It is therefore expected that the broad bimodal MW distribution and branched structure of gluten will result in enhanced strain hardening and a bimodal distribution of relaxation times [Li *et al.*, 2003].

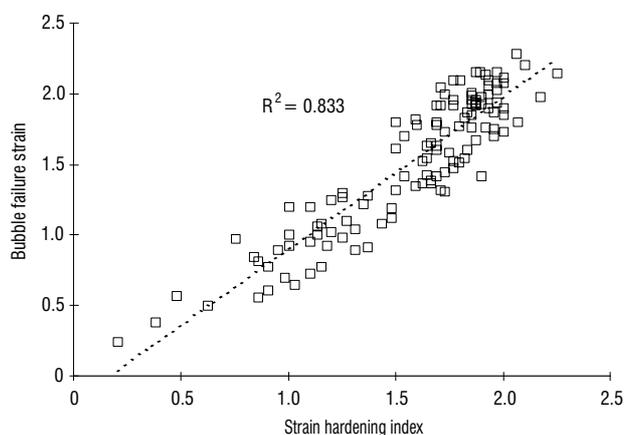


FIGURE 2. Maximum bubble wall (Hencky) failure strain vs. strain hardening index for dough bubble inflation using SMS Dough Inflation System. Strain hardening calculated as exponential curve fit to stress-Hencky strain curve as in Figure 3.

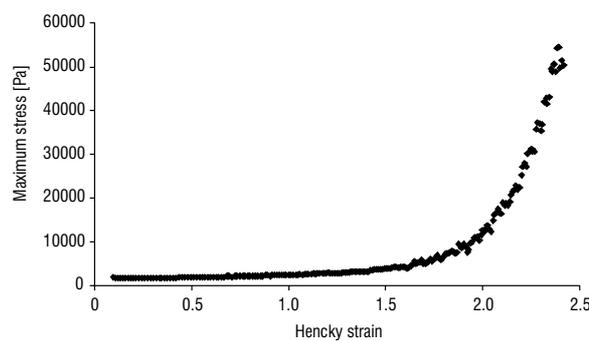


FIGURE 3. Typical J-shaped stress-Hencky strain curve in biaxial extension for a dough bubble inflated at 50°C and constant strain rate (0.1 s<sup>-1</sup>). Bubble inflation using SMS Dough Inflation System, maximum stress and Hencky strain calculated for bubble wall polar region.

Gas cell wall failure in expanding dough bubbles can be predicted using the Considere criterion for instability in extension for polymers [Dobraszczyk & Roberts, 1994; Wikström & Bohlin, 1999]. This criterion states that the stability in extension of a viscoelastic material is guaranteed

provided the strain is less than that at which a maximum occurs in the force-extension plot and defines a critical strain beyond which failure is inevitable on further extension. Uniform extension of a viscoelastic membrane during inflation is guaranteed provided the strain does not reach this maximum. Beyond this critical value of strain the criterion states that the material cannot be extended homogeneously and instead undergoes a dynamic failure event [MacKinley & Hassager, 1999]. During large extension of materials, plastic strain is uniform throughout the sample up to the point of maximum force. Beyond this point, force begins to decrease and it is at this point that localised and non-uniform plastic deformation begins to occur. The cross-sectional area begins to change in a non-uniform way, and a neck or localised constriction forms, which can either stabilise or propagate in an unstable manner to failure. If the cross section at any point is slightly less than elsewhere or there are any irregularities in the sample when the force is increasing in plastic flow, the stress will increase locally. Whilst the force is increasing the deformation will be stable, *i.e.* any local constrictions are self-arresting. In contrast, under a decreasing force the deformation is no longer stable, leading to the formation and cumulative increase of necking and eventual failure. Hence the force maximum defines a point of instability in tension, beyond which fracture is inevitable. The occurrence of strain hardening (sometimes called work hardening) in a material stabilises any regions of incipient localised thinning that could lead to unstable necking and eventual fracture during high extensions, and can allow much larger extensions before rupture than would otherwise be possible.

Recent work has shown that bread doughs exhibit strain hardening in large deformations such as bubble expansion, and that these extensional rheological properties are important in baking performance [Kokelaar *et al.*, 1996; Dobraszczyk *et al.*, 2003; Dobraszczyk & Roberts, 1994; Wikström & Bohlin, 1999; Janssen *et al.*, 1996]. Strain hardening allows the expanding gas cell walls to resist failure by locally increasing resistance to extension as the bubble walls become thinner, and appears to provide the bubbles with greater stability against early coalescence and better gas retention. It is expected therefore that doughs with good strain hardening characteristics should result in a finer crumb texture (*e.g.* smaller gas cells, thinner cell walls and an even distribution of bubble sizes) and larger baked volume than doughs with poor strain hardening properties. It has been shown that good bread-making doughs have good strain hardening properties and inflate to larger single bubble volume before rupture, whilst poor bread-making doughs inflate to lower volumes and have much lower strain hardening [Dobraszczyk, 1997].

## MATERIALS AND METHODS

**Biaxial extensional rheology of doughs at elevated temperatures.** The rheological properties of doughs in biaxial extension were obtained using a method described by Dobraszczyk [1997]. Doughs were inflated on a Dough Inflation System attachment mounted on a TAXTPlus texture analyser (Stable Micro Systems Ltd., Godalming, U.K.) at various temperatures (25–60°C) and at a target constant strain rate of 0.1 s<sup>-1</sup>. This new version of the texture analyser

has the option of continuously variable speed which allows rheological measurements to be performed at constant strain rate. Because dough is viscoelastic, its rheological properties vary with both strain and strain rate. Therefore it is necessary to separate out the effects of strain and strain rate by keeping one constant whilst varying the other. It was not possible to achieve constant strain rate using the older version TAXT2 texture analyser because the crosshead speed could not be varied during the test. In the previous method, dough bubble inflation was limited to a fixed rate of inflation where both strain and strain rate varied throughout the test. In the new TAXTPlus system dough inflation test, strain is varied and calculated as the bubble inflates, and by exponentially changing the speed at which the bubble is inflated, strain rate is kept approximately constant. A constant strain rate was used to inflate dough bubbles up to failure, and stress, Hencky strain and failure strain were recorded during bubble inflation. Strain hardening was calculated by fitting an exponential curve to the stress-Hencky strain curve. Tests were performed at various temperatures from 25°C to 60°C by placing the entire texture analyser in a heated cabinet.

Six different flour varieties from the 1999 harvest were used to provide a wide spread of baking performance: five U.K. flours (Charger, Hereward, Rialto, Riband and Soissons) and a commercial US flour provided by Pillsbury. The analytical and baking properties of these flours are given in Table 1. Doughs were mixed on a Brabender Farinograph to optimum consistency of 600 BU using a simple recipe of 300 g flour, 6 g salt and water. Samples for bubble inflation were prepared according to the method described by Dobraszczyk [1997]. The samples were placed in the thermal cabinet at the desired temperature and allowed to equilibrate for 30 min. To prevent sample drying the surface of each sample was coated using paraffin oil and covered with clingfilm. Water was allowed to evaporate in the cabinet to provide excess humidity. Samples were then inflated at the set strain rate using the heated moist air circulating in the cabinet. Test baking was carried out on the six flour samples using two methods: a Chorleywood Bread Process (CBP) baking procedure at Weston Research Laboratories Ltd., U.K., equivalent to that used in commercial practice in the UK, and a lower energy long fermentation procedure using a Mixograph to mix the dough at Amylum, Belgium. For the CBP procedure, doughs were mixed to a fixed work input of 10 Wh/kg in a Morton z-blade mixer and baked into 400 g single-piece unlidged loaves. The recipe used, based on 1 kg flour was: flour 100%, salt 1.95%, yeast 2.35%, soya flour 1.8%, malt flour 1%, beaded palm oil 1%, fungal alpha-amylase 0.15%, ascorbic acid 100 ppm. Water addition level was calculated from the Farinograph water absorption (600 BU) + 3.9% water as shown in Table 1. Target dough temperature after mixing was 30°C. Proof time was 45 min at 45°C at R.H. = 80%, baking time was 30 min at 208°C. Dough and bread heights were measured immediately following proof and baking, and baked loaf volume was measured by seed displacement. An assessment of the texture was made by visual inspection. The Amylum baking procedure used 100 g flour mixed in a Mixograph to optimum time and water addition based on the 600 BU Farinograph water absorption. The recipe used was 100 g flour, 6 g sugar, 1.5 g

salt, 3.5 g yeast. Fermentation time was 120 min at room temperature, followed by sheeting and proof for 47 min at 30°C, and baking time was 24 min at 225°C. Loaf volume was measured by seed displacement.

TABLE 1. Flour and baking data.

Flour Analysis

	Hereward	Riband	Rialto	Soissons	Charger	Pillsbury
Protein (Nx5.7) [% <sup>1</sup> ]	10.6	7.5	10.0	11.5	9.5	10.0
Water Absorption [% <sup>2</sup> ]	59.3	53.0	60.4	59.4	57.4	55.1
Starch Damage [%]	36	11	38	30	31	22
Hagberg Falling No.	403	236	356	343	381	439

Baking Data (Westons)

	Hereward	Riband	Rialto	Soissons	Charger	Pillsbury
Water addition [%]	63.2	56.9	64.3	63.3	61.3	59.0
Oven Spring [cm]	3.2	0.8	3.7	3.4	3.3	3.4
Loaf Height [cm]	15.6	12.6	15.5	14.8	15.1	15.8
Loaf Volume [cm <sup>3</sup> ]	1780	1450	1720	1620	1680	1750

Baking Data (Amylum)

	Hereward	Riband	Rialto	Soissons	Charger	Pillsbury
Water addition [%]	57.4	51.4	58.5	57.9	56.2	55.0
Mixing Time	3m10s	1m55s	3m	4m10s	2m40s	4m35s
Loaf Volume [cm <sup>3</sup> ]	580	445	563	611	548	656

<sup>1</sup> protein determined by Dumas method; <sup>2</sup> Brabender Farinograph (300 g flour) mixed to 600BU.

## RESULTS

Figures 4a and 4b show stress-strain curves measured at a constant strain rate ( $0.1 \text{ s}^{-1}$ ) at various temperatures for 2 flours: Hereward (a standard breadmaking variety in the UK) and Riband (a standard biscuit flour in the UK). Hereward doughs maintain good strain hardening properties until around 50°C, beyond which the bubbles

become unstable, showing a decrease in strain hardening and failing at lower strains. Riband shows some strain hardening at 25°C but starts to decline rapidly at higher temperatures, showing a dramatic decrease in failure strain. This indicates bubbles in Riband will have little resistance to failure and will coalesce rapidly at higher temperatures, whereas bubble walls in Hereward remain stable until beyond 50°C. Figure 5 shows changes in strain hardening against temperature for the six wheat varieties. Strain hardening decreased with increasing temperature for most flours, with the exception of Pillsbury and Soissons flours which showed a maximum at around 50°C. Riband started at a relatively low strain hardening value just above 1.0 and then decreased rapidly beyond 40°C. It is expected that below a strain hardening value of around 1.0 bubble stability is no longer maintained and that this level marks an effective failure point below which bubbles will fail and coalesce on further expansion, as predicted by the Considere failure criterion [Dobraszczyk & Roberts, 1994]. Riband, Rialto and Charger all fall below the  $n=1$  line at temperatures between 45–50°C, whereas Hereward, Soissons and Pillsbury do not fall below this line up to 60°C. This effectively discriminates two groups of flours, those where the bubble walls remain stable until starch gelatinisation occurs (at around 65–70°C), and those where the bubble walls become unstable at lower temperatures at around 45–50°C (Figure 6). It is predicted that this second group of flours should have poorer baking performance than the first group, due to their bubble walls becoming unstable and coalescing at much lower temperatures than the first group. This is confirmed by baking data where Rialto and Charger have lower baking volume than Pillsbury, Soissons and Hereward flours (Figure 6). Large differences in oven spring and baking volume were observed for Rialto between 1998 and 1999 flours, with the

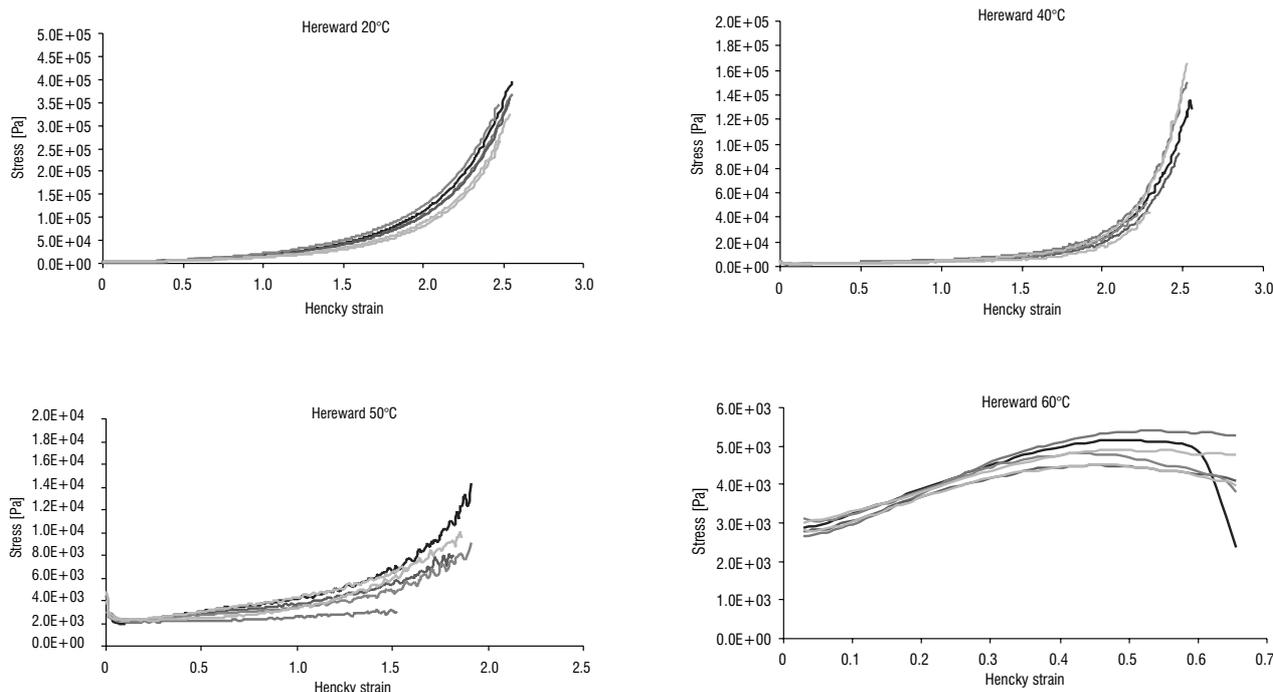


FIGURE 4a. Stress-Hencky strain curves measured at constant strain rate ( $0.1 \text{ s}^{-1}$ ) at various temperatures for a standard UK breadmaking flour (Hereward).

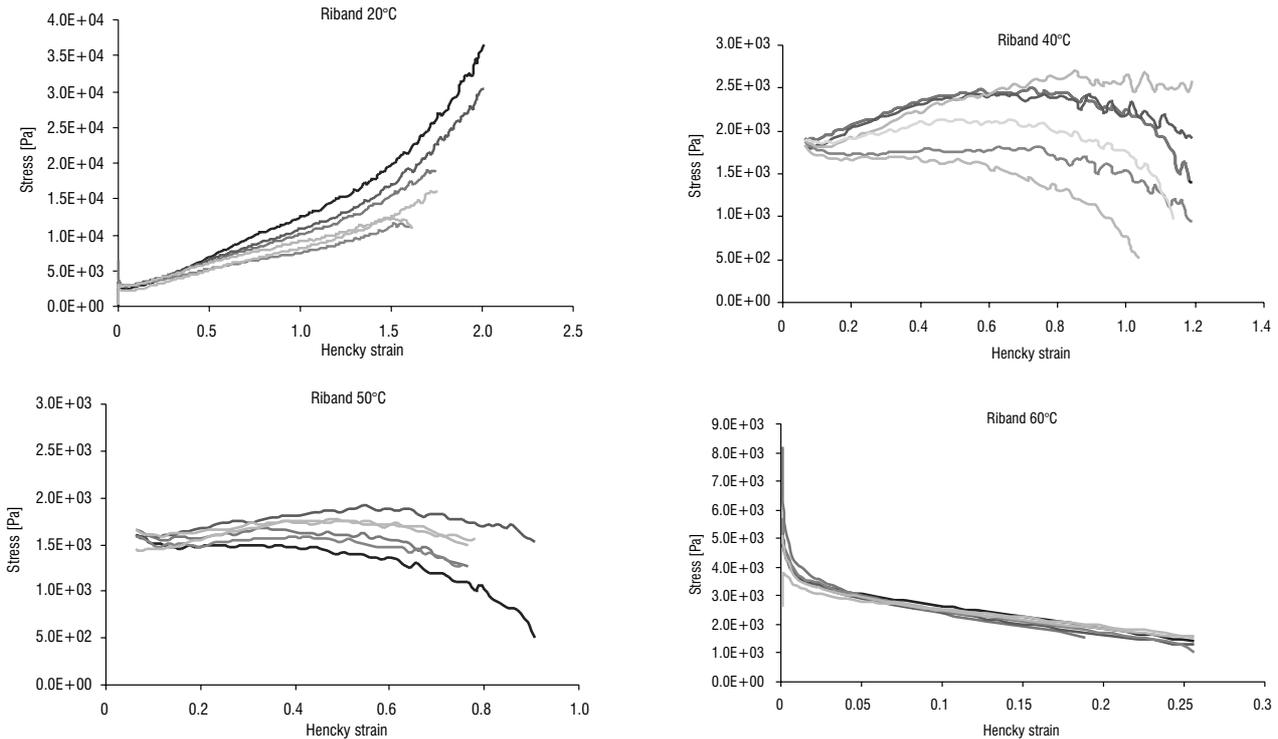


FIGURE 4b. Stress-Hencky strain curves measured at constant strain rate ( $0.1 \text{ s}^{-1}$ ) at various temperatures for a standard UK biscuit flour (Riband).

1999 flour having much better baking performance than the 1998 flour. The differences in baking performance between Rialto 1998 and 1999 flours are clearly reflected in their strain hardening behaviour, with Rialto 1998 strain hardening values intersecting the  $n=1$  line at around  $45^\circ\text{C}$  and 1999 Rialto at around  $52^\circ\text{C}$ . This indicates that 1998 Rialto dough should be less stable than the 1999 dough, with 1999 Rialto maintaining bubble stability over a longer temperature range than the 1998 flour.

The Considere instability criterion predicts that above

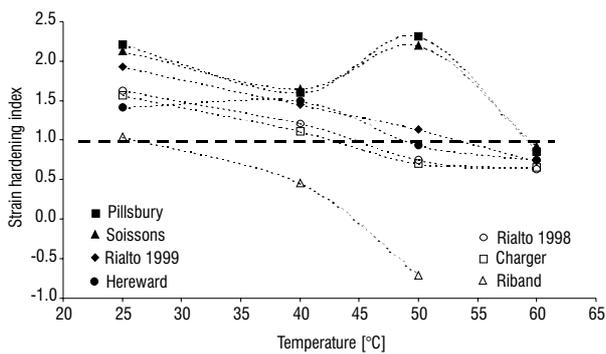


FIGURE 5. Mean bubble cell wall strain hardening values ( $n=6$ ) for a number of wheat varieties inflated at constant strain rate ( $0.1 \text{ s}^{-1}$ ) at various temperatures on the SMS Dough Inflation System. The dashed line at strain hardening index = 1.0 defines the region below which expanding bubble walls become unstable.

a strain hardening value of 1 ( $n=1$ ) the bubble walls should be stable and that the failure strain of the bubble walls should be directly proportional to their strain hardening properties. Below  $n=1$  the bubble walls should be unstable and it is expected that their failure strain should decrease rapidly. Figure 7 shows bubble wall failure strain *versus* strain hardening index for all flour varieties used at various

temperatures. This shows two distinct regions: one above a strain hardening value of 1 where failure strain is linearly related to strain hardening, and one below  $n=1$ , where the failure strain of the bubble walls decreases rapidly with decreasing strain hardening, which are mainly samples inflated at higher temperatures. This confirms the validity of the Considere instability criterion, and indicates that a strain hardening value of 1 defines a region below which the bubble walls are unstable and fail rapidly. It is suggested that once the strain hardening of bubble walls falls below  $n=1$ , the bubble walls are no longer stable and will coalesce rapidly, resulting in lower baking volume and poorer texture. Thus, a value for strain hardening of 1 effectively acts as an indicator of baking performance: if the dough properties remain above this value during the expansion phase (proof and the early stages of baking) encompassing a temperature range from  $30^\circ\text{C}$  up to starch gelatinisation

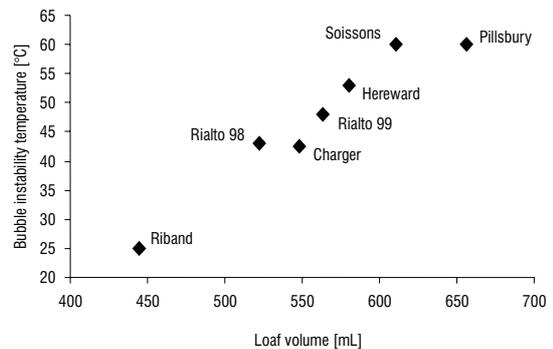


FIGURE 6. Temperature at which dough bubble walls become unstable (at which their strain hardening value drops below 1) for a number of flour varieties *vs.* loaf volume.

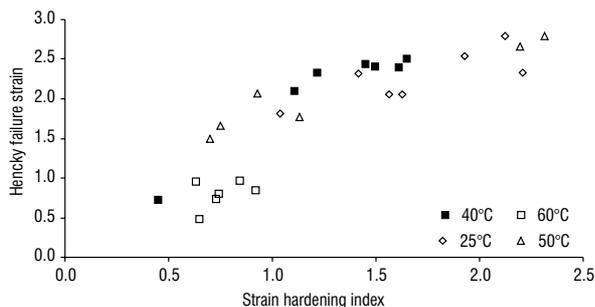


FIGURE 7. Considere instability criterion for doughs: mean maximum bubble cell wall Hencky failure strain values ( $n=6$ ) vs. strain hardening index for a number of wheat varieties inflated at constant strain rate at various temperatures.

(approximately 65°C), then the bubble walls remain stable and steady expansion will occur. If the strain hardening properties fall below 1 over this range, then bubble wall instability occurs giving rise to coalescence and release of gas and the cessation of expansion.

Loaf volume for a number of commercial white flour doughs has been related directly to the failure strain and strain hardening properties of single dough bubbles measured at elevated temperatures in biaxial extension. Figure 8 shows baking volume (CBP process) related to strain hardening measured at 50°C and constant strain rate for a large number of commercial flour blends of varying quality provided by Weston Research Laboratories Ltd. using constant strain rate ( $0.1 \text{ s}^{-1}$ ) dough inflation. This clearly shows that a strain hardening value of around 1.2 discriminates well between commercial flour blends of poor to moderate quality and those considered to be good and excellent. This is in contrast to a strain hardening value of 1, which discriminated baking quality for flours mixed using the lower energy long fermentation (Amylum) procedure (Figure 6).

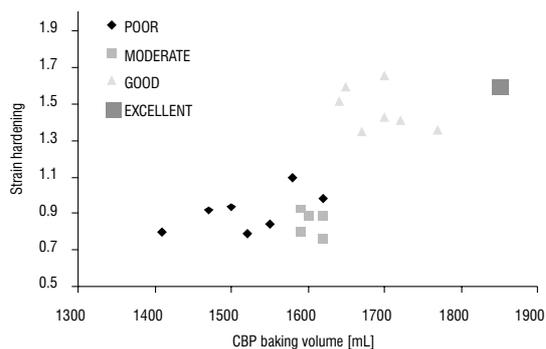


FIGURE 8. Discrimination of CBP baking performance for a range of commercial flour blends of varying baking quality using mean bubble cell wall strain hardening properties obtained at 50°C and constant strain rate ( $0.1 \text{ s}^{-1}$ ).

## CONCLUSIONS

It would appear that for HMW polymers such as gluten, large deformation extensional rheological properties are sensitive to changes in MWD, polymer entanglements and branching. Insoluble HMW glutenins have been shown to be best related to variations in baking quality. Strain

hardening has been shown to be a sensitive indicator of entanglements and long-chain branching in HMW polymers, and is well related to baking performance of bread doughs. As predicted by the Considere failure criterion, when strain hardening falls below a value of around 1, bubble walls are no longer stable and coalesce rapidly, resulting in loss of gas retention and lower volume and texture. Bubble walls with good strain hardening properties remain stable for longer during baking, allowing the bubbles to resist coalescence and retain gas for much longer. Strain hardening in poorer breadmaking varieties starts to decrease at much lower temperatures, giving earlier bubble coalescence and release of gas, resulting in lower loaf volumes and poorer texture.

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