Modelling the Extension Testing of Wheat Flour Dough

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Abstract In order to assess wheat and flour quality in terms of the baking performance of the doughs that they make, extension measurements, performed on the fully mixed dough just before it is baked, have become an integral part of the daily testing of wheat flour dough. However, except at a purely qualitative level, little has been done to examine the relationship between the extension measurements and the protein content of the flour being examined. The purpose of this paper is an examination of the modelling implications of the result that, experimentally, the "*Ext*" measurements, determined in a standard extension test, increase linearly as a function of the increasing (percentage) protein content, whereas the corresponding values of R^{max} remain more or less constant. It is shown that this result cannot be adequately explained in terms of (simple) spring network models, and, in addition, represents a key non-trivial constraint for the assessment of (mechanical) rheological models of the flow and deformation properties of wheat flour dough.

1. INTRODUCTION

The invention of the Mixograph^{TM} and the Brabender Farinograph^{TM} in the early 1930's heralded a new era in cereal chemistry, because they recorded graphically the mixing of a flour with water and other ingredients as it occurred. For the first time, cereal chemists could obtain and compare mixing curves for various wheat flours and their doughs, and, thereby, assess flours in terms of the qualitative differences between their mixing curves. However, mixing curves alone could not yield the required correlation between flour types and baking performance, which was needed to allow reliable decision-making about wheat and flour quality. This was only achieved when the qualitative information in the mixing curves was coupled with results from the extension testing of the developed dough. The recognition of the relevance of extension testing predates the invention of the abovementioned mixers. The Chopin alveograph was invented in 1921. It recorded the extension of the dough but not its mixing. It was not until 1936 that the Brabender Company introduced the Extensograph^{TM} as an integral part of their Farinograph^{TM} system.

Because the action performed on the dough by a mixer, and especially by mixers like a Mixograph^{TM}, is essentially elongational in nature, a mixing curve itself is a record of an extension test (Anderssen *et al.* (1997)). However, its utility was limited by the lack of a mathematical model which would allow non-trivial quantitative extensional information to be recovered from its graphical record. The way around this difficulty was to perform an independent extension test of the developed dough, and then couple this information with a qualitative assessment of the corresponding mixing curve.

Nevertheless, modern technology has generated a requirement for improved quantitative assessments of the various processing involved such as a formal rheological characterization of the different stages of the mixing of the dough, and the interpretation of the results of subsequent extension testing. For example, improvements in plant breeding protocols depend on enhancing the current understanding of how, during the mixing, the proteins, starches, water and other ingredients interact to form the dough that they make.

This paper will focus on the interpretation of the results of extension testing performed on different flours. In particular, the paper examines the modelling implications of the experimentally observed behaviour of extension-plots as a function of the increasing (percentage) protein content of the flour being tested. It is shown that such experimental observations cannot be adequately explained in terms of (simple) spring network models, and, in addition, represents a key non-trivial constraint for the assessment of (mechanical) rheological models of the flow and deformation properties of wheat flour dough.

2. EXTENSION TESTING AND FLOUR PROTEIN CONTENT

In an extension (e.g. Extensograph^{TM}) test, one (a) first prepares a cylindrical dough sample (Rasper and Preston (1991)), which is loaded into the extension tester; (b) applies a hook, to the centre of the dough sample between the clamps of the extension tester, in order to elongate the sample at a given constant speed; (c) measures the force with which the dough sample resists the elongation being performed by the hook until the sample ruptures; and (d) finally, plots the force as a function of the distance travelled by the hook, to obtain a standard extension-plot (Rasper and Preston (1991)). In general, no effort is made to normalize the extension-plots to their corresponding stress-strain counterparts, even though the details on how to do this have been published (Rasper and Preston (1991)). Often, for the same dough, one repeats the elongation for a representative set of speeds of the hook to obtain a set of plots.

In the standard commercial assessment of a flour which made the dough, as well as in many cereal chemistry considerations, the only information utilized from such plots is the values of the parameters R^{max} and Ext which measure, respectively, the maximum force which the hook experiences during the experiment and the distance travelled by the hook at the time the dough ruptures. Decision-making about the differences in flours is based on these two parameters (Gupta *et al.* (1992)). In the analysis and interpretation of such data, it is normal practice to work on a purely comparative assessment basis. Though this has generated useful qualitative correlations between extension measurements (which are assumed to characterize the dough being tested) and baking performance, it avoids the real issue of the relationship between the microscopic characteristics of a dough and its baking performance.

One way in which the formulation of such a relationship can be pursued is to view the extension-plots as the link concept between the microscopic characteristics and the baking performance, and to thereby reduced matters to an examination of the relationship between the microscopic characteristics and the structure of the extension-plots. Though, in the cereal chemistry literature, various mechanical rheological models (cf. Walker and Hazelton (1996)) have been formulated to explain the flow and deformation properties of wheat flour dough, the process has been rather *ad hoc* in that no rigorous analysis of such proposals has been undertaken. For example, no rigorous comparison has been made between the predictions of such models and the stress-strain behaviour encapsulated in extension-plots. In fact, it is not difficult to show (Seo and Anderssen (1998)) that the stress-strain behaviour of the standard mechanical rheological models, such as Maxwell, Kelvin-Voigt, etc, does not correspond to the stress-strain morphology of the extension-plots, and that partial qualitative agreement is only possible if one introduces a stick-slip element into such models.

On the other hand, the simplest way to characterize the microscopic structure of a flour is to consider the relative proportions of the protein and starches. Thus, the formulation of a simple relationship between the microscopic characteristics of a dough and the results of extension testing can be based on the experimentally observed relationship between R^{max} and Ext as a function of percentage protein content, for the same wheat variety. In Gupta *et al.* (1992), Figure 6, it is shown that, experimentally, the "Ext" measurements, determined in a standard extension test, increase linearly as a function of the increasing (percentage) protein content, whereas the corresponding values of R^{max} remain more or less constant.

In cereal chemistry, it is common practice to invoke, at least intuitively, the *Glutenin Hypothesis* that (cf. the comment *"··· glutenin contributes to the elastic properties"* in Tsiami *et al.* (1997))

> *"at least to first order, the properties of the dough are determined by the nature of the glutenin network which has been formed in the dough as a result of its mixing".*

Within this context, along with the components making up the flour, the structure of the glutenin network will be a function of the water added along with other chemicals as well as the amount of energy accumulated by the dough during the mixing. Though this hypothesis is an approximation, it is representative of the situation occurring in the dough. What is already clear from the above discussion of mechanical rheological models is that, as well as the glutenin network, other factors in the molecular structure of the flour and the resulting dough must be taken into account when formulating a relationship which explains the general stress-strain morphology of the extension-plots in terms of the microscopic characteristics of the dough. However, this leaves open the question as to the extent to which the R^{max} and Ext values are controlled by the glutenin network within the dough.

Consequently, it is unclear how the *Gluten Hypothesis* should be interpreted and applied. It is therefore necessary to examine some consequence of the hypothesis which can be tested against experimental data. A natural corollary of the hypothesis is the conclusion that, when fully extended, at the time of rupture of the dough in an extension test, the glutenin network behaves like a spring network which dominates the rheology of the dough. This leads naturally to the conclusion that the measured values of R^{max} and Ext, for different flours of the same wheat variety, can be modelled in terms of spring networks. Conceptually, the formulation of such a model implies that, though the stress-strain characteristics of the dough before the rupture involve viscous as well as elastic behaviour, the elastic behaviour dominates at the time of the rupture of the dough. Consequently, the validity or otherwise of this corollary will yield a clearer understanding of the role played by the glutenin network within the dough.

3. SPRING NETWORK MODELS

If the above corollary is correct, then, among other things, it would imply that

1. simple spring network models are sufficient to explain the observed difference in the values of Ext and $R^{(max)}$, as a function of protein content, for different flours of the same wheat variety, and
2. when comparing two flours $\mathcal{A}$ and $\mathcal{B}$ of the same wheat variety, the relative proportions of the glutenin they contain represents a key factor in assessing their flow and deformation characteristics.

In order to analyse the consequences of these implications, the first step is to define the type of spring network models which will be analysed. Without loss of generality, let the network consist of M parallel springs, each of which consists of N springs connected in series, with all of the springs being of the same size and having the same elastic modulus k. This will be called an (M, N, k)-network. Then the force F which the extension tester records for an elongation Ext of the dough, at the time of rupture, will satisfy

$$F(Ext; M, N, k) = \frac{kM}{N} Ext. \qquad (1)$$

For two different flours $\mathcal{A}$ and $\mathcal{B}$, let the corresponding (M, N, k)-networks be denoted by $(M_{\mathcal{A}}, N_{\mathcal{A}}, k_{\mathcal{A}})$ and $(M_{\mathcal{B}}, N_{\mathcal{B}}, k_{\mathcal{B}})$, respectively, and the corresponding Ext and $R^{(max)}$ values by $Ext_{\mathcal{A}}$, $R_{\mathcal{A}}^{(max)}$ and $Ext_{\mathcal{B}}$, $R_{\mathcal{B}}^{(max)}$.

If it is assumed that the R^{max}-values are representative of the force being applied at the time the corresponding Ext-values are measured, then one obtains from (1) that

$$Ext_{\mathcal{A}} = \frac{N_{\mathcal{A}}}{k_{\mathcal{A}} M_{\mathcal{A}}} R_{\mathcal{A}}^{(max)}, \qquad Ext_{\mathcal{B}} = \frac{N_{\mathcal{B}}}{k_{\mathcal{B}} M_{\mathcal{B}}} R_{\mathcal{B}}^{(max)}.$$

Note. From a mathematical modelling point of view, it would have been more appropriate to work with the extension Ext^{max} of the dough at the time R^{max} occurs, rather than with the extension Ext at the time of rupture. This concatenation of Ext^{max} and Ext is most likely historic, in that it reflects the poor resolution of early extension experiments in which $Ext^{max} \approx Ext$.

After performing the extension experiments on the two flours, one can determine the real values θ and ϕ such that

$$R_{\mathcal{B}}^{(max)} = \theta R_{\mathcal{A}}^{(max)}, \qquad \text{and} \qquad Ext_{\mathcal{B}} = \phi Ext_{\mathcal{A}}. \quad (3)$$

It therefore follows from equations (2) and (3) that

$$Ext_{\mathcal{B}} = \phi Ext_{\mathcal{A}} = \phi \frac{N_{\mathcal{A}}}{k_{\mathcal{A}} M_{\mathcal{A}}} R_{\mathcal{A}}^{(max)},$$

and, hence, that

$$\theta \frac{N_{\mathcal{B}}}{k_{\mathcal{B}} M_{\mathcal{B}}} R_{\mathcal{A}}^{(max)} = \phi \frac{N_{\mathcal{A}}}{k_{\mathcal{A}} M_{\mathcal{A}}} R_{\mathcal{A}}^{(max)}.$$

In this way, the following basic identity relating the (M, N, k)-networks of the two flours is obtained

$$\theta \frac{N_{\mathcal{B}}}{k_{\mathcal{B}} M_{\mathcal{B}}} = \phi \frac{N_{\mathcal{A}}}{k_{\mathcal{A}} M_{\mathcal{A}}}. \qquad (4)$$

The second step in the analysis of the corollary is a discussion of how the glutenin content in the dough will be modelled in terms of the spring network models. In this paper attention is limited to flours of the same wheat varieties which are grown in different locations and using different fertilizer conditions. Because they are of the same variety, their genetics ensures that they contain the same types of proteins in the same relative (number) proportions. Consequently, in the above network model, the only term which can be changed to characterize the difference between two doughs made from two different flours of the same wheat variety which have different protein contents is the numbers of springs in parallel and series. On the basis of the above remarks, the elastic moduli must remain the same because the flours are from the same wheat variety grown under different environmental conditions.

From extension experiments performed on flour $\mathcal{A}$ containing 6% protein and flour $\mathcal{B}$ containing 12% protein, it is found that $R_{\mathcal{A}}^{(max)} \approx R_{\mathcal{B}}^{(max)}$ $Ext_{\mathcal{A}} \approx 2Ext_{\mathcal{B}}$; namely, in terms of the parameters θ and ϕ defined above, $\theta = 1$, and $\phi = 2$.

It therefore follows from equation (4) and the constraint $k_{\mathcal{A}} = k_{\mathcal{B}}$ that

$$\frac{N_B}{N_A} = 2\frac{M_B}{M_A}. \tag{5}$$

If one argues that $N_A = N_B$, because the length of the specimen remains the same, one obtains the contradictory conclusion that $M_A = 2M_B$; namely, that, as the protein content of the flour doubles, the number of springs in parallel must be halved. It is logical to conclude that, as the protein content increases, the number of springs in parallel increases. If it is assumed that the number of springs in parallel increases by a factor α, then the number of springs in series must increase by a factor 2α. But, on isotropic volumetric grounds, the increase in springs in series should be equal to the increase of springs in parallel.

On the other hand, if one invokes the isotropic volumetric condition that the numbers of springs in parallel and series increase in the same proportion and relax the constraint that $k_A = k_B$, then equation (4) yields

$$k_A = 2k_B; \tag{6}$$

namely, the elasticity of the springs decreases as the protein content of the flour increases, which is quite counter-intuitive. No evidence exists which supports such a conclusion for doughs from the same wheat variety.

4. CONCLUSIONS

The above analysis proves that spring network models do not correctly predict the rheology of the dough at the point of rupture in extension tests of doughs made from the flours of the same wheat variety grown under different environmental conditions. So, when fully extended, at the time of rupture of the dough in an extension test, the glutenin network does not behave like a spring network which dominates the rheology of the dough. In many ways, it is not a surprising result, since spring network models are the simplest of all the mechanical rheological models which could be invoked to explain the observations. On the other hand, from a modelling and simulation perspective, it illustrates that due care must be taken when proposing notional models for some given process. Scientifically, it is a natural first step to focus on the rheology of the glutenin network as the primary source of the rheology of the dough and to think of it notionally as a network of springs. But, such an interpretation can only remain a notional model, as long as it does not contradict representative observations.

In fact, a closer inspection of a standard extension-plot indicates that there is a change in the stress-strain characteristics of an extension-plot in the time between R^{max} being attained and Ext occurring. Slippage or partial rupture in the glutenin network could have occurred during this time which cannot be ignored. In addition, given the increased precision of extension testing, there is a need, in future, to work with Ext^{max}, the value of the extension of the dough when R^{max} occurs, rather than Ext.

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