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INCREASING COMPETITIVENESS OF HOME-GROWN WHEATS THROUGH IMPROVED METHODS FOR QUALITY EVALUATION AND OPTIMISED MILLING

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INCREASING COMPETITIVENESS OF HOME-GROWN WHEATS THROUGH IMPROVED METHODS FOR QUALITY EVALUATION AND OPTIMISED MILLING

by

M WHITWORTH

Campden and Chorleywood Food Research Association, Chipping Campden,
Gloucestershire GL55 6LD

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Increasing competitiveness of home-grown wheats through improved methods for quality evaluation and optimised milling

HGCA project No. 2023

Abstract

Martin Whitworth, CCFRA, June 1999

To ensure the competitiveness of U.K. wheats, it is important that they have the appropriate qualities to perform well in food processes, including breadmaking and biscuitmaking. To assist processors in identifying wheats of suitable quality at intake, small-scale tests are required with good capability to predict processing performance. Additionally, such tests are required by breeders to assist them in the development of new varieties with good processing characteristics. Limitations in the predictive capability of current small-scale tests have been recognised. The aim of this project was therefore to evaluate the performance of various flour quality tests and to identify new or modified tests that could provide a better prediction of the biscuitmaking and breadmaking potential of wheats.

The project demonstrated that many of the flour quality tests currently in use have the capability to distinguish the widely differing baking properties of **nabim** group 1 and 2 wheats from those of groups 3 and 4. However, test baking remains the most effective method of discriminating performance within these populations. For breadmaking performance, gel-protein rheology remains one of the most useful small-scale tests. It was shown that good results could be obtained with a low cost rheometer. However, the cost of sample preparation remains an obstacle to the widespread adoption of the test. Among rheological tests of dough, the Alveograph is not widely used in the U.K., except for export specification, but showed promise for prediction of breadmaking potential. The new Stable Micro Systems D/R instrument provided reasonable agreement with the Alveograph, and offers a promising alternative to it. An alternative Alveograph protocol was evaluated, using the new Consistograph instrument to produce doughs with adapted hydration levels. However, although these more closely reflect the optimum hydration levels for baking, greater discrimination of breadmaking potential was provided under the conventional, constant hydration test conditions. Enhanced interpretation of Alveograph data was obtained by calculating stress-strain characteristics from the normal curves, from which a new parameter was developed that gave a good discrimination between varieties of differing protein quality. More widespread adoption of this test in the U.K. may provide improved capability to predict breadmaking quality, used in combination with existing tests.

For semi-sweet biscuitmaking, soft group 3 and 4 wheats produced better quality biscuits than hard group 1 and 2 varieties, and could readily be distinguished from them by several tests. However, no effective prediction of quality within the group 3 and 4 wheats could be found, including methods currently relied on for this purpose.

Many of the rheological properties of doughs measured were partially determined by the water absorption of the flours used. To ensure consistent flour performance in baking processes, it is important for millers to produce flours to a consistent water absorption. The Farinograph is well suited to measurement of water absorption for breadmaking flours. However, for biscuitmaking, it provided inconsistent prediction of the water absorption measured more directly by extrusion of biscuit doughs, and a bias was seen between harvest years. An NIR calibration against the extrusion test provided better results. NIR calibrations for water absorption are already in use in industry, and introduction of a specific calibration for biscuit flours might provide more consistent performance than the use of a general-purpose calibration against the Farinograph for all flour types.

Summary

Introduction

As is the case with many natural products, wheats vary considerably in their fitness for processing into foods for human consumption. To ensure the competitiveness of U.K. wheats, it is important that they have the appropriate qualities to perform well in food processes, including breadmaking and biscuitmaking, and that they are processed in ways which will allow these qualities to be realised to their maximum potential. To assist processors in identifying wheats of suitable quality at intake, small-scale tests are required with good capability to predict processing performance. Additionally, such tests are required by breeders to assist them in the development of new varieties with good processing characteristics. Many tests have been devised, and are used in evaluating parcels of wheat and flour for manufacture of bread, biscuits and other food products. However, limitations in their predictive ability have been recognised. These not only affect the ability of processors to select wheats at intake but, if overused by breeders to the exclusion of test baking, could lead to the introduction of varieties which perform well within the limited scope of these tests, but are disappointing in actual processes.

The aim of this project was to evaluate the performance of various flour quality tests and to identify new or modified tests that could provide a better prediction of the biscuitmaking and breadmaking potential of wheats. In recent years, some success has been achieved with rheological tests of flours and of gluten proteins extracted from flours, and an emphasis has therefore been placed on tests that measure rheological properties of doughs and of protein extracts. The work has included re-evaluation of existing test methods and identification of new ways in which the data from these may be used to provide improved measurements, evaluation of recently introduced flour testing instruments, and assessment of new methodologies.

The approach has involved the preparation of flour samples from a wide range of varieties, over several harvest years, and with a range of protein contents and starch damage levels. Each of these has been test baked to produce bread and semi-sweet biscuits, and thus to identify its actual processing characteristics. The flours have also been subjected to a wide range of quality tests and the results have been analysed to identify which measurements provided the best prediction of the processing performance.

Materials and methods

Wheat samples were collected from the 1995, 1996 and 1998 harvests, including a total of 13 varieties with a wide range of rheological characteristics. Examples of each wheat variety were selected with up to 3 different protein contents in each year and were milled to produce flours with up to 4 levels of starch damage. In total, 60 wheat samples were milled to produce 186 flours. Each flour was test baked to produce bread and semi-sweet biscuits. For biscuit baking, no sodium metabisulphite was used, so that the inherent suitability of the wheat itself could be assessed. Each flour was also subjected to a range of quality tests, including the following:

- Moisture content
- Protein content
- Pentosan content
- Falling number
- Starch damage
- Farinograph
- Extensograph
- Gel-protein mass and rheology
- Consistograph
- Alveograph

The results were compared with the baked product quality assessments to determine which tests could be used to provide the best prediction of suitability for biscuitmaking or breadmaking. Particular emphasis was focussed on rheological tests, including small strain oscillatory and stress relaxation testing of the bread and biscuit doughs, as well as the standard flour quality tests listed above.

Results

Water absorption

Many of the rheological characteristics of doughs were found to be related to their water content. Consideration was therefore given to the factors affecting the water absorption capacity of flours. An equation developed by Farrand (1969) gives a good model of Farinograph water absorption as a function of starch damage, protein and moisture content. Using the data obtained in this project, it was found that improved prediction could be obtained by omitting a correction term included by Farrand. The constants used in the equation to represent the water absorption capacity of each flour component were reviewed. Slight improvements could be obtained, but the apparent values were different for the 1995/96 and the 1998 samples, suggesting that a reliable model should also include other factors. One factor considered was the pentosan content of the flour. It was shown how Farrand's model could be extended to include this, but little improvement was obtained in the fit to the 1995/96 data. It is possible that high pentosan content of the 1998 samples could explain their higher average water absorption values, but this was not measured for these samples.

In addition to water absorption measurements using a Farinograph, measurements were also made with a Chopin Consistograph. Water addition for biscuitmaking purposes was determined using an extrusion test, and Near Infra-red (NIR) calibrations were also developed for this measurement and for Farinograph values. Consistograph water absorption values were typically slightly lower than Farinograph values (600 line). They provided greater separation between flours milled from hard and soft varieties, but a lower sensitivity to differences within either of these populations. Notable outliers were seen for samples of the variety Beaver, for which Consistograph values were about 10% lower than Farinograph values. It is possible that this may be due to the existence of the 1B/1R translocation in this variety, which can produce sticky doughs that might behave differently in the two instruments. High maximum pressures achieved for these samples in Alveograph tests under adapted hydration conditions (determined using the Consistograph) suggest that the Consistograph values may have underestimated the optimum hydration level for these samples.

Water absorption for biscuit doughs, as measured by an extrusion test, was correlated with Farinograph values. However, although the Farinograph showed an increase in average water absorption between the 1995/6 and 1998 flours, the extrusion test showed no such change in requirements for biscuitmaking. Farinograph values are often used to set specifications for biscuit flours as well as for bread flours. These findings therefore suggest that biscuit water addition determined on this basis might require adjustment at a changeover between harvests and that a test specifically suited to biscuit doughs might be more appropriate. Although use of the extrusion test might be inconvenient, an NIR calibration developed against this test could provide a simple alternative and was a more accurate predictor of extrusion values than the Farinograph.

Dough rheology

Small strain rheological testing of full recipe doughs
Small strain rheological tests were conducted of the bread and biscuit doughs used for test baking. Biscuit doughs had higher elastic and viscous moduli than bread doughs, with slightly higher phase angles. For both types of dough, the moduli were greater for weaker varieties, but there was considerable overlap between varieties. This may be because doughs were prepared with water addition determined according to a measured water absorption. This is determined as a level which produces a constant dough extrusion time for biscuit doughs or a constant maximum torque in a Farinograph. It therefore also tended to minimise variations in the small strain rheological properties of the doughs. Such control of hydration did not, however, make doughs similar in all aspects of their rheology, and variations were seen in the phase angle of biscuit doughs, which was lower for higher levels of dough water content.

Although effects of water content were seen, small strain rheological measurements showed little response to the processing quality characteristics of the flours themselves. The suitability of a flour for a particular process is instead more likely to be determined by the way in which it behaves under the higher strains typical of processes such as mixing, proving, sheeting or moulding. Many of the established rheological tests for flour quality are based on large strain geometries, and showed a greater discrimination of flours according to processing performance.

Extensograph
The Extensograph tests doughs by stretching them uniaxially to very high strains. The force required is measured as the resistance, and the maximum distance through which the dough is stretched is measured as the extensibility. Under comparable conditions, the resistance would be much lower for varieties suitable for biscuitmaking than for those suitable for breadmaking and in some cases could be too low to be measured. Therefore, in practice, weak flours are tested under a modified protocol with different salt and water addition. Because of this, it is not possible to compare results directly between flours tested under the different protocols. Within either set, however, correlations were seen between Extensograph parameters and other rheological test results. However, the discrimination of flours with different processing performance was not as good as with some other tests.

Alveograph and D/R dough inflation system
An alternative method of testing the rheology of a dough is by stretching it in a sheet under biaxial tension. The most common way of achieving this is by inflating a sheet of dough to form a bubble. Tests were made in this way using the Chopin Alveograph and the more recently developed Stable Micro Systems D/R dough inflation system. Both instruments measure the pressure used to inflate a bubble of dough as a function of the volume of gas pumped into it. The established ways of characterising such doughs are by the maximum pressure attained (P), two values related to the volume of the bubble at the point of rupture (L and G), and the energy required to inflate the bubble to rupture (W). Good agreement in these values was found between the two instruments, although with some significant outliers.

Under the standard Alveograph protocol, doughs are prepared to a constant hydration level. Because water absorption varies between flours, the chosen hydration level does not always correspond to the way in which doughs would be hydrated for processing. Thus, some differences in measured properties may be more indicative of differences in flour water absorption than of differences that could be expected in rheological properties during processing. Tests were therefore also conducted under a new adapted hydration protocol in which doughs were hydrated to a level measured with a Consistograph. Dough properties measured in this way may provide a more direct comparison with the rheological characteristics of doughs during processing.

Under constant hydration conditions, *P* was capable of distinguishing wheats in **nabim** groups 1 and 2 (breadmaking) from soft wheats in groups 3 and 4 (biscuit, cake and other types), but achieved little discrimination within these. Under adapted hydration, the discrimination was poorer suggesting that much of the discriminatory power of *P* is due to the different water absorption of flours in the two categories. The parameter *L* is directly related to the failure strain of a dough. It was positively correlated with loaf volume, possibly because to achieve the gas retention necessary for high volume, the gas cell walls in a bread dough must be capable of high strain without rupture. However, high volume is not the only criterion of loaf quality, and some samples of Hunter and Consort gave high volumes and *L* values, but had poor crumb texture and are not recommended for breadmaking purposes. *L* gave similar results to *A*, the equivalent value under adapted hydration conditions, suggesting that the extensibility of a dough is not strongly affected by its water content. *W* measures the energy required to inflate the bubble to rupture, which is proportional to the area under the alveogram. It was thus correlated with both *P* and *L*, which are related to the height and length of the alveogram. *W* showed a good discrimination of varieties, those suitable for breadmaking having intermediate values, with stronger varieties having higher values and weak (group 3 and 4) varieties having lower values. It may therefore provide a better indication of overall breadmaking suitability than *L*. Its discriminatory power was reduced under adapted hydration conditions, presumably for similar reasons to *P*, with which it is correlated.

The values normally measured by an Alveograph are not all fundamental rheological characteristics of the dough, and are specific to the geometry used. Instead, the rheology can be studied more easily by consideration of the stress and strain in the dough sheet, calculated from the measured pressure and volume data. The D/R system performs this calculation automatically, but it has been shown how similar calculations can also be made using Alveograph data. When the data are analysed in this way, it is apparent that the stress and strain increase steadily throughout the test until the point of rupture is attained, and that the peak pressure typical of untransformed alveograms does not correspond to a maximisation of any actual dough property. Typically, the stress-strain curve has a positive curvature, indicating that the modulus of the dough also increases with strain. This phenomenon is known as strain hardening and arises due to the orientation of polymers within the plane of the dough and thus in the direction of the stress. This acts as a stabilising mechanism against rupture.

Stress-strain curves were modelled as a power law:

$$Stress = K \times strain^{n}$$

The strain hardening index, *n*, was calculated, and was indeed correlated with the failure strain. In a plot of *K* against *n*, grouping of samples according to variety was apparent. By consideration of this plot, a new flour quality parameter $\sigma^{*}=Ke^{n}$ was derived, which quantified the basis on which the varieties were separated. Further variation within varieties was quantified as $\sigma^{\dagger}=Ke^{-n}$, but did not appear to be related to relevant flour or product quality attributes. σ^{*} can be interpreted as the stress attained at a strain of e ($\approx$2.718), which is related to the pressure attained at a drum distance of approximately 143mm in an extrapolated Alveograph curve. It was closely correlated with *W*, and achieved a similar discrimination of varieties. Although *W* is simpler to calculate, the derivation of σ^* provides a better basis for believing that this optimises varietal discrimination.

Gel-protein measurements

Major contributors to functional differences in wheat quality are the high molecular weight proteins. The properties of an SDS-insoluble protein extract (known as gel-protein) provide an excellent indicator of breadmaking potential. Some potential is provided by the mass of gel-protein obtained from a given mass of flour, but this fails to discriminate all breadmaking wheat varieties from less suitable types. Much better performance is provided by measurement of the rheological characteristics of gel-protein and, in particular, its elastic modulus, *G'*. Optimum breadmaking potential is obtained from flours with intermediate values, typically of 15 to 40Pa. Low values signify weaker flours, including those suitable for biscuitmaking, and higher values are characteristic of varieties that may be too strong for use as dominant components of a breadmaking grist.

Measurement of *G'* requires expensive equipment, including an ultracentrifuge to prepare gel-protein samples and a rheometer to measure their elastic modulus. It is a sufficiently useful test that it would be desirable if it could be made more affordable for widespread use. The Bohlin VOR rheometer currently used at CCFRA is a more sophisticated instrument than is required for the test and an evaluation was therefore made of a simpler rheometer (the TA CSL^2_{100}). This provided similar results and offers potential as a lower cost alternative to the VOR instrument. The possibility was also investigated of measuring the sound propagation properties of gel-protein as an indicator of its rheology and an alternative to the use of a rheometer. Comparative measurements were made of the propagation times of ultrasound pulses through samples of gel-protein placed in cuvettes of standard dimensions. No significant differences were measured for gels with a wide range of elastic moduli. However, it is possible that this may have been due to difficulty in loading the samples into the cuvettes without air bubbles, and the potential for using sound propagation to measure gel rheology cannot be ruled out.

Near infra-red (NIR) spectroscopy

NIR instruments are in common use in the grain processing industry, and provide a rapid alternative to several reference test methods. They are particularly well suited to measurement of moisture, protein and hardness, although calibrations have also been developed for several other wheat and flour properties. The flours prepared in this project were scanned with an NIR instrument to produce a spectrum for each flour. The spectra were analysed to assess the possibility of developing calibrations against several of the other reference measurements available. No robust calibrations could be obtained against the baked product attributes tested or against dough or gel-protein rheological characteristics. Good calibrations were obtained, however, against starch damage, and against water absorption measured with a Farinograph or measured for biscuit doughs by an extrusion test. All of these measurements are dependent on related flour characteristics, and calibrations for the first two have been demonstrated previously. As mentioned above, direct measurements of water addition for biscuits are not widely used for flour specification. An NIR calibration might provide a convenient way of achieving this and was an improvement on the use of Farinograph measurements for this purpose.

Prediction of breadmaking performance

Gel-protein elastic modulus, *G*', Alveograph *W* (under constant hydration conditions), and the newly derived alveograph parameter, σ^*, all provided a good indication of breadmaking quality in a Chorleywood Bread Process at an energy input of 11Wh/kg, with optimum quality being achieved for flours with intermediate values. Since the standard Alveograph test employs Chopin milled rather than Buhler milled flours, further work would be necessary to establish whether the Alveograph parameters retain their discriminatory capability for such flours, and to establish the ideal range of values. Alveograph *L* or *A* provided a better correlation with loaf volume, but did not reflect other important loaf quality attributes.

Prediction of biscuitmaking performance

For biscuitmaking, varieties fell into two distinct populations. Soft group 3 and 4 varieties produced soft textured biscuits. These varieties had low water absorption and, possibly as a direct result of this, produced biscuits with low moisture content. Hard group 1 and 2 varieties, which had higher water absorption, produced unacceptably hard biscuits with high moisture content. Due to the lower moisture content of the former set of samples, these produced greater problems with checking (cracking of biscuits due to uneven drying), but these were the biscuits of overall highest quality. Because of the separation of biscuit quality into two populations with differing water absorption, many tests that were related to this could also be correlated with biscuit quality. However, none of these tests produced a good prediction of biscuit quality within either population. Indeed, even the well-established correlation between flour protein content and biscuit hardness appeared only to be a result of variations in water absorption. One of the possible causes for the poor predictive ability of the tests assessed was poor repeatability in biscuit baking performance itself, and in the measurement of water absorption by the dough extrusion test. This may be due to the fact that the biscuits were baked without SMS, which was done in order to assess the inherent characteristics of each flour. Practical experience suggests that, through modification of dough rheology, SMS also achieves an important function of improving the consistency of baking performance.

Conclusions

This project has demonstrated that many of the flour quality tests in use today have the capability to distinguish the widely differing baking properties of **nabim** group 1 and 2 wheats from those of groups 3 and 4. However, test baking remains the most effective method of discriminating performance within these populations. It was found that water absorption is a significant contributor to results measured by many current methods based on dough rheology at constant hydration. Improvements in the Farrand equation for prediction of Farinograph water absorption were developed. This equation is based on starch damage, protein and moisture content. However, it did not provide consistent results across harvest years, suggesting that additional factors also need to be included. Water absorptions measured by the new Consistograph instrument did not show a simple relationship with Farinograph values, and could not be modelled so effectively in this way. An effective NIR calibration was demonstrated for Farinograph water absorption, and such calibrations are already in use in industry. It was shown that an effective calibration could also be developed against the dough extrusion test used for biscuit water absorption, and that this provided a better prediction of biscuit water absorption than a value based on a Farinograph measurement. The adoption of such a system in biscuit flour specifications might therefore provide an improvement on current practice.

For breadmaking performance, gel-protein rheology remains one of the most useful small-scale tests, but involves expensive equipment. It was shown that a simpler rheometer than the Bohlin VOR currently used could provide comparable results; however, the cost still remains significant. Small-scale rheological tests of doughs showed little potential for prediction of processing performance, and it is appropriate to concentrate attention on large strain tests, which have greater relevance to typical processing conditions. Among such tests, the Alveograph is not widely used in the U.K., but showed promise for measurement of breadmaking potential. The new Stable Micro Systems D/R instrument also provided reasonable agreement with the Alveograph, and offers a promising alternative to it. The Alveograph *P* value clearly discriminated group 1 and 2 wheats from group 3 and 4 wheats. No such discrimination existed under adapted hydration conditions and this discrimination is therefore probably partially due to differences in water absorption. The *L* parameter, and its equivalent, *A*, under adapted hydration showed some correlation with loaf volume. This alone, however, is insufficient since some samples produced loaves of high volume, but which were otherwise of poor quality. A good prediction of overall breadmaking quality was provided by *W*, which was similar to that provided by gel protein elastic modulus. A more fundamental understanding of dough rheology was obtained by transforming Alveograph data into stress-strain relationships, a calculation which the D/R system performs automatically. Considered on this basis, it was apparent that dough extensibility was determined by the strain hardening properties of the dough. A combination of rheological properties, σ^*, was identified which provided optimal discrimination of flours on a varietal basis. This measurement was very similar to *W* in its predictive capability.

For biscuitmaking performance, samples could be subdivided into two populations: Hard group 1 and 2 wheats had high water absorption and produced biscuits with an unacceptably hard texture and a high moisture content. Soft group 3 and 4 wheats were more suitable for biscuitmaking and produced biscuits with softer texture and lower moisture. Many tests were able to discriminate these two populations. However, no effective prediction of quality within the group 3 and 4 wheats could be found, including methods currently relied on for this purpose. This may reflect the difficulty in obtaining consistent baking quality under small-scale test baking conditions, particularly in the absence of SMS.

Contents

1. Introduction

As is the case with many natural products, wheats vary considerably in their fitness for processing into foods for human consumption. Small-scale tests are required by the industry as full scale baking is not an option at intake. Many tests have been devised, and indeed are used in evaluating parcels of wheat and flours for manufacture of bread, biscuits and other food products. However, limitations in their predictive ability have been recognised. These are further exposed as promising tests are adopted by breeders who then breed new varieties to comply not with actual processing requirements but with the limited spectrum of parameters measured by the small-scale test, potentially leading to the introduction of varieties with unbalanced quality characteristics.

The aim of this project was to evaluate the performance of various flour quality tests and to identify new or modified tests which could provide a better prediction of the biscuit and breadmaking potential of wheats. In recent years, much knowledge has been gained on the composition of functional wheat proteins and this knowledge has been related to the performance of flours in processing. Considerable success has also been achieved with rheological tests on both flours and on gluten proteins extracted from flours. An emphasis has therefore been placed on tests which measure rheological properties of doughs and of protein extracts. The measurement of the elastic modulus (G') of the gel-protein fraction of wheat flour was developed at FMBRA, Chorleywood. This measurement is now performed routinely on bread flours as part of the National and Recommended List trialling system. The stress relaxation properties of a dough can be related to its breadmaking performance. Lindahl and Svensson (1988) have ranked Swedish wheat varieties in terms of their breadmaking potential by measuring the stress generated in a standard flour/water dough. In an HGCA sponsored project, the rate at which induced stress relaxed in full recipe bread doughs was correlated (r=0.82) with loaf volume (Pritchard *et al.*, 1993). The relaxation rate for flours of poor breadmaking performance was lower than that obtained with good quality breadmaking flours.

Semi-sweet biscuits account for approximately 15% of sales in the UK biscuit market and were chosen for the study as they have higher flour quality requirements than other biscuit types such as short dough biscuits. Semi-sweet biscuit doughs contain a developed gluten protein network that gives the dough a viscoelastic nature. The viscoelastic properties of the dough need to be controlled as the elastic properties of the gluten may lead to contraction of the biscuit dough piece during processing (Thacker, 1993). Dough piece contraction can lead to variability in product dimensions, moisture content and texture. This behaviour may cause problems in the packaging of the product. Dynamic oscillatory measurements of semi-sweet doughs have been used to predict the likelihood of dough piece contraction occurring (Oliver *et al.*, 1995). The flour properties that affect the viscoelastic nature of the dough are primarily protein content and quality. In commercial practice, variability in dough viscoelasticity is typically minimised through the choice of wheat varieties with the desired quality characteristics or by chemical modification of the gluten proteins. Chemical modification of the gluten proteins is commonly achieved by using sodium metabisulphite (SMS) as a recipe ingredient (Wade, 1988). SMS acts as a source of sulphur dioxide, which is able to break some of the disulphide bridges in the gluten proteins. This weakens the elastic properties of the gluten and reduces the likelihood of dough piece contraction. There is currently a desire to move away from the use of SMS and the intention in this study has been to identify tests that can predict processing performance in recipes without SMS.

Starch damage is an important attribute that can be created during milling to increase the water-absorbing properties of a flour, thus extending the period of freshness of bread. The level of damage which can be tolerated by a flour depends upon protein content and as UK-grown wheats tend to have lower protein content than some imported wheats, the home-grown types are disadvantaged in this regard. A noticeable upward trend has occurred in starch damage levels over a long period and it is considered by some that excessive levels are now used. There is a need to carry out comparisons of flours milled from the same grists, to different levels of starch damage, in order to define the flour characteristics that influence acceptability of increased damage levels and to define optimal levels based on an understanding of these characteristics.

In the study described here, fundamental rheological measurements have been used to study the characteristics of bread doughs and semi-sweet biscuit doughs. In dynamic oscillatory measurements the test material is subjected to a sinusoidally varying strain and the resultant stress is measured. For an elastic solid, the stress generated will be perfectly in phase with the applied strain. For a liquid, the stress generated will be 90° out of phase with the applied strain, the difference in phase of the stress and strain being termed 'phase angle'. Doughs are viscoelastic in nature and therefore the phase angle is intermediate between 0° and 90° and is in fact in the region between 20° and 40°. From oscillatory measurements, it is possible to determine the storage (elastic) modulus and the loss (viscous) modulus of the test material. By performing oscillatory measurements at a range of frequencies it is possible to develop a mechanical fingerprint of a material. Additionally, the data collected at low frequencies provides information on how the material will behave over long time scales and the data collected at high frequencies relates to how the material will behave over short time scales. Stress relaxation measurements are complimentary to oscillatory measurements in that they provide information on the viscoelastic properties of a material. The stress relaxation method is more suited for longer time-scale measurements than the oscillatory measurement. Stress relaxation measurements are performed on controlled strain rheometers and involve subjecting a sample to a sudden strain that is held constant while the decay in stress in the sample is monitored. Typical outputs from stress relaxation measurement are the relaxation modulus and the relaxation spectrum (relaxation time) of the material.

In baking processes such as mixing, sheeting, moulding and proof, doughs undergo large strains. In addition to measurements made with a rheometer under low strain conditions, tests have therefore been conducted at higher strains using instruments more familiar in flour testing. An Extensograph has been used to subject doughs to large uniaxial strains and an Alveograph has been used for biaxial testing. In the latter case, analysis of fundamental rheological properties has been possible.

It is estimated that the potential contribution of home-grown wheats in the U.K. bread industry is approximately 90%, although this is not always achieved. To maximise the usage of home-grown wheats in high value applications their full potential value must be delivered. This requires that samples best suited to a particular end-use are selected by reliable methods and that they are processed optimally. This project aims to identify methods which can be used to predict the suitability of wheat samples for bread or semi-sweet biscuit production and which could be used by processors to select suitable wheats at intake, and by breeders to assist in selection of new varieties with desirable characteristics for baking.

2. Materials and methods

2.1 *Wheat varieties*

A range of wheat varieties were selected to provide a broad range of both milling and baking quality characteristics in order to test relationships between end-use quality and predictive tests. To ensure commercial relevance, advice was sought from wheat buyers in several large UK milling companies on varieties currently favoured for production of bread and biscuit flours and on those sometimes considered, but likely to provide a wider range of rheological properties. For the main assessments, wheat samples were obtained from the 1995 and 1996 harvests and used to identify tests which showed potential for predicting their processing performance. For validation of this potential, further wheat samples were obtained from the 1998 harvest and subjected to the most promising tests. Most of the wheats grown in the U.K. were of varieties fully recommended on the respective NIAB recommended lists (NIAB, 1995, 1996, 1998). Exceptions, which were among the varieties selected from the 1998 harvest for validation purposes, were Claire and Malacca which were provisionally recommended in 1999 (NIAB, 1999), and Spark which although recommended in 1998 was becoming outclassed in 1999. Examples of imported wheats of relevance to the UK market were also included. Details of the varieties selected are given below, listed according to the **nabim** group classification system (**nabim** 1997, 1998, 1999).

2.1.1 Breadmaking varieties

The following breadmaking wheat varieties were selected to provide a range of milling and breadmaking qualities.

*2.1.1.1 **nabim** group 1: Varieties likely to gain a full breadmaking premium*

(a) Proven varieties

Mercia: A variety with good milling and standard breadmaking qualities. Removed from the Recommended list in 1998 but still regarded by all millers as good for breadmaking (**nabim**, 1998).

Hereward: Currently considered the best UK variety for breadmaking (NIAB, 1996).

Spark: A hard endosperm variety acceptable for all breadmaking processes. (NIAB, 1998) Scores well in breadmaking tests and acceptable to all millers (**nabim**, 1997, 1998).

(b) Varieties not yet proven in commercial use

Malacca: New variety which promises excellent breadmaking performance and is newly included on the recommended list with provisional recommendation.

*2.1.1.2 **nabim** group 2: Varieties which have some breadmaking potential but which are not as good as those in group 1*

Cadenza: Recommended by NIAB as "A hard endosperm variety with similar bread-making potential to Mercia". However, Cadenza may be unacceptable to some millers as it may yield excessively high starch damage levels.

Soissons: Also a hard endosperm variety suitable for some breadmaking purposes but with a tendency to be extra strong and to yield low levels of starch damage. The French-bred variety Soissons would be classified as being of superior breadmaking quality in France and is included here as a typical example of a continental wheat which could be imported into the U.K.

2.1.2 Biscuitmaking varieties

The following varieties were chosen to represent the range of UK biscuitmaking wheat varieties available during the project.

2.1.2.1 ***nabim** group 3: Soft varieties for biscuit, cake and other flours*

Riband: "Current mainstay for millers of biscuit flour" (**nabim**, 1997), accounting for approximately 80% of total biscuit grists (Johnson, 1995).

Consort: "Variety offering similar potential to Riband. Also popular with millers for its improved dough extensibility" (**nabim**, 1997).

Beaver: "May be used for biscuit milling, but not a preferred variety" (**nabim**, 1997). Beaver has declined in popularity and was removed from the recommended list in 1996. Due to lack of commercial relevance and reduced availability, it was therefore not used in the second year of this study.

Claire: A soft endosperm **nabim** group 3 variety with biscuitmaking quality (NIAB, 1999). "Tests by millers suggest a biscuitmaking potential better than Riband and as good as Consort" (**nabim**, 1999).

2.1.3 Feed varieties

In addition to the group 3 wheats selected for their biscuitmaking potential, a feed variety from group 4 was also included to increase the range of quality characteristics included in the study.

2.1.3.1 ***nabim** group 4: Other wheat varieties*

Hunter: "A soft endosperm feed variety." (NIAB, 1996), "...not generally suitable for biscuit flour." (**nabim**, 1997)

2.1.4 Imported wheats

The following imported wheats were also selected, typical of those likely to be imported into the UK.

Canadian Western Red Spring (CWRS):
A hard wheat class with high protein content and excellent breadmaking quality.

German Elite grade:
A grade of wheat suitable for breadmaking, and common among wheat types imported to the UK.

Where possible, each of the varieties was obtained at several protein levels. Samples were ordered to a minimum specification of 76 kg/hl specific weight and 250 s Falling number. Tables 1, 2 and 3 show the samples received from the 1995, 1996 and 1998 harvests respectively.

2.2 *Wheat variety identification*

Polyacrylamide gel electrophoresis was used to establish the purity of the wheat samples. For the 1995 and 1998 harvest samples, 14 grains were tested from each sample. For the 1996 harvest samples, most samples were delivered in several sacks. To ensure that these had been correctly identified, 7 grains were tested from each sack. Collating the results for each sample, this typically yielded up to 28 grains for assessment of purity. The identities of the tested grains are listed in Tables 1, 2 and 3.

Table 1 - Wheat samples received from the 1995 harvest

Variety and sample number	Wheat protein content (14 % moisture)	Grain Identity (number of grains)	Range of possible purity as labelled (95% confidence)
Beaver	9.15 ± 0.07	14 Beaver	76-100%
Cadenza No.1	10.15 ± 0.07	14 Cadenza	76-100%
No.2	11.70 ± 0.01	11 Cadenza, 3 Spark	49-95%
No.3	12.60 ± 0.01	12 Cadenza, 2 Soissons	57-98%
Consort No.1	10.55 ± 0.06	14 Consort	76-100%
No.2	9.28 ± 0.10	14 Consort	76-100%
CWRS	13.5*	*Not tested*	*Not tested*
Hereward No.1	10.45 ± 0.07	14 Hereward	76-100%
No.2	11.75 ± 0.07	7 Hereward, 6 Mercia, 1 Axona	23-76%
No.3	12.05 ± 0.21	14 Hereward	76-100%
Hunter No.1	10.15 ± 0.07	14 Hunter	76-100%
No.2	10.05 ± 0.07	13 Hunter, 1 Slejpner	66-100%
Mercia No.1	11.05 ± 0.07	14 Mercia	76-100%
No.2	11.50 ± 0.14	14 Mercia	76-100%
No.3	12.60 ± 0.14	14 Mercia	76-100%
Riband No.1	10.25 ± 0.07	1 Hereward, 13 Hussar - *rejected*	0-24%
No.2	9.35 ± 0.21	14 Riband	76-100%
No.3	10.85 ± 0.07	14 Riband	76-100%
Soissons No.1	12.05 ± 0.07	14 Soissons	76-100%
(U.K. No.2	12.55 ± 0.07	13 Soissons, 1 Unknown	66-100%
grown) No.3	12.25 ± 0.07	14 Soissons	76-100%

* Value stated by supplier

Table 2 - Wheat samples received from the 1996 harvest

Variety and sample number	Wheat protein content (14% moisture)	Grain Identity (number of grains)	Range of possible purity as labelled (95% confidence)
Cadenza No.1	11.0	28 Cadenza	87-100%
No.2	9.9	25 Cadenza, 2 Hussar, 1 Charger?	71-98%*
Consort No.1	9.5	28 Consort	87-100%
No.2	8.1	21 Consort	?-100%
No.3	10.3	28 Consort	87-100%
German E No.1	12.4	*Not tested*	-
No.2	12.5	*Not tested*	-
No.3	12.7	*Not tested*	-
Hereward No.1	12.1	28 Hereward	87-100%
No.2	12.6	28 Hereward	87-100%
No.3	10.5	27 Hereward, 1 Brigadier	82-100%
Hunter No.1	9.7	28 Hunter / Encore	87-100%
No.2	8.9	27 Hunter / Encore, 1 Consort	82-100%
No.3	10.7	28 Hunter / Encore	87-100%
Mercia No.1	11.9	28 Mercia	87-100%
No.2	10.8	28 Mercia	87-100%
No.3	10.4	28 Mercia	87-100%
Riband No.1	7.9	28 Riband	87-100%
No.2	9.4	28 Riband	87-100%
No.3	9.4	*Not tested - sample rejected*	-
Soissons (UK) No.1	9.7	28 Soissons	87-100%
(UK) No.2	12.1	27 Soissons, 1 Unknown	82-100%
(French) No.3	11.0	26 Soissons, 1 Brigadier?, 1 Rossini	76-99%*

* Assuming that the grains of uncertain identity are not of the intended variety.

Table 3 - Wheat samples received from the 1998 harvest

Variety and sample number		Wheat protein content (14% moisture)	Grain Identity (number of grains)	Range of possible purity as labelled (95% confidence)
Cadenza	No.1	9.07	14 Cadenza	76-100%
	No.2	11.32	14 Cadenza	76-100%
Claire	No.1	10.96	9 Claire, 3 Buster, 1 Rialto, 1 Madrigal	34-87%
	No.2	10.87	11 Claire, 2 Madrigal, 1 Buster	49-95%
Consort	No.1	9.04	14 Consort	76-100%
	No.2	10.43	11 Consort, 2 Consort?, 1 Abbot	49-95%*
CWRS	No.1	14.02	14 CWRS	76-100%
	No.2	14.90	12 CWRS, 2 Unknown	57-98%
Hereward	No.1	10.21	12 Hereward, 1 Brigadier, 1 Unknown	57-98%
	No.2	12.16	14 Hereward	76-100%
Hunter	No.1	9.94	12 Hunter / Encore, 1 Buster, 1 Unknown	57-98%
	No.2	10.15	14 Hunter / Encore	76-100%
Malacca	No.1	11.32	14 Malacca	76-100%
	No.2	12.07	14 Malacca	76-100%
Mercia	No.1	10.83	14 Mercia	76-100%
	No.2	11.56	14 Mercia	76-100%
Riband	No.1	9.22	11 Riband, 2 Consort, 1 Damaged	49-95%
	No.2	10.87	13 Riband, 1 Damaged	66-100%
Soissons	No.1	10.67	13 Soissons, 1 Soissons?	66-100%*
	No.2	11.33	13 Soissons, 1 Riband	66-100%
Spark	No.1	12.04	8 Spark, 3 Hereward, 3 Abbot	28-82%
	No.2	11.26	14 Spark	76-100%

* Assuming that the grains of uncertain identity are not of the intended variety.

2.3 *Wheat protein*

Wheat protein content was determined by near infra-red reflectance spectroscopy (NIR). For samples from the 1995 harvest, each sample was divided into two batches and the protein content of each batch was measured. Mean results are shown in Table 1. For the samples from the 1996 and 1998 harvests, subsamples were taken from each sack in which a single sample was delivered. These were combined in equal proportions to yield a test sample. Results are shown in Tables 2 and 3.

2.4 *Wheat grain size*

The sizes of 400 grains of each wheat sample from the 1995 harvest were measured by image analysis. The grains were fed along a grooved perspex tray mounted above a light box and the grains were imaged in silhouette using a CCD camera. Images were digitised and analysed with a Sprynt 40MHz board (Synoptics Ltd., Cambridge) installed in a PC computer, using programs written by CCFRA within the Semper for Windows (Synoptics Ltd.) application program. For each grain image the area, length, breadth and perimeter were measured. Before each set of measurements, the camera aperture was adjusted to give a constant image brightness (assessed with the aid of coloured contours of brightness) and the magnification was calculated using a ruler placed on the sample tray. The system was calibrated by measuring a set of metal cylinders of known dimensions and adjusting the brightness threshold between the objects and the background until the measured area was in agreement with the true value.

2.5 *Wheat milling*

A trial hard wheat and a trial soft wheat were milled using a Buhler MU202 Laboratory Mill under different conditions to establish those conditions which would yield high and low starch damage. The wheat samples from the 1995 and 1996 harvests were then milled under these conditions to yield flours with high and low starch damage levels. In the tables of flour data in the Appendix, these have been identified by a nominal starch damage level of 'HIGH' or 'LOW' respectively. For each wheat the high and low starch damage flours were in most cases blended to yield flours with two intermediate starch damage levels, denoted 'SD1' and 'SD2', formed respectively as 33:67 and 67:33 blends of the 'LOW' and 'HIGH' flours. For some flours, insufficient quantities were available and only one intermediate 50:50 blend was made, denoted 'SD3'. As a result each wheat sample yielded a total of either three or four flours.

In practice, this procedure was found to yield a smaller range of starch damages for each wheat than had been hoped. Therefore, for the validation samples from the 1998 harvest, the procedure was altered in an attempt to achieve a wider range. Each wheat sample was conditioned in bulk and was then subdivided into two fractions which were milled simultaneously on two different Buhler MU202 laboratory mills to produce a high and a low starch damage flour. Because these flours were only used for validation purposes, fewer samples were required and no blended samples were made. For high starch damage, CCFRA's normal protocol uses roll gap dial settings of 6, 4, 3 and 2, where 6 corresponds to a gap of 60µm (although the 1st break roll has a smaller diameter than the other rolls and therefore a larger gap than this). For these experiments, the gap was decreased to settings of 6, 4, 1.5 and 1 in order to achieve higher starch damage levels than normal. For the low starch damage protocol, the roll gap dials were set to 10, 7, 7 and 3 and the mill was run without scalpers to prevent blockages which can occur when milling large quantities of soft wheat.

In total, 19 wheats were milled from the 1995 harvest to produce 71 flours, 19 wheats were milled from the 1996 harvest to produce 71 flours, and 22 wheats were milled from the 1998 harvest to produce 44 flours.

2.6 *Flour quality measurements*

2.6.1 Protein and moisture

Flour protein and moisture contents were determined by near infra-red reflectance (NIR).

2.6.2 Starch damage

Starch damage was determined by the Farrand Method (Farrand, 1964).

2.6.3 Pentosan content

Pentosan content of flours was measured by a colourimetric method based on that of Douglas (1981). For determination of total or soluble pentosans, an aqueous suspension or a water extract respectively was reacted with a solution containing acetic acid, hydrochloric acid, phloroglucinol and glucose to form a coloured product. The absorbance was measured at 552 and 510nm, from which the pentosan content was calculated by reference to a standard curve.

2.6.4 Farinograph

Farinograph measurements were determined by Flour Testing Working Group method No. 0004 (CCFRA, 1997). Measurements were made using a 300g bowl and using the 600 line.

2.6.5 Extensograph

Extensograph measurements of flours milled from breadmaking varieties were made according to Flour Testing Working Group Method No. 0003 (CCFRA, 1997), using doughs made from flour, 6g salt, and water sufficient to achieve the level of the 500 line on a Farinograph. For weak flours, this recipe may produce a dough with insufficient resistance to be measurable. Therefore, for the varieties Beaver, Riband, Hunter, Consort and Claire, tests were conducted according to Flour Testing Working Group Method No. 0016 (CCFRA, 1997), in which 12g of salt was used and water was added to achieve the level of the 600 line on a Farinograph.

2.6.6 Chopin Alveograph

The Alveograph is an empirical instrument that is used to measure flour quality. A dough is mixed, sheeted into a flat piece, and secured in the instrument. The instrument then uses air pressure to blow a bubble in the dough piece and measures the pressure during the inflating operation. Results are output as an alveogram, which provides information about the elastic and extensibility characteristics of doughs. The Alveograph stretches the dough sheet in all directions, and the stretching is therefore biaxial and is similar to the type of expansion that occurs in fermenting doughs. Several parameters characterising the dough properties were measured from each alveogram.

The Chopin Alveograph test can be split into three main phases:

2.6.6.1 A. Test milling

Normally, flours for use in Alveograph testing are milled with a Chopin mill. For this project, the tests were instead carried out using the same flours as for other testing, milled as described in section 2.5.

2.6.6.2 B. Dough mixing and extrusion

Doughs were mixed under two protocols. In the constant hydration protocol, a fixed amount of sodium chloride solution (2.5g / 100ml), calculated on the basis of the flour moisture content, was added to 250g of flour and the dough was mixed for a total of 7 minutes. In the adapted hydration protocol, the water and flour quantities were instead determined by a Consistograph according to the water absorption of the flour. After stopping the mixer a small shutter was raised, the mixer was started again and a strip of dough extruded out onto a small oiled plate. The first 2cm of the extruded dough was discarded and the dough sample was then divided into five approximately equal sized pieces.

2.6.6.3 C. Dough relaxation and inflation

The five dough pieces were sheeted to a pre-determined thickness before being cut into discs and allowed to rest for 20 minutes at a controlled temperature of 25.0 ± 0.2°C. The discs of dough were held between two circular plates, the upper one having a circular hole through which the bubble expanded. The lower plate has a valve connected to a small air chamber which is connected to a large burette where water is used to create the pressure, a manometer being used to record the actual pressure within the bubble against time. The disc of dough was inflated under standard conditions to form a bubble and the pressure was recorded as a function of time until the bubble eventually burst.

For most of the measurements, data were collected from the Alveograph using an Alveolink computer. These data were copied to a spreadsheet program and manipulated to calculate the stress and strain of the dough in addition to the standard

Alveograph measurements (see section 3.5.3). For samples measured using a recording manometer, similar data were obtained by measuring the pressure at approximately 5mm intervals along the horizontal axis of the trace and also transferring these values into the spreadsheet.

2.6.7 Dobraszczyk Roberts dough inflation system

The Dobraszczyk Roberts (D/R) dough inflation system (Stable Micro Systems, Godalming, UK) was used to test doughs in biaxial extension for comparison with the Alveograph. To provide a direct comparison, doughs were prepared in the same manner as for the Alveograph test and were mixed using the Alveograph mixer. The doughs were collected from the mixer bowl without sheeting and were manually rolled out into sheets using an oiled roller as specified in the D/R manual. One at a time, five discs were cut from each sheet, placed in sample pots and compressed to a controlled thickness for 1 minute. The pots were stacked with a lid on the top one, and the samples were left to rest in them for 30 minutes. The samples were then tested in order of preparation. The dough inflation system used a piston to force air through a nozzle beneath the dough sheet and to inflate it. The air pressure and volume were recorded to produce a trace for each sample. Data could be presented in several ways, including stress–strain relationships and pressure-drum distance values, calculated for comparison with Alveograph data. To calculate values corresponding to the Alveograph *P*, *L*, *G* and *W* parameters, a 'macro' calculation was used to locate the maximum pressure automatically. The 'burst point' corresponding to rupture of the bubble could not be reliably identified using the software provided, and was therefore identified manually. Once these points had been identified, the software then calculated the required parameters.

2.6.8 Chopin Consistograph

The Chopin Consistograph is a relatively new instrument. One of its uses is to provide a measurement of flour water absorption, which is used to determine water addition for Alveograph tests conducted under adapted hydration conditions. For this purpose, doughs were first mixed in the Consistograph under constant hydration conditions, using 250g of flour and the same level of salt water addition as in a standard Alveograph test. The pressure of the dough against the side of the mixing bowl was measured as a function of time. From the pressure-time curve, the instrument estimated the hydration level (on a 15% moisture basis) necessary to attain a pressure of 2200mb, and calculated the quantities of flour and salt water required to mix a dough to this hydration level. Further tests were conducted using these quantities (adapted hydration conditions), and the estimate of the hydration level was refined until a maximum pressure within 7% of the target value of 2200mb was attained. The final hydration level (HYDHA) was taken as a measure of the water absorption of the flour. This was the hydration level used for Alveograph tests under adapted hydration conditions (section 2.6.6).

2.6.9 Near infrared reflectance scanning

Near infra-red reflectance spectra were measured for 67 of the flour samples from the 1995 harvest and all of those from the 1996 and 1998 harvests. Three subsamples of each flour were taken for scanning and were maintained at ambient temperature before analysis. The samples were presented to an NIRSystems 6500 spectrometer using a standard cup with a ceramic tile backing and were scanned in reflectance over a wavelength range of 400 to 2500nm. A reference scan was measured before each sample scan to check the operation of the instrument. Replicate samples for each flour were presented in sequence and the spectra for the replicates were averaged to provide a single combined spectrum for each flour.

2.7 Gel-protein mass and rheology

For the 1995 and 1996 samples, gel-protein was extracted from flours by the following method. Flour (10g) was de-fatted with 25ml petroleum ether (b.p. 40-60°C) for 1 hour, filtered through Whatman No. 1 paper and air-dried. A 5g sample of the defatted flour was agitated using a magnetic stirrer in 90ml of 1.5% sodium dodecylsulphate (SDS) for 10 minutes at 10°C and then centrifuged at 63000*g* for 40 minutes. The product was refrigerated for 30 minutes. The liquid supernatant was decanted and the gel-protein was then scraped from the opaque starch-rich sediment and weighed. The wet mass of the gel was recorded as the mass of gel-protein per 5g of flour. For the 1998 samples, a new centrifuge was used at a g-factor of 185,500*g* and the procedure was modified to use 15g of flour, 40ml of petroleum ether and 75ml of 1.8% SDS, with a centrifuging time of 35 minutes. These conditions had been shown in separate trials to produce comparable results to those obtained previously.

The rheology of the gel-protein was tested immediately after isolation using a Bohlin VOR controlled strain rheometer (Bohlin Instruments Ltd, Cirencester, England). All measurements were made at 25°C using a 17.88 g cm torsion bar. Dynamic oscillatory measurements were made as a frequency sweep between 0.1 and 10Hz at a strain of 0.103 (amplitude 50%). Data at a frequency of 1Hz were recorded.

2.7.1 TA CSL$^2_{100}$ rheometer

Further tests of gel-protein prepared from selected samples were made using a TA CSL$^2_{100}$ rheometer (TA Instruments Ltd, Leatherhead, Surrey, UK), which is a simpler, lower cost rheometer than the Bohlin VOR. Gels were prepared for eight replicates of a control flour and for four replicates each of a Consort, a Cadenza and a Soissons flour, chosen to have differing rheology. Each was divided into two subsamples, one of which was analysed with each rheometer. The tests were conducted in an oscillatory mode, using frequency sweeps of 0.1 to 10Hz in linear increments for the TA rheometer and logarithmic increments for the Bohlin rheometer. The results were then compared for the two instruments and the repeatability of each procedure was evaluated.

2.7.2 Ultrasound

The sound propagation properties of materials are influenced by their density and rheology. Tests were therefore conducted to determine whether measurements of ultrasound propagation through gel-protein could be used to make inferences about its rheology as a possible, low cost alternative to the use of a rheometer. Samples of gel-protein were placed into cuvettes (Sarstedt No. 67.741, internal dimensions 10mm×10mm×45mm, wall thickness 1mm), filled to the brim. To measure a sample, transducers were placed against the smooth faces of the cuvette, using a layer of ultrasound couplant gel (Ultragel II, Diagnostic Sonar Ltd, Scotland) to ensure good acoustic coupling between the transducers and the sample. One transducer was used as a transmitter and one as a detector (Figure 1). The transmitter was driven with a 5V, 1.25MHz signal generated with a Hewlett Packard Pulse / Function generator. This was modulated at a frequency of approximately 10kHz with a square or sawtooth waveform generated by a Philips PM 5132 function generator to produce pulses of ultrasound. The signal received by the transducer used as a detector was amplified (20dB gain) and compared with the input waveform using a two-channel oscilloscope (LeCroy 9400). The time delay between the start of the falling part of the input and the start of the falling part of the envelope of the output was measured.

Two alternative transducer geometries were tested. In the first example, the cuvette was placed between two ultrasonic transducers (Sonatest SLM) with an active diameter of 30mm, held in place with a strong elastic band as shown in Figure 1. One transducer was used as the transmitter and one as the receiver, with the ultrasound pulses passing once through the gel and the two smooth faces of the cuvette. Figure 2 shows an example output trace from this geometry, together with the pulse used to modulate the input waveform. In this example, a square pulse was used. The delay before detection of the transmitted pulse at the second transducer can be seen. The received pulse is slightly broadened, probably due to dispersion in the fluid. Secondary and tertiary pulses can also be seen, corresponding to multiple reflections of the ultrasound pulse.

Figure 1 – Apparatus used for measuring the speed of sound in gel-protein samples

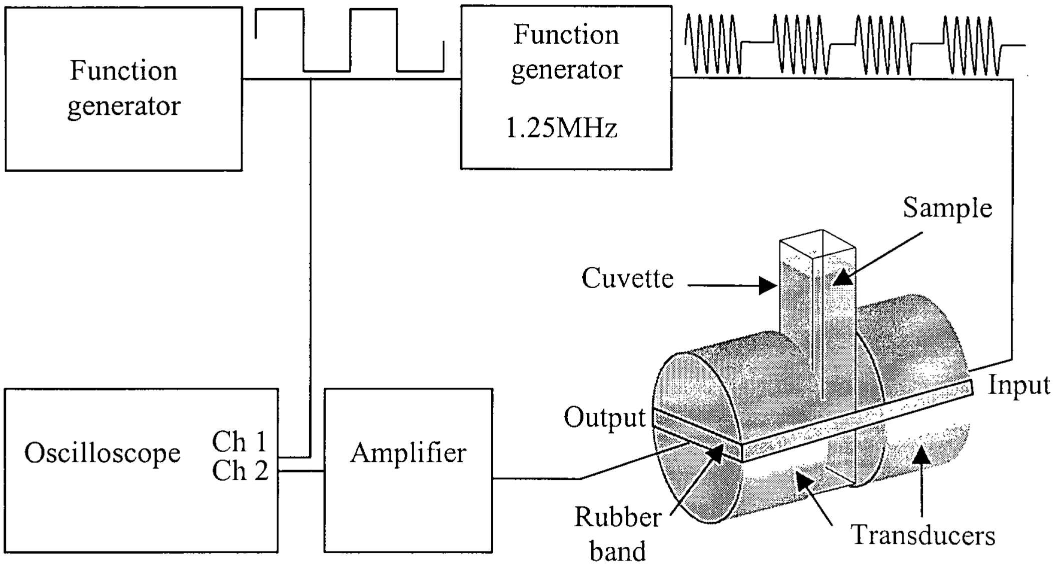
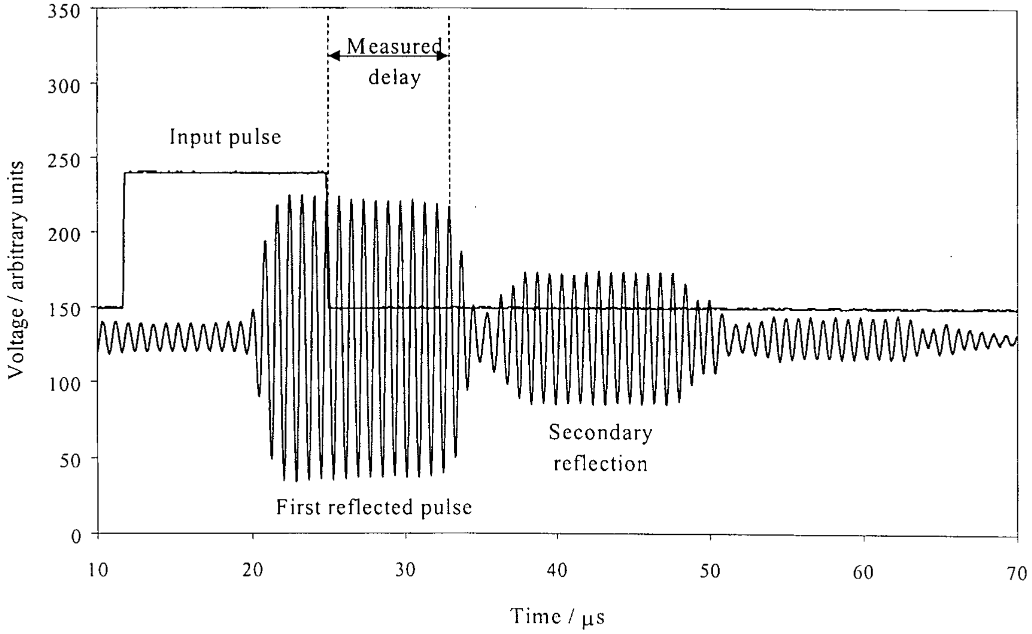
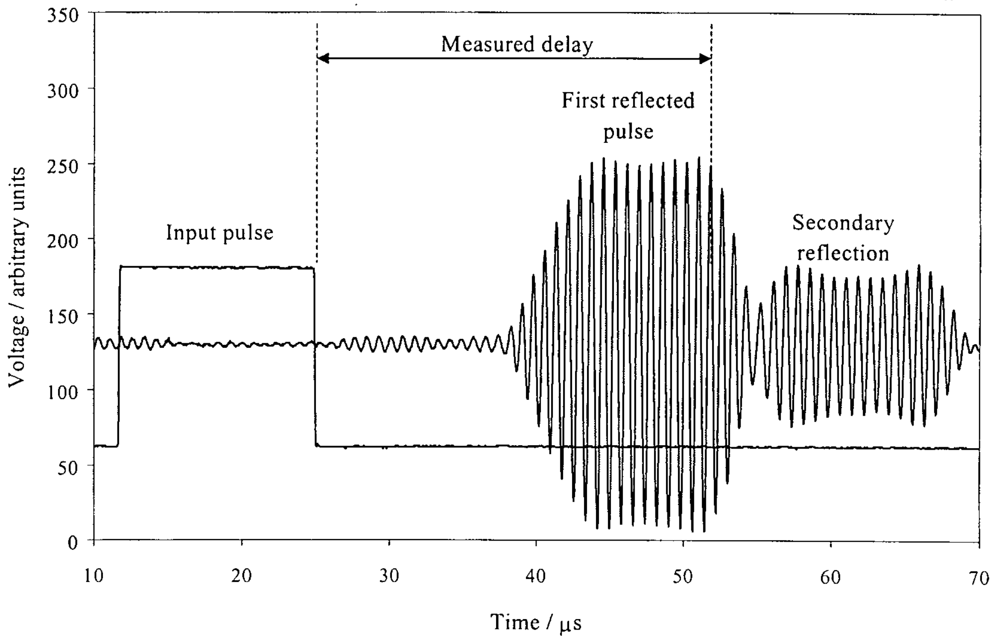


Figure 2 – Example input and output waveforms for ultrasound propagating through glycerine.



In the alternative geometry, a single transducer (Sonatest TMPS) with a diameter of 20mm was placed against one surface of the cuvette. This transducer was split into two semicircular parts separated by a 1mm thick layer of cork. One half acted as an ultrasound transmitter and the other as a receiver. The sound pulse passed through the gel once, was reflected from the far surface of the cuvette, returned through the gel and was detected by the other half of the transducer, thus resulting in a path length approximately double that of the first geometry. An example trace is shown in Figure 3.

Figure 3 – Example waveforms for a single, split transducer (glycerine sample).



2.8 *Bread baking*

400g loaves of bread were prepared according to the following recipe:

Table 4 - Bread recipe

Ingredient	**Quantity**
Flour	1400g
Yeast	2.5% of flour weight
Salt	2%
Fat	1%
Fungal α-Amylase	As required to total 80 Farrand Units. (Fungal α–amylase activity 600000)
Ascorbic acid	0.01%
Water	As determined by Farinograph water absorption

Doughs were mixed in a Morton z-blade mixer to a total work input of 11Wh/kg (~40kJ/kg). After final moulding, doughs were proved to a height of 10 cm at a temperature of 43°C. Doughs were then baked for 25 minutes at a temperature of 244°C. For most of the flours, duplicate doughs were prepared and baked.

2.9 *Bread quality assessments*

2.9.1 Oven spring

After baking, a strap of four loaves in their pans was placed into a height measuring instrument. Probes were lowered onto the surface of each loaf and the mean height was determined by the instrument. To calculate the oven spring (i.e. the amount by which the loaves rose during baking), the final proof height of 10 cm was subtracted from this value.

2.9.2 Loaf volume

Measurements of loaf volume were obtained by seed displacement. Two cups of pearl barley were poured into a box of known volume, into which the loaf was then placed. A further known quantity of barley was poured into the box around the loaf. Excess barley was levelled off and the amount of overspill was weighed. From this, the volume of the loaf was calculated. Before measurement, the barley was first warmed up to a constant operating temperature by passing it through the volume measuring apparatus five times. The precise amount of barley to be used was then adjusted by calibration using a plastic loaf of known volume.

2.9.3 Specific volume

In addition to its volume, the mass of each loaf was also measured. The specific volume was calculated as the ratio of the volume to the mass.

2.9.4 Crumb score

Loaves were cut open and the crumb was inspected visually. A score was allocated in the range 1 (poor) to 10 (good) based on aspects such as the uniformity of the crumb structure, the cell wall thickness and any visible damage such as streaking. Scores greater than about 7 indicate loaves of acceptable to good quality.

2.9.5 Crumb whiteness

Two loaves were cut in half and placed face up under the aperture of a Hunterlab tristimulus colorimeter (Model D25M-9). This measured the colour of the crumb against a CIE tristimulus X, Y, Z scale. The Y value was recorded as a measure of the whiteness of the crumb. Measurements were made for each cut surface of the two loaves and the mean value was recorded.

2.10 *Bread dough rheology*

A Bohlin VOR controlled strain rheometer (Bohlin Instruments Ltd, Cirencester, England) was used to perform bulk rheological tests of the bread doughs. All measurements were made at 30°C, the temperature of the doughs at the end of mixing, using a cone and plate (30 mm diameter, cone angle 5°). Strain sweep measurements at a frequency of 1 Hz showed a linear viscoelastic region centred around a strain of 5×10^{-3}. Dynamic oscillatory measurements were therefore made at a strain of 5×10^{-3}. Oscillatory measurements were made up to 5 minutes after dough mixing was completed. They were collected as a frequency sweep between 0.1 Hz and 10 Hz and the value at 1Hz was quoted. Stress relaxation measurements were made between 5 and 10 minutes after mixing was completed by applying a strain of 4.5×10^{-2} to the dough in a time of 0.02 s. Triplicate oscillatory measurements and duplicate stress relaxation measurements were made for each dough.

2.11 *Semi-sweet biscuitmaking*

The basic recipe formulation for semi-sweet biscuits was as shown in Table 5. The quantity of flour given is typically sufficient for 13 to 16 biscuits. Doughs were produced without SMS addition at an optimised water level. The water addition for each variety was determined by production of a dough to a target extrusion time of 50 ± 5s, which had been shown previously to provide doughs of satisfactory consistency (Barron, 1979). In order to determine extrusion time a 60g sample of the bulk dough was rolled out into a cylindrical shape and pressed firmly into a simple extruder with a water jacket set at 40°C. After 10 minutes a plunger with a 2375g mass was placed on top of the dough piece. The time taken for the plunger to travel 1cm was recorded. The test was repeated with doughs mixed to varying water addition levels until the target extrusion time was achieved. The mass of water added to the mix (for 200g flour) was recorded as a percentage of the flour mass.

Table 5 – Semi-sweet biscuit recipe

Ingredient	Quantity
Flour	200 g per mix
Fat	16% of flour weight
Sugar	21%
Salt	0.35%
Cream powder (sodium acid pyrophosphate and corn starch)	0.35%
Skimmed milk powder	2.5%
Sodium bicarbonate	0.55%
Ammonium bicarbonate	0.55%
Water	Variable

For biscuit production, doughs were mixed in a modified Farinograph mixer at 120 rpm until they reached a temperature of 40°C. Following mixing, the doughs were allowed to rest for 15 minutes in a constant temperature cabinet at 37.8°C. Doughs were then sheeted and cut by hand with a standard cutter to a length of 67.0mm in the direction of machining with a width of 63.0mm. For the flours prepared from the 1995 harvest, doughs were baked at 195°C in a NEFF fan assisted oven with the baking time set at 7 minutes. This was found to produce insufficiently uniform baking and for the samples from the 1996 and 1998 harvests, a Spooner forced convection conveyor oven was therefore used. For this oven, a baking temperature of 195°C was also set, with a baking time of 5½ minutes. Top and bottom heat was equally distributed for each bake. For all flours, duplicate doughs were prepared in random order. After cooling, the baked biscuits were packaged in an impermeable film to prevent moisture uptake or loss prior to assessment.

2.12 Biscuit quality assessment

Several assessments of biscuit quality were carried out and recorded. For each flour sample, biscuit size and reflectance measurements were recorded as the mean values for ten biscuits.

2.12.1 Biscuit size

Direct measurements were made of biscuit weight, thickness, length and width. From these, the eccentricity and bulk density of the biscuits and the package weight for a 145mm package were derived.

To measure thickness, ten biscuits were placed on their edge on a biscuit thickness meter and a gauge was moved to rest against the pile. Length was measured by arranging ten biscuits against a ruler, aligned so that any writing on them was perpendicular to the scale, while width was measured by rearranging the biscuits so that the writing was parallel to the scale.

Eccentricity, packet weight and bulk density were calculated as follows:

$$\text{Eccentricity} = \frac{\textit{Mean Length}}{\textit{Mean Width}} \tag{1}$$

$$\text{Packet weight (g)} = 145 \times \frac{\textit{Weight}\,(\text{g})}{\textit{Thickness}\,(\text{mm})} \tag{2}$$

$$\text{Bulk density (g cm}^{-3}\text{)} = 1000 \times \frac{\textit{Weight}\,(g)}{\frac{\pi}{4} \times \textit{Thickness}\,(\text{mm}) \times \textit{Width}\,(\text{mm}) \times \textit{Length}\,(\text{mm})} \tag{3}$$

2.12.2 Biscuit moisture

Biscuit moisture was determined in triplicate by drying crumbed or ground biscuits in an oven at a controlled temperature of 130-133°C for 90 minutes. Moisture was calculated as a percentage by weight as follows:

$$\textit{Moisture}(\%\textit{wwb}) = 100 \times \frac{\textit{Weight loss after drying}}{\textit{Initial sample weight}} \tag{4}$$

2.12.3 Biscuit colour

Biscuit colour was determined using a bench reflectance instrument (Beaconsfield Instruments Co. Ltd.). This instrument was initially calibrated by placing a white tile over the light source and adjusting the instrument to give a reading of 99.5 on the display. Samples were then placed over the light source, covered with a black top, and the measurement was then taken and recorded.

2.12.4 Biscuit hardness

Biscuit hardness was measured as the time taken to cut through a stack of biscuits using a Baker Perkins Texture Meter (Peterborough, England), harder biscuits taking longer times to cut. 35 seconds is the acceptable upper limit for semi-sweet biscuits (Oliver *et al.*, 1995).

2.12.5 Biscuit checking

The top surface of each biscuit was visually examined for hairline cracks. Checking was recorded as the percentage of biscuits containing any such cracks, or ranked on a scale of "None", "Slight" or "Severe".

2.13 Biscuit dough rheology

A Bohlin VOR controlled strain rheometer (Bohlin Instruments Ltd, Cirencester, England) was used to perform bulk rheological tests of the biscuit doughs. All measurements were made at 40°C, the temperature of the doughs at the end of mixing, using a cone and plate (30mm diameter, cone angle 5°). Strain sweep measurements at a frequency of 1Hz showed a linear viscoelastic region centred around a strain of 4×10^{-4}. This strain was below the measurement range for dynamic oscillatory measurements and these were therefore made as a frequency sweep between 0.1Hz and 10Hz at a strain of 3.3×10^{-3}. Oscillatory measurements were made 5 minutes after dough mixing was completed. Data quoted were collected at a frequency of 1Hz. Stress relaxation measurements were made between 5 and 10 minutes after mixing by applying a strain of 4.3×10^{-3} to the dough in a time of 0.02 s. Triplicate oscillatory measurements and duplicate stress relaxation measurements were made for each dough.

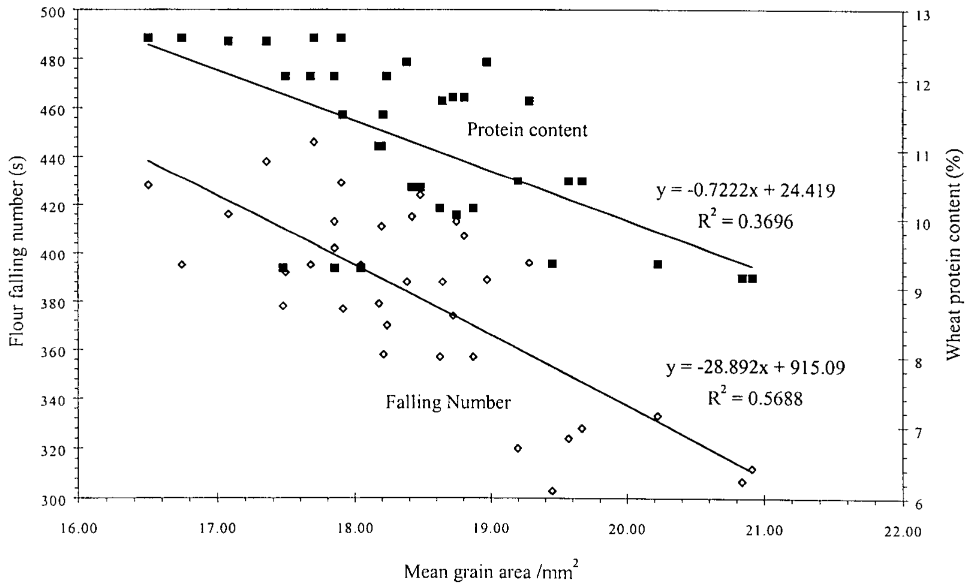
3. Results and discussion

Laboratory flour milling was performed for 19 of the 21 wheat samples received from the 1995 harvest, 19 of the 23 samples received for 1996 and for all 22 of those received from the 1998 harvest. The remaining 6 samples were rejected as not meeting the requirements for the project. With a few omissions, all of the flours were tested and baked to produce bread and biscuits by the methods described above. The results of particular tests are discussed in the following sections and summarised in tables in the appendix.

3.1 Wheat grain size

Wheat grain size has been shown previously to be correlated with several wheat and flour quality attributes. In addition to factors on which it may have a direct, causal influence such as hectolitre weight and milling extraction rate, correlations have been reported with protein content, protein quality, Falling Number (Evers, 1996a,b) and flour water absorption (Preston, private communication[1]). Many of these effects were confirmed for U.K. wheats in grain size measurements of samples from the 1995 HGCA Cereals Quality Survey, which were reported by Millar *et al.* (1997). In the present study, a further opportunity was taken to validate these findings. Measurements were made of mean grain size for the wheats collected from the 1995 harvest and have been compared against several of the above quality attributes. Figure 4 shows the relationship with wheat protein content and with flour Falling Number. Both showed a negative correlation with grain size, which is consistent with previous studies. However, no relationship was seen with flour water absorption, the correlation coefficient being $R^2 = 0.13$.

Figure 4 – Relationship of wheat protein and flour falling number with wheat grain size for the 1995 harvest samples.



It is thought that the negative correlation of wheat protein content and grain size arises from the greater scope for variation in the absolute quantity of starch in a grain than of

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[1] K. Preston, Canadian Grain Commission

protein. Thus, greater deposition of starch causes both an increase in grain size and a dilution of the protein present in the grain. Although not yet fully understood, the correlation between grain size and Falling Number is thought to be related to variations in the size and structure of the endosperm cavity. Wheat varieties which have a tendency to produce large grains, in many cases also have proportionately larger endosperm cavities. Although these cavities do not always persist as an open structure during grain development, larger loops of cavity aleurone persist within the endosperm and may result in elevated levels of amylase activity and a low Falling Number. In particular, the aleurone cells in the vicinity of the endosperm cavity have been shown to have the greatest activity of late maturity *alpha*-amylase (Evers, 1996b).

3.2 Starch damage

3.2.1 Starch damage levels achieved

Tables A.1a, b and c (see Appendix) show the measured properties of the flours milled from the 1995, 1996 and 1998 harvest wheats respectively. For the 1995 and 1996 samples, despite the differences in milling protocols used to produce a range of starch damage levels, only a limited range in measured values was achieved for each wheat. The mean increase in starch damage between flours milled under the high and low starch damage protocols was only 3.1 Farrand units and it is thought unlikely that this will have been sufficient to cause significant effects on the baking performance or other flour properties. The primary source of variation was between hard wheat varieties which yielded starch damage levels typically greater than 30 units, and soft varieties which yielded one value of 26 and a maximum starch damage level of 16 Farrand units for all other samples. In the light of these results, the milling procedure was modified for the 1998 harvest samples in an attempt to produce greater differences in starch damage levels. It can be seen from Table A.1c that this was more successful, and that increases in starch damage between the low and high protocols were measured in all but one case (for which they were equal). The mean increase in measured starch damage between flours milled under these protocols was 11.5 Farrand units, providing better potential for observing effects of starch damage on other flour quality attributes or on baking performance.

3.2.2 Optimisation of starch damage levels for end-uses

There has been a trend towards increased starch damage levels in U.K. breadmaking flours over recent years. However, it is known that if starch damage levels become excessive, this has an adverse effect on breadmaking performance (e.g. Chamberlain *et al.*, 1966). A possible mechanism for this is that damaged starch granules swell more than undamaged granules when hydrated during dough mixing. Therefore, at higher levels of starch damage, the surface area of starch granules in a dough is greater. The granules are suspended in a gluten matrix. As the surface area of the granules increases, the gluten between them becomes more thinly spread and the dough is weakened. As subsequent sections will show, reduced dough strength tends to be associated with poorer breadmaking performance. Farrand (1969) suggested a criterion for the optimum starch damage level as a function of flour protein content, based on a constant hydrated starch surface area per unit starch mass:

$$\text{Surface area} = \text{Undamaged starch} + K_1 \times \text{Damaged starch} = K_2 \qquad (5)$$

where K_1 and K_2 are the specific surface areas of damaged starch and total starch respectively, measured relative to a unit surface area for undamaged starch. Farrand determined K_1 and K_2, based on measurements for flours that he assessed as having optimal starch damage. Expanding equation (5) in terms of the flour protein content, P, and the starch damage level, D, he derived the criterion:

$$D = \frac{100P - 410}{39 - 0.48P} \approx \frac{P^2}{K_3} \approx \frac{P^2}{6} \tag{6}$$

A better, although less memorable approximation can be obtained as a first order expansion in terms of $\delta P = P - 10$:

$$D = \frac{100\delta P + 590}{34.2 - 0.48\delta P} = \frac{2.924\delta P + 17.25}{1 - 0.014\delta P} \approx (2.924\delta P + 17.25)(1 + 0.014\delta P)$$

$$= 17.25 + 3.166\ \delta P + 0.041\ \delta P^2 \approx 17.3 + 3.2\ \delta P = 3.2\ P - 14.7 \tag{7}$$

It would appear that Farrand considered that his criterion of a constant value for the specific starch granule surface area implied a constant thickness of protein coating the starch. However, to achieve this, a flour with high protein content actually requires a greater starch surface area than one with low protein content, not a constant value. A better approximation to Farrand's implied criterion of constant protein thickness would be a constant ratio of starch surface area to protein mass. Using Farrand's data, this would correspond to $K_1=10$, $K_2=1820$ (defined as in equation 5), and an optimum starch damage condition of

$$D = \frac{1920P - 8100}{729 - 9P} \tag{8}$$

The expressions given in equations (6) and (7) remain good approximations to this. However, the value of $K_1=10$ as a ratio of the surface area of damaged and undamaged starch granules is unrealistic under the conditions where damaged starch is defined as absorbing its own mass in water. The original criterion of constant surface area gave a more realistic value of $K_1=1.48$. Thus, although not in fact corresponding to constant protein thickness, this criterion is in closer agreement with Farrand's observations. This implies that under conditions of optimum starch damage, the protein is in fact more thickly spread over starch granules as the protein content increases. An understanding of why this is the case would be a valuable approach to understanding hydration processes in doughs and to optimising starch damage for particular grists and end-uses.

The approach outlined above provides an indication of the functional relationship between the protein content of flour and the optimum starch damage level, based on the necessity to maintain a sufficient thickness of gluten to provide dough strength. However, the rheological properties of the gluten are also an important determining factor, since a flour with stronger protein may be able to maintain adequate dough strength with a thinner coating of the starch granules, and will be able to sustain higher starch damage levels. Thus, the optimal surface area value, K_2, should be an increasing function of protein strength. The value K_3 in equation (6) decreases with increasing K_2. Since the functional protein in modern wheats is better able to support damaged starch than the varieties studied by Farrand in 1969, a value of K_3 lower than Farrand's suggested value of 6 may therefore be justified. Butler (1997) suggests that a constant of 5.2 is currently more appropriate, giving a criterion of $D = P^2/5.2$. However, it should be remembered that a universal criterion for optimal starch damage levels cannot be based on protein content alone, but should also include a measurement of protein rheology. The above discussion suggests a general approach by which this might be achieved. However, as indicated in section 3.2.1, insufficiently high starch damage levels were created to produce significant effects on product quality, and it was therefore not possible to develop such a criterion explicitly.

3.3 Water absorption

3.3.1 Farinograph water absorption

Full Farinograph tests were conducted for all of the flour samples. The results are shown in Tables A.2a, b and c for the 1995, 1996 and 1998 harvest samples respectively. One factor of interest is the water absorption, which is influenced by several of the variables measured, including protein content, moisture, starch damage and pentosan content (Tables A.1a, b, c). In particular, water absorption increases with the concentration of protein and of damaged starch, since both of these components have greater water absorbing capacity than native starch. Moisture content has a negative correlation with water absorption, since this represents water already present and reduces capacity for absorption of further water. These factors were included in an equation developed by Farrand (1969). Farrand modelled flour as being composed of moisture, protein and starch in percentages by mass of M, P and S respectively. The total content of remaining unspecified components (including free fatty material, ash, sugars, pentosans, gums etc) was represented as U. Farrand considered the summed contribution of each of these components to the total water absorption of the flour. Protein was assumed to have an absorption capacity of 2.0 (=mass of water absorbed / dry mass of protein), relative to a defined level of 1.0 for damaged starch. Based on measurements for a reference flour, the total contribution of other components was calculated as 0.60. This resulted in an equation,

$$A = 1.4P + 0.38D - [1.6M + 0.004D(M + P)] + 57.3 \qquad (9)$$

where A is the Farinograph water absorption (600 line, 300g bowl) and D is the Farrand starch damage. For flours differing from the reference flour (M=14.5, P=12.0, D=24), Farrand found deviations from this equation, and added a correction factor based on the deviation of the protein content from 12.0%, and of the starch damage from a level at which the starch surface area was constant (see section 3.2.2), giving:

$$A = 1.4P + 0.38D - [1.6M + 0.004D(M + P)] + \frac{12}{P}\left(\frac{6D}{P^2} - 1\right) + 57.3 \qquad (10)$$

This equation is now widely used by the milling industry, often in an inverted form to calculate starch damage as a function of moisture, protein and water absorption measurements. Figure 5 shows the agreement between the water absorption measured by the Farinograph and that predicted by equations (9) and (10), based on the measured values of protein, moisture and starch damage for the 1995 and 1996 harvest samples. It can be seen that for these data, the water absorption is better predicted by equation (9).

Farrand assumed values for the water absorbing capacities of some of the flour components. To assess the validity of these assumptions, let the absorption capacities of the constituents be represented by the variables shown in Table 6.

Figure 5 - Comparison of Farinograph water absorption measurements with values predicted by the Farrand equation and a modification thereof.

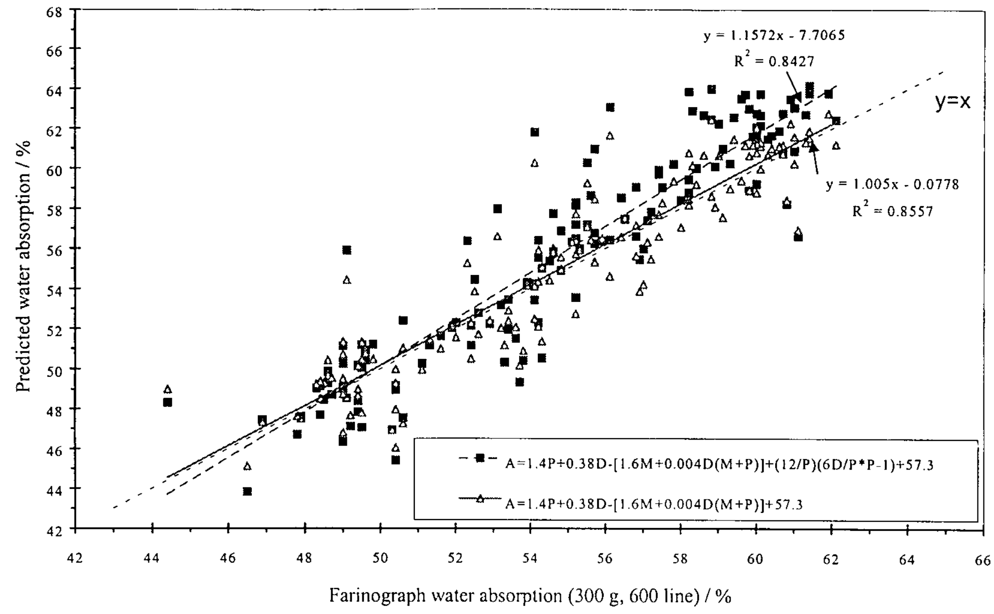


Table 6 – Constants used for relative water absorption capacities of flour components.

Component	Absorption factor	Factor assumed by Farrand, 1969
Protein	α	2.0 (stated)
Damaged starch	β	1.0 (defined)
Undamaged starch and free water associated with unspecified components	γ	k = 0.6 (calculated, based on values for a single reference flour)

Following Farrand's methodology, but retaining the absorption factors as variables, the following equation is derived, equivalent to equation (9):

$$A + M = \alpha P + \beta D\left(1 - \frac{U + M + P}{100}\right) + \gamma\left(1 - \frac{U + M + P}{100}\right)(100 - D) \qquad (11)$$

This has the form:

$$A + M = \alpha F + \beta G + \gamma H \qquad (12)$$

Therefore, using the values of A, M, P and D measured in this study, and assuming a value of U=4.5% as used by Farrand, multiple linear regression can be performed to obtain a best fit to this equation, yielding coefficients of

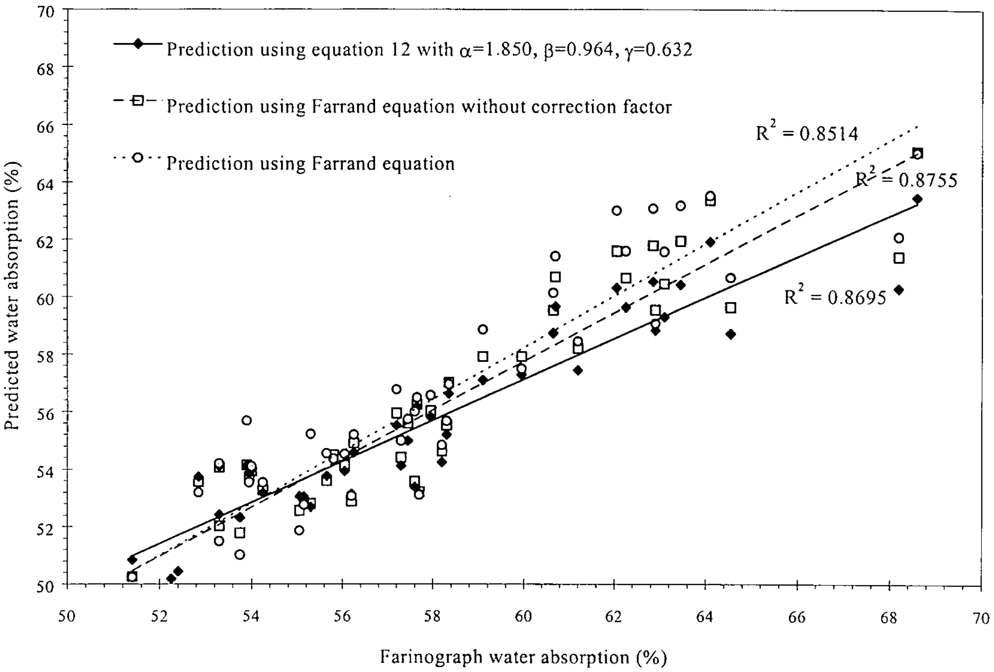
$$\alpha = 1.850, \qquad \beta = 0.964, \qquad \gamma = 0.632$$

which approximate well to the values used by Farrand of

$$\alpha = 2.0, \qquad \beta = 1.0, \qquad \gamma = 0.60.$$

The regression provided a good correlation, with $R^2 = 0.856$ and a standard deviation of residuals of 1.64, compared with a standard deviation of 4.26 for the measured water absorption values.

Figure 6 – Performance of water absorption predictions for the 1998 samples.



The prediction was tested using the measurements made for the independent set of flour samples milled from the 1998 harvest wheats. Figure 6 shows predicted water absorption values against the measured values, using several different prediction methods. These include the Farrand equation with and without the correction factor of $(12/P)(6D/P^2-1)$, as also used in Figure 5. Additionally, a prediction is shown using equation 12, but with the newly calculated values of $\alpha=1.850$, $\beta=0.964$ and $\gamma=0.632$, calculated by regression to the 1995 and 1996 data. As for the previous samples, the Farrand equation gave a stronger correlation with measured water absorption values when the correction factor of $(12/P)(6D/P^2-1)$ was omitted. However, the gradients of the comparisons between predicted and measured values were lower for the 1998 samples and, unlike the situation for 1995 and 1996, the full Farrand equation therefore gave the better fit to the measured values. The newly derived constants give a lower sensitivity to protein and damaged starch content than those used by Farrand and these therefore also gave a poorer fit to the 1998 results than the Farrand equation. Multiple linear regression of equation 12 to the 1998 data yields coefficients of

$$\alpha = 2.131, \qquad \beta = 1.014, \qquad \gamma = 0.607$$

suggesting that the water absorption capacity of the protein and damaged starch were higher for the 1998 than for the 1995 and 1996 samples.

An alternative approach to predicting water absorption is to perform multiple linear regression of the water absorption directly against the measured values M, P and D. By this approach, Farrand obtained the expression:

$$A = 68.26 + 0.878P + 0.334D - 1.97M \qquad (13)$$

Other authors have obtained variations on this as summarised by Stevens (1987).

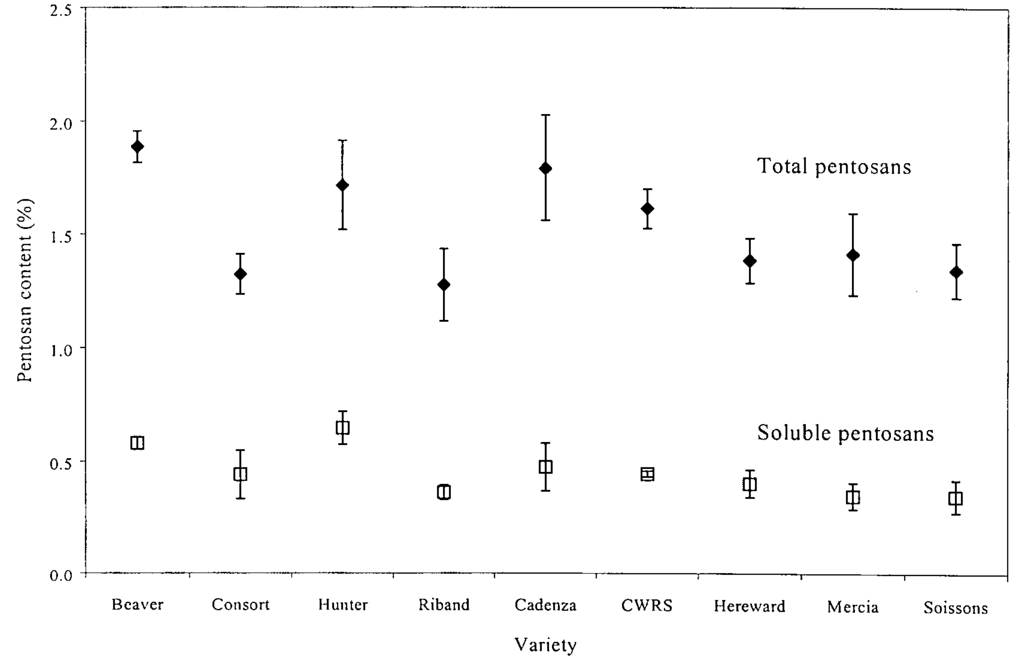
For measurements of 140 flours from this study for 1995 and 1996, multiple linear regression against P, M and D gave the equation

$$A = 1.148\,P + 0.242\,D - 1.725\,M + 62.214 \qquad (14)$$

with a regression coefficient of R^2=0.857 and a standard deviation of residuals 1.65. For comparison, the standard deviation of the measured water absorptions was 4.31.

Farrand included a constant factor to account for the combined water absorbing capacity of undamaged starch and of other components such as non-starch polysaccharides, minerals etc. One of the more highly absorbent species within this category is likely to be the pentosans. Previous attempts to include measurements of pentosans in multiple regression fits to the water absorption are summarised by Stevens (1987). In general, total pentosan content was not found to be significant, but soluble pentosan content was.

Figure 7 – Mean pentosan measurements classified by variety for the 1995 and 1996 samples. Error bars represent standard deviations between samples.



Measurements of total and soluble pentosan content were made for each of the 1995 and 1996 flours. Results are given in Tables A.1a and b, and Figure 7 shows the range of values obtained for each wheat variety. Inclusion of total pentosan content, TP in a multiple linear regression gave the equation

$$A = 1.160\,P + 0.237\,D - 1.589\,M + 1.428\,TP + 58.197 \qquad (15)$$

with regression coefficient R^2=0.863 and standard deviation of residuals 1.62. Additional inclusion of the soluble pentosan results (SP) gave:

$$A = 1.171\,P + 0.228\,D - 1.596\,M + 1.902\,TP - 1.799\,SP + 58.489 \qquad (16)$$

with regression coefficient R^2=0.865 and standard deviation of residuals 1.61. Neither the inclusion of total pentosans or the additional inclusion of soluble pentosans yielded much improvement over the fit to equation (14).

The approach detailed in equations (9) to (12) has benefits over the simple multiple regression approach in attempting to represent more usefully the physical basis of water absorption in flours. Extending this approach, it is possible to consider a more detailed breakdown of flour composition such that the unspecified components previously taken as being in proportion U (assumed as 4.5%) are now subdivided into total pentosans, TP and unspecified components U'. In the measured data for the samples from the 1995 harvest, TP has the mean value 1.526, so let $U'=U-1.5 = 3.0$. Then,

$$A+M=\alpha P+\beta D\left(1-\frac{U'+TP+M+P}{100}\right)+\gamma\left(1-\frac{U'+TP+M+P}{100}\right)(100-D)+\delta TP \tag{17}$$

Extending from equation (12), this has the form

$$A+M=\alpha\, F+\beta\, G+\gamma\, H+\delta\, TP \tag{18}$$

Multiple linear regression was performed to obtain a best fit to this equation for the 1995/1996 data, yielding coefficients of

$$\alpha=1.838, \qquad \beta=0.918, \qquad \gamma=0.592, \qquad \delta=2.057$$

with a regression coefficient $R^2=0.861$ and a standard deviation of residuals 1.61. The values of α, β, and γ remain similar to those derived from equation (12), representing the water absorption capacities by mass of protein, damaged starch, and undamaged starch+free water respectively. However, this fit also provides an estimate of the total water absorption capacity, δ, of pentosans, being 2.1 times their own weight in water – a greater absorbancy than the other flour components.

The same approach has been applied to the separate consideration of soluble and insoluble pentosans. By subdividing the quantity of total pentosans, TP into soluble and insoluble pentosans (SP and IP respectively), equation (17) can be extended to include these components independently:

$$A+M=\alpha P+\beta D\left(1-\frac{U'+TP+M+P}{100}\right)+\gamma\left(1-\frac{U'+TP+M+P}{100}\right)(100-D)+\lambda\, SP+\mu\, IP \tag{19}$$

Multiple linear regression yielded coefficients of

$$\alpha=1.848, \qquad \beta=0.907, \qquad \gamma=0.595, \qquad \lambda=0.675, \qquad \mu=2.557$$

with a regression coefficient $R^2=0.863$ and a standard deviation of residuals 1.61. It was thus apparent that the explicit inclusion of pentosan content, either total or subdivided into soluble and insoluble fractions, provided only slight improvement in the above model for Farinograph water absorption.

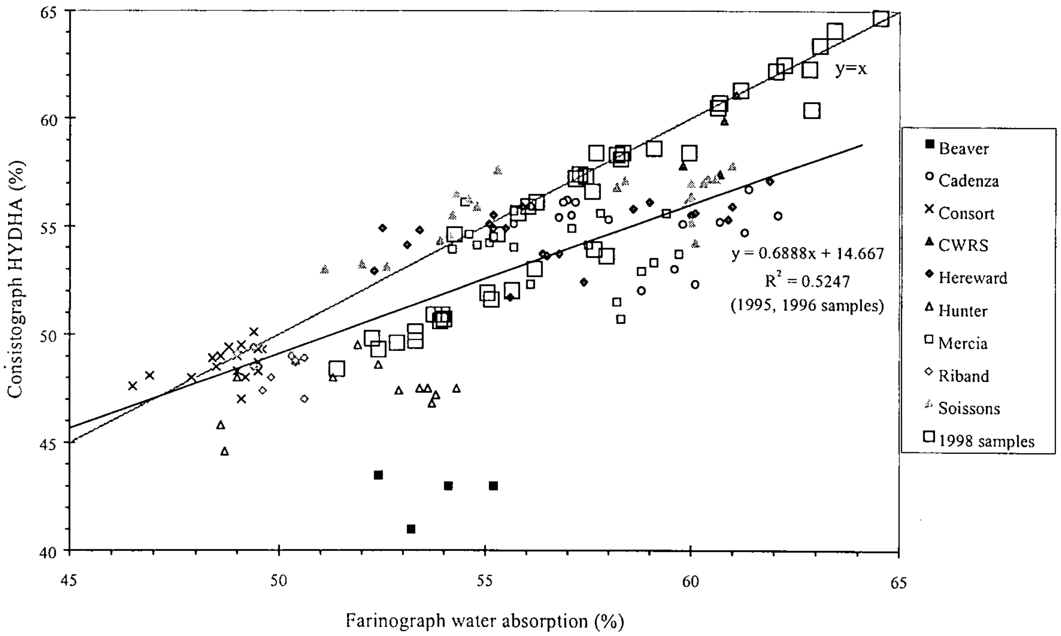
In conclusion, it is possible to model Farinograph water absorption as a function of the main variables which influence this, including moisture content, protein content and starch damage. A simple approach is to use multiple regression against these variables, but a model with a better physical basis is to consider the water absorption as a sum of the independent contributions of each of the flour constituents. This is the approach adopted by Farrand (1969). By considering each component to have a constant water absorption capacity, a good fit was obtained to the datasets for the 1995 and 1996 flours ($R^2 = 0.856$) and for the 1998 flours ($R^2=0.852$). However, the method yielded higher water absorption capacities of protein and damaged starch for the 1998 flours than for the 1995 and 1996 flours. The values assumed by Farrand are intermediate between these and could be used as a compromise. However, for improved modelling of water absorption, an additional factor would be necessary to account for this difference. Farrand himself added an additional term of $(12/P)(6D/P^2-1)$ to correct for poorer agreement of the model when the starch damage was different from a putative optimum level of $P^2/6$. However, in this study, inclusion of this term reduced the quality of the fit, and it was better omitted. One additional factor that may contribute to differences in water absorption is the pentosan content of flours. Previous studies have included this in empirical models, but in this study it has also been incorporated directly as an extension of Farrand's approach for the 1995 and 1996 samples. Only a small improvement in water absorption prediction was obtained either by inclusion of total pentosan content in the model, or by separate inclusion of soluble and insoluble pentosan fractions. However, it remains a possibility that elevated pentosan content could have been responsible for the apparent increase in water absorption capacities for the 1998 samples, although no pentosan measurements were made for these samples. Notwithstanding this possibility, further factors may remain to be identified to explain the differing fits of the model to the 1995/96 and 1998 results.

3.3.2 Consistograph water absorption

In addition to Farinograph measurements, flour samples were tested using a Chopin Consistograph. This also determines a measure of water absorption, referred to as the hydration rate, HYDHA, and quoted as a percentage. As for the Farinograph, doughs are tested iteratively at different levels of water addition until a suitable consistency is achieved, based on a target value for the peak of the mixing curve. At each stage, the instrument suggested the water addition level to be used for the next trial. However, this did not always result in rapid convergence to the required water addition, and many replicates were often required. In one case (1998, Hereward No. 2, low starch damage), eight tests were required to determine the water absorption.

Results for the Consistograph measurements are given in Tables A.2a, b and c. Although this measurement of water absorption is not intended to be identical to that determined by the Farinograph, it was of interest to study the relationship of this relatively new measurement to the more widely established Farinograph measurement. Figure 8 shows the relationship between Consistograph and Farinograph water absorption values. The Consistograph provided a clear discrimination of the hard breadmaking varieties, which had a high water absorption, from the soft biscuit and feed varieties which had consistently lower water absorptions. Although this is to be expected due to the typically lower protein content and starch damage of the soft varieties, the separation was more distinct than for Farinograph water absorption, in which some overlap was seen between these classes of wheat. Within each of these populations, there was a particularly strong relationship between the two methods for the 1998 samples. However, for the 1995 and 1996 samples, the Farinograph showed a greater discrimination of samples within each population than the Consistograph. The strongest outliers from a straight line relationship between the two methods are the samples of Beaver. It is of interest to note that this variety contains the 1B/1R translocation. This is often associated with stickiness of doughs and sticky doughs are known to be capable of yielding greater Farinograph water absorption values than would be considered appropriate. It is possible that the different mode of operation of the Consistograph may make it less susceptible to such an effect, and that this could be a possible explanation for the presence of Beaver as an outlier. The only other variety in the study which contains the 1B/1R translocation is Hunter, which is also a slight outlier among the group 3 and group 4 wheats for 1995 in Figure 8. Removal of the Beaver and Hunter samples from the regression in Figure 8 would improve the correlation between the two methods from R^2=0.5247 to 0.6754 for 1995 and 1996. Further testing would be necessary to establish whether dough stickiness is indeed the explanation for the observed outliers, and whether the Consistograph is more tolerant of such doughs than the Farinograph.

Figure 8 - Water absorption measured by Consistograph and by Farinograph



Following the approach used by Farrand to predict Farinograph water absorption, and described earlier, an attempt has been made to develop a prediction of Consistograph water absorption in the same way. Using equation (11) as before, but taking A to represent the water absorption measured by the Consistograph, multiple linear regression was performed for 122 samples to obtain a best fit to the equation. In this case, this yielded coefficients of:

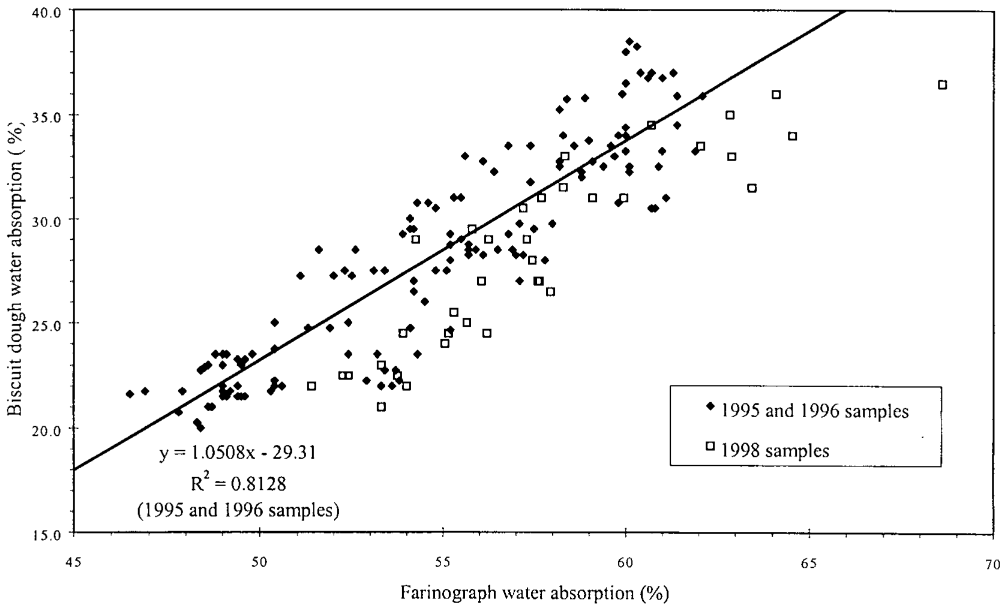
$$\alpha = 2.475, \qquad \beta = 0.729, \qquad \gamma = 0.553$$

for the water absorption capacities of protein, damaged starch and other components respectively. For this regression, the correlation was poorer than for the Farinograph, giving R^2=0.59 and a standard deviation of residuals of 2.83 (standard deviation of Consistograph water absorption values used = 4.35). This suggests that although Farinograph water absorption can be reasonably well modelled as a sum of the independent contributions of several flour components, each with a constant water absorption capacity, the water absorption measured by the Consistograph is dependent on additional factors.

3.3.3 Biscuit dough extrusion test

To measure the water absorption for biscuitmaking purposes, an extrusion test was used in which biscuit doughs were prepared with different levels of water addition until a dough was achieved with a consistency that allowed it to be extruded through a hole at a standard rate. Although the requirements for biscuit and bread doughs are very different, as are the recipes and dough mixing procedures, the flour attributes contributing to water absorption can be expected to be similar. Figure 9 confirms this by showing that there was a good correlation of R^2=0.81 between water absorption measured for biscuitmaking (by extrusion) and for breadmaking (by Farinograph). By comparison, the correlation between biscuit dough extrusion values and Consistograph water absorption was only 0.59. Although the Farinograph and Consistograph water absorptions were higher, on average, for the 1998 samples than for the other flours, no increase in the biscuit dough water absorption was seen.

Figure 9 - Comparison of water absorption measured by extrusion for a biscuit dough, and by Farinograph



3.4 *Further Farinograph measurements*

In addition to water absorption, Farinograph measurements of development time, stability and degree of softening are listed in Tables A.2a, b and c. The Consistograph also has the capability to provide measurements of a similar type, but these values were not studied in this project.

The biscuitmaking varieties Beaver, Riband, Claire and several of the Consort samples gave the lowest stability and the highest degree of softening. However, some of the other Consort samples and the feed variety Hunter gave values not dissimilar to some of the breadmaking samples tested. Differences in Farinograph measurements were often seen between the several examples of each variety. For example, flours milled from Hereward No. 1, 1995 had lower stability than other Hereward samples, Mercia No. 3, 1995 had a much lower degree of softening than other Mercia samples and three of the Soissons wheats from 1995 gave stability >10 minutes and a degree of softening < 60B.U. while the other Soissons samples never did so. However, these differences did not appear to be related to the variations in protein content between multiple examples of the same variety, and are not reflected in other measurements made for these flours. These inconclusive results are indicative of the limitations of the Farinograph test as a means of predicting suitability of flours for particular end uses.

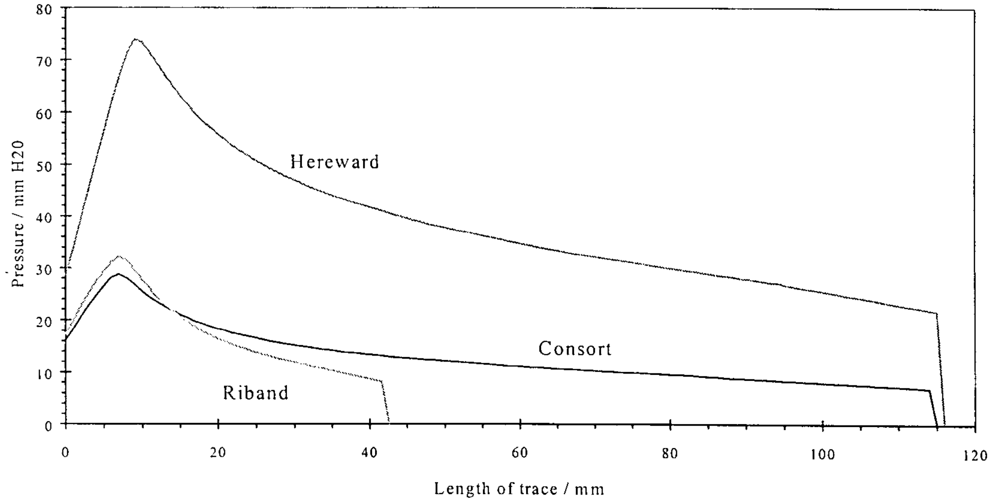
3.5 *Biaxial extension of dough sheets*

In breadmaking, gas bubbles are introduced into dough during mixing and subsequently expand during proof and baking. As the bubbles expand, they distort one another, developing polyhedral facets separated by thin dough sheets which are stretched in biaxial extension. Rupture of these sheets causes coalescence of bubbles, ultimately limiting the loaf volume and affecting the fineness of the crumb cell structure. The point at which rupture occurs is affected by the flour properties and several tests have therefore been devised to test the rheological properties of doughs in biaxial extension. Most notably, these include the Chopin Alveograph, which inflates a single bubble from a sheet of dough. Recently, the Stable Micro Systems D/R dough inflation system has been marketed, which uses a similar geometry. An alternative approach used for biaxial testing is to compress a lubricated sheet of dough normal to its surface. This method has been used by Van Vliet *et al.* (1992), for example. A further method, described by Morgenstern *et al.* (1996), involves the deformation of a flat sheet of dough stretched across a circular opening by a cylindrical probe pressed normally against the sheet. Such methods can be applied to doughs of a wide range of specifications, prepared in various different ways. For wheat and flour testing purposes, a standard protocol (ICC Standard No. 121) is available for use with the Alveograph. However, within this project, tests have also been conducted at adapted hydration using a new protocol in which the appropriate hydration level is determined using the recently developed Consistograph, and have all been conducted using flours milled with a Buhler mill.

3.5.1 The Chopin Alveograph

Example Alveograph traces (known as alveograms) are shown in Figure 10, obtained using an Alveolink computer.

Figure 10 - Alveograph traces measured using the Alveolink computer



The parameters normally measured for alveograms are as follows:

P : The maximum pressure achieved during the test, which is related to the resistance of the dough to stretching. Strong or tough doughs produced under the standard mixing conditions employed in the Alveograph test will produce high *P* values.

L : The length of the alveogram up to the point of rupture, which is related to the extensibility of the dough.

W : The area under the curve, equivalent to the energy required to inflate the bubble to bursting point, which provides a measure of protein strength.

G : The square root of the volume of air required to inflate the bubble until it bursts, equivalent to $2.2 \sqrt{L}$.

For tests under adapted hydration conditions, equivalent parameters are measured, but are instead denoted as follows:

T : Equivalent to *P*, the maximum pressure.
A : Equivalent to *L*, the length of the alveogram to the point of rupture.
Fb : Equivalent to *W*, the energy to rupture.
Ex : Equivalent to *G*, the square root of the volume at rupture.

The Chopin Alveograph was originally designed for use with soft wheat flours but has been used with stronger breadmaking flours over recent years. It is not commonly used by the UK grain trade, but is generally part of the export specification used as a means of assessing wheat quality for a particular end-use (i.e. bread or biscuits). The Alveograph is used to classify wheat varieties into those suitable for breadmaking, those suitable for biscuitmaking, and those unsuitable for either bread or biscuitmaking.

The Alveograph test is conventionally performed with a constant level of water addition (corrected for the original flour moisture). A consequence of testing flours at constant hydration is that the consistency of the dough tested does not relate directly to the consistency of a dough that would be prepared for breadmaking, in which the water addition would be adjusted according to the water absorption of the flour. This may therefore reduce the ability of the measured parameters to predict the performance of the flour in breadmaking. It was thought that the introduction of a test under adapted hydration conditions might provide a better measurement of the properties of flours under conditions relevant to the way in which they will be used. Tests were therefore also conducted for doughs at adapted hydration levels. The water addition used for test baking was determined according to Farinograph measurements of water absorption. For the adapted hydration Alveograph tests, a Chopin Consistograph was used to determine the water absorption, since this instrument has been designed specifically for use in conjunction with the Alveograph. The relationship between water absorption values determined by the Consistograph and the Farinograph was shown earlier in Figure 8.

Measurements of the flour samples have been made under constant and adapted hydration conditions, and are shown in Tables A.3a, b and c. Figure 11 shows *P* plotted against *L* for the data from the 1995 and 1996 samples. Figure 12 shows an equivalent plot for *T* and *A* measured under adapted hydration conditions.

Figure 11 - Maximum pressure and length of alveograms (Buhler milled flours)

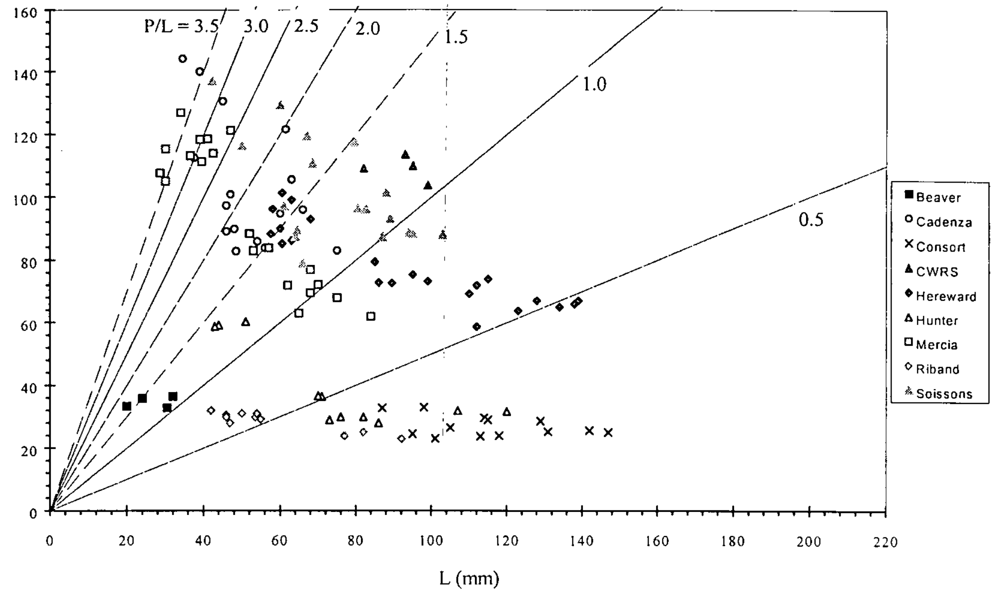
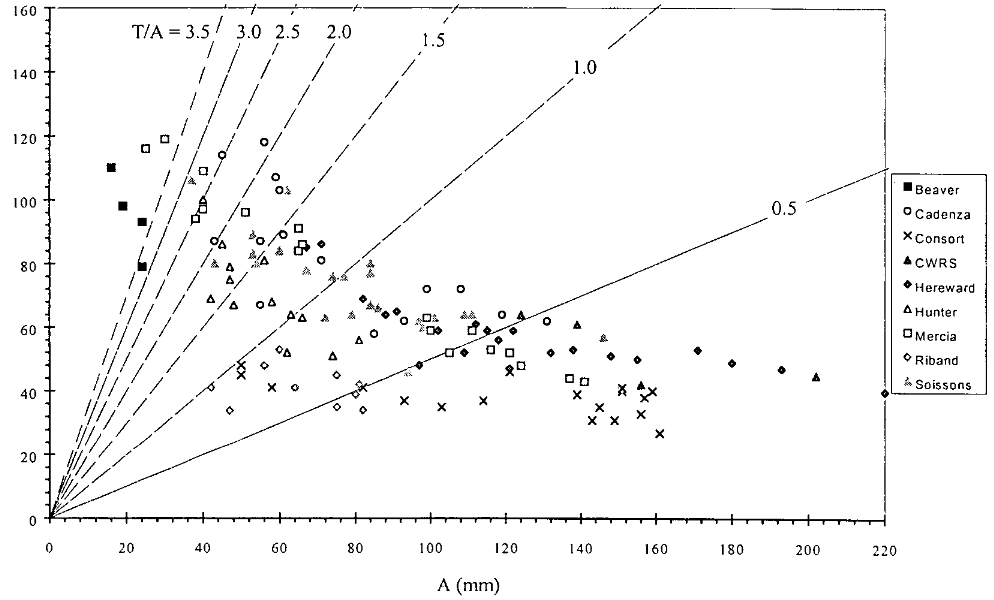


Figure 12 - Maximum pressure and length of alveograms under adapted hydration conditions (Buhler milled flours)



The ratio *P*/*L*, known as the "configuration ratio" may be calculated from Alveograph values and provides a measure of the balance of dough resistance to extensibility. Lines indicating particular values of this ratio (or *T*/*A*) are shown in Figures 11 and 12. Changes in either *P* or *L* can affect this ratio and wheat importers consider this balance very important to provide the quality characteristics required for bread or biscuit manufacture. It should be noted, however, that because the flours used in this study were produced on a Buhler mill rather than the Chopin mill normally used for Alveograph testing, they have higher starch damage levels, yielding *P*/*L* ratios greater than the values normally associated with specifications for Alveograph results.

A notable distinction was seen in the *P* values between breadmaking varieties and biscuit and feed varieties. Varieties in **nabim** groups 1 and 2, and CWRS had a minimum *P* value of 58.7mm, while varieties in **nabim** groups 3 and 4 had a maximum *P* of 60.3mm and only two samples with *P*>58.7mm. The low values of *P* obtained for biscuit and feed varieties are indicative of their weak gluten, which develops a relatively low stress under biaxial strain. However, the discrimination of these classes is poorer for the parameter *T*, obtained under conditions of adapted hydration. This suggests that the differences in *P* are partially attributable to the fact that under constant hydration conditions, the group 1 and 2 flours are under-hydrated and therefore stiffer, and that the group 3 and 4 flours are over-hydrated and therefore more compliant. As shown previously in section 3.3.1, differences in water absorption capacity are primarily attributable to protein content and starch damage, rather than differences in protein strength. The observed effects of hydration level are therefore consistent with the observation (Alveograph Handbook) that for constant water addition, increases in damaged starch content cause an increase in values of *P* (and also a reduction in *L* and *G*). This is also the reason why the *P/L* values obtained for Buhler milled flours are greater than those normally associated with specifications for Alveograph results, based on Chopin milling.

Figure 13 - Values of Alveograph maximum pressure for tests under adapted hydration (*T*), and constant hydration (*P*).

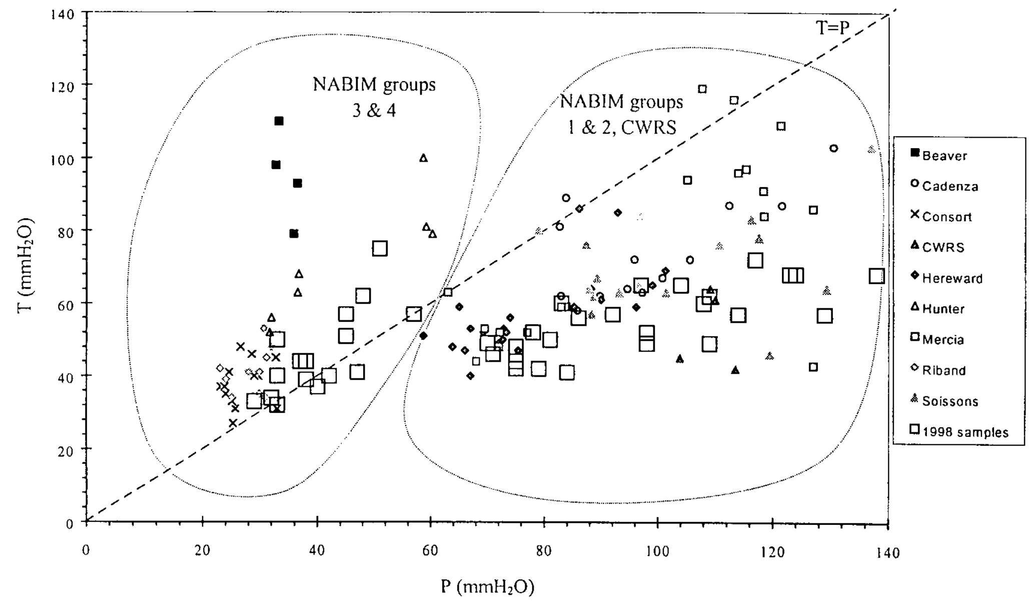


Figure 13 shows a more direct comparison of the *T* values obtained from the Alveograph under adapted hydration conditions, and the corresponding *P* values for the same flours at constant hydration. The better segregation of groups 1 and 2 from groups 3 and 4 by *P* than by *T* is clear. It can also be seen clearly that the (high water absorption) group 1 and 2 samples generally lie below the line *T*=*P* and thus have *T*<*P*; the group 3 and 4 samples instead generally lie above this line, with *T*>*P*.

Several outliers from the main groups of points are apparent. In particular, the samples of Beaver gave considerably higher *T* values than *P* values. It is possible that this is due to an underestimation of their water absorption by the Consistograph, which would be consistent with the fact that these water absorption values were outliers from the trend against Farinograph water absorption given in Figure 8 (and would represent an alternative interpretation of these outliers to that offered in section 3.3.2). If the water absorption has indeed been underestimated, this will have resulted in under-hydration of the samples under adapted hydration and an abnormally high value of *T*.

Figure 14 shows the comparison between *A* and *L* values for the same doughs. For these parameters, there is a stronger overall agreement between the results measured under the differing hydration conditions for all three harvest years and for samples of high and low water absorption.

Figure 14 - Values of Alveograph drum distance to bubble failure for tests under adapted hydration (*A*), and constant hydration (*L*).

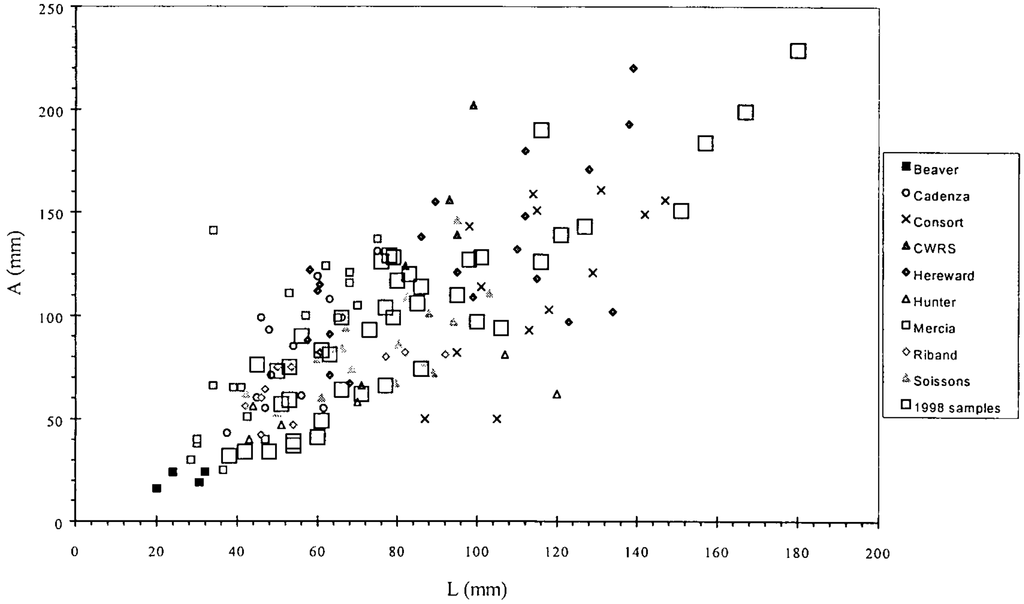
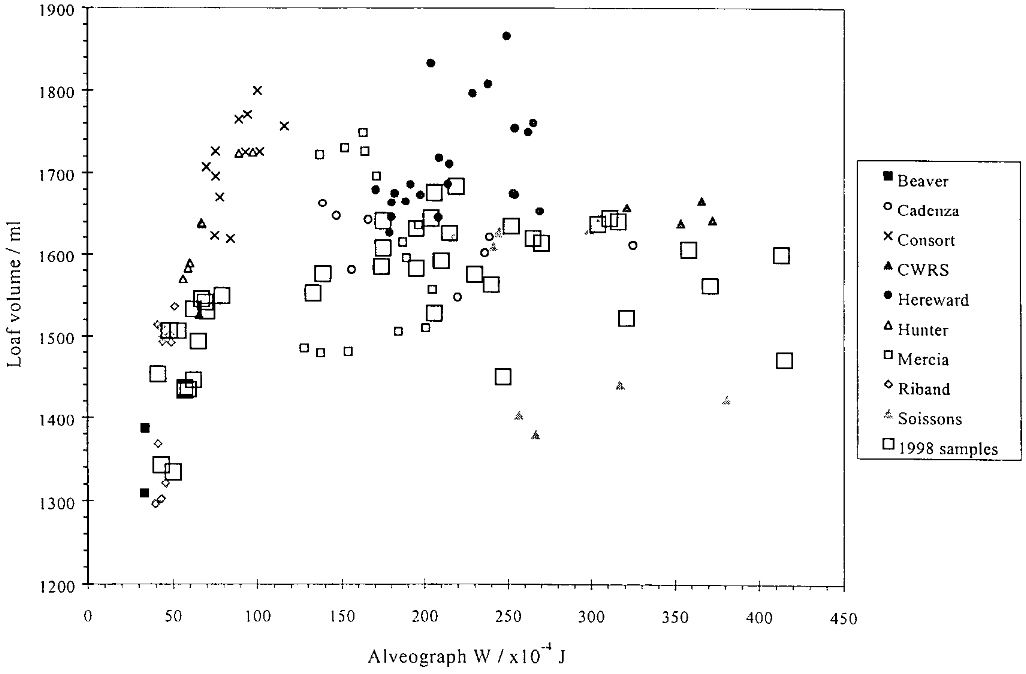


Figure 15 – Mean loaf volume against Alveograph *W* value



Among the standard measurements obtained from alveograms, the work input, *W* is also calculated and is proportional to the area under the curve up to the point of rupture. Previous studies have shown a positive correlation between *W* and loaf volume. For example, Bloksma (1957b) demonstrated a correlation of r=0.48 for a set of 213 samples including 17 different wheat varieties. Figure 15 shows the corresponding relationship observed in this study. Some correlation can be seen, with the Riband and Beaver samples showing low values of *W* and loaf volume. However, within the breadmaking varieties, little correlation is seen. In particular, the flours from the 1995 Soissons No. 2 wheat yielded low loaf volumes despite high values of *W* comparable with those for CWRS samples with higher loaf volumes. Despite this, *W* provided a good discrimination of the samples by variety: Group 3 and 4 varieties gave results of $W<120\times10^{-4}$J and all samples of group 1 and 2 varieties gave higher values. Further separation of varieties also occurred within these groups, and was consistent between the different harvest years.

Figure 16 – Mean loaf volume against Alveograph *Fb* value

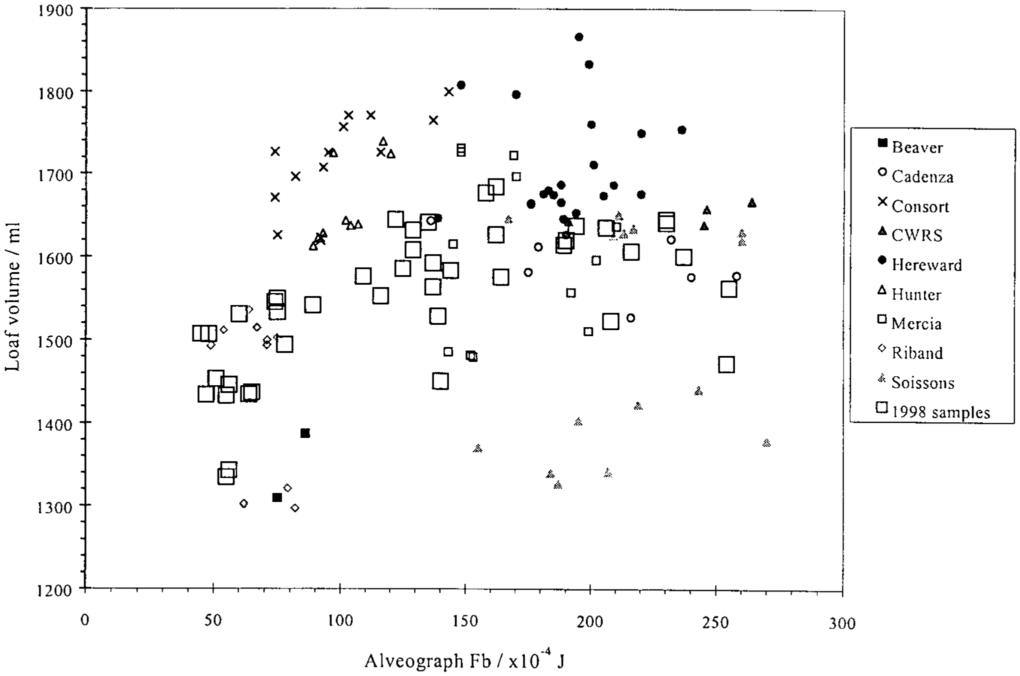


Figure 16 shows the relationship of loaf volume to *Fb*, the equivalent value to *W*, under adapted hydration conditions. Similar rankings of samples by variety exist, but are weaker, and the correlation with loaf volume is poor. One of the main effects of the adapted hydration conditions has been a reduction in the range of *Fb* values compared with those for *W*. In particular, there has been an increase of typically about 5 mJ (50 units) for samples of Beaver, Hunter and Riband, which gave the lowest *W* values, and a decrease of about 10 mJ (100 units) in the highest values, which were obtained for samples of CWRS and Soissons. As for the other Alveograph measurements, this may be because the former samples were over-hydrated under the standard test conditions, which could have reduced the energy required to inflate a bubble, whereas the latter samples may have been under-hydrated and therefore required greater energy. The adapted hydration conditions had been determined by hydrating the doughs to give more consistent properties during mixing in the Consistograph. This may therefore also have resulted in more consistent rheological properties as measured by rupture energy under biaxial tension in the Alveograph. This gives further support for the suggestion that some of the differences in dough rheology measured by the Alveograph under constant hydration conditions are caused by inappropriate hydration, and reflect differences in flour water absorption. However, it can be seen from Figure 16 that even when the hydration is adapted varietal differences persist, with the highest *Fb* values being measured for varieties normally regarded as strong.

Figure 17 – Loaf volume against Alveograph *L*.

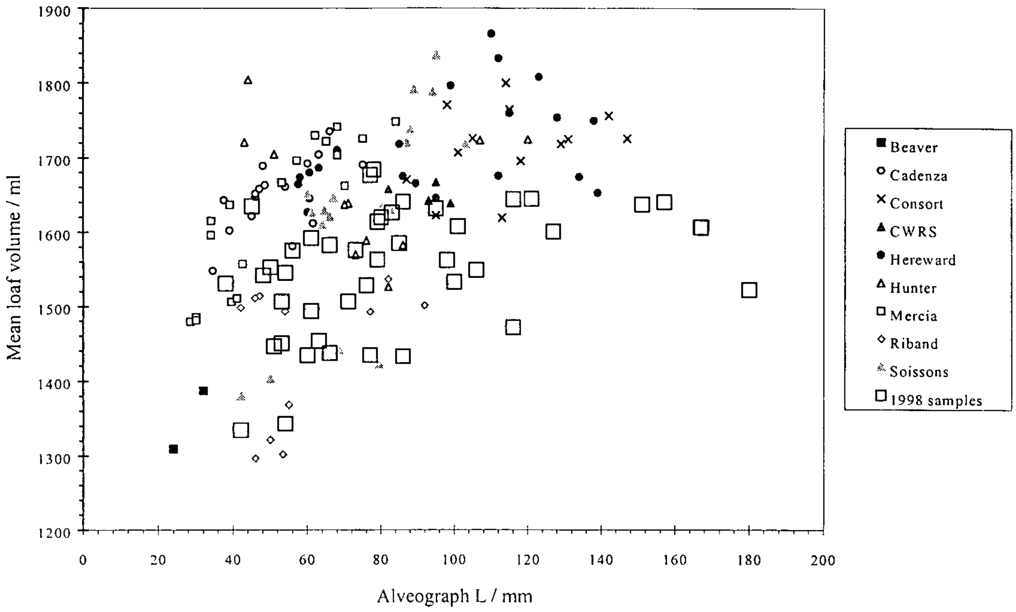
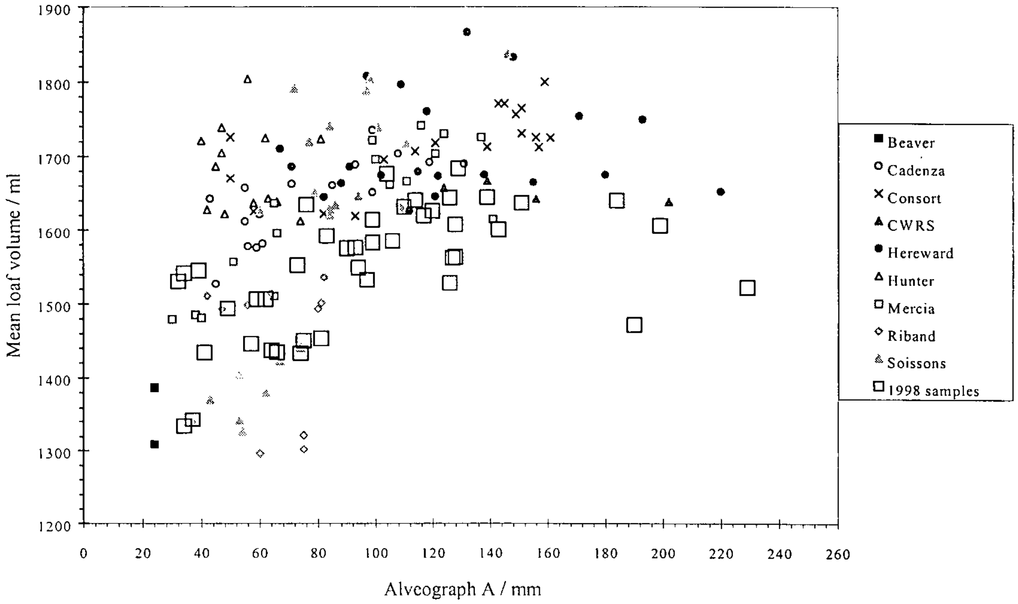


Figure 18 – Loaf volume against Alveograph *A*.



Particular exceptions to a positive correlation between loaf volume and *W* or *Fb* are several samples of Soissons that produced small loaf volumes, but had large energies to rupture. Despite the high *W* and *Fb* values of these samples, they ruptured at relatively low *L* and *A* values, and a better relationship is seen between loaf volume and these values, as shown in Figures 17 and 18, although the varietal discrimination is poorer. The correlation between loaf volume and *A* or *L* may be related to the fact that to achieve a large loaf volume, a dough must expand considerably during final proof and baking, during which the dough sheets between the bubbles must achieve a high biaxial strain without rupture. It should be noted, however, that high loaf volume is not the only determinant of bread quality, and that although high volumes were achieved for some samples of Consort, for example, these loaves had poor texture. Thus, although *A* and *L* gave the better correlations with loaf volume, *W* gave a better prediction of overall breadmaking suitability.

The maximum pressure, *P*, showed little correlation with loaf volume. Dobraszczyk and Roberts (1994) remarked that the maximum pressure signifies the point at which a necking instability occurs, but the maximum in the pressure curve has little direct significance in terms of the rheological properties of the dough, and is also a function of the testing geometry. This is apparent when the pressure traces are transformed into stress-strain curves (see section 3.5.3), which show a smooth increase in stress as a function of strain. Bloksma (1957a) and Hlynka and Barth (1955) have suggested that the curve height at an arbitrarily chosen volume or dough thickness is a better measure than *P*. Bloksma noted that the maximum pressure might be useful as a secondary measurement, since it decreased with increasing relaxation time, which Halton and Scott Blair (1937) had found to be high for good bread doughs. The ratio of the curve height at $V = 100\ \text{cm}^3$ to the maximum curve height was proposed, yielding higher values for longer relaxation times. Bloksma (1957b) showed a correlation between this value and loaf volume, but concluded that the correlation was no better than previously observed correlations of loaf volume with *W*.

3.5.2 Dobraszczyk Roberts dough inflation system

The Dobraszczyk Roberts dough inflation system (Stable Micro Systems, Godalming, Surrey, U.K.) uses a similar geometry to the Alveograph. Discs of dough are prepared and inflated using air pumped from a piston. Pressure is measured using an electronic transducer. Data can be presented in a variety of formats including pressure against time (which can be converted to a drum distance equivalent to the Alveograph). Software is also included to allow stresses and strains to be presented.

Figure 19 – Comparison of maximum pressure (*P*) for the Alveograph and D/R dough inflation system

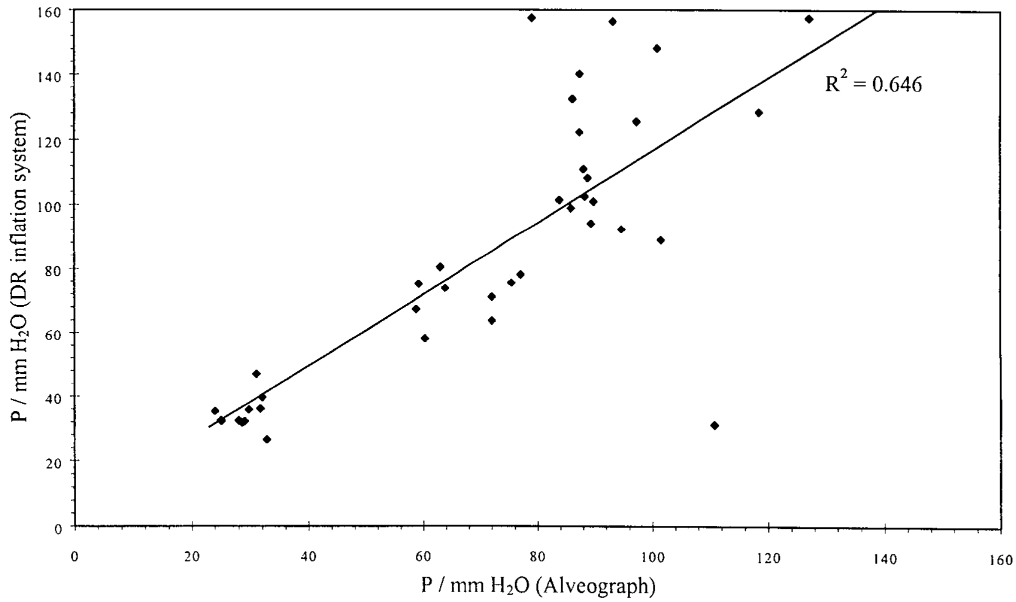


Figure 20 – Comparison of *L* for the Alveograph and D/R dough inflation system

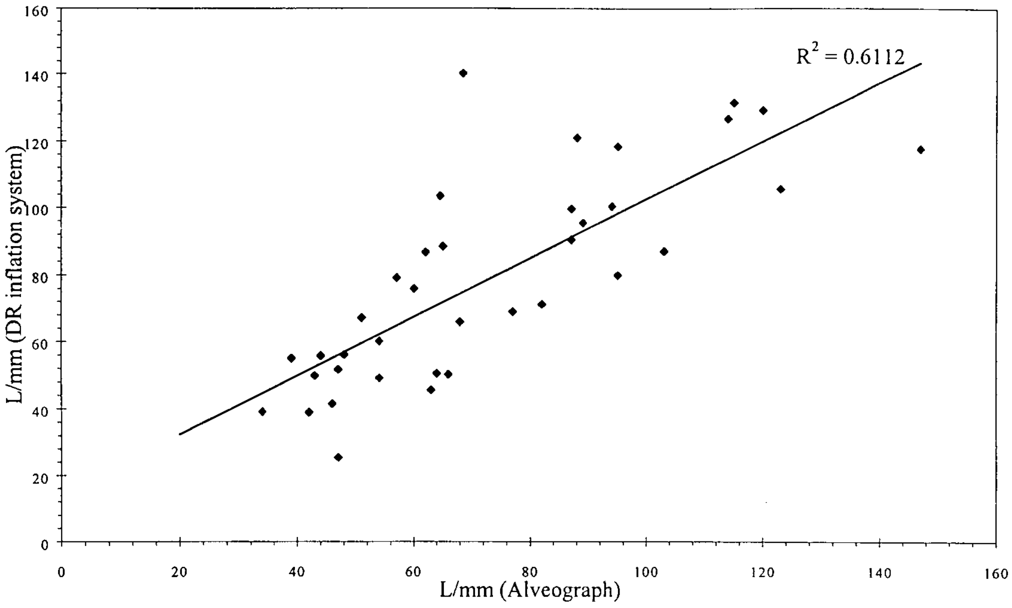
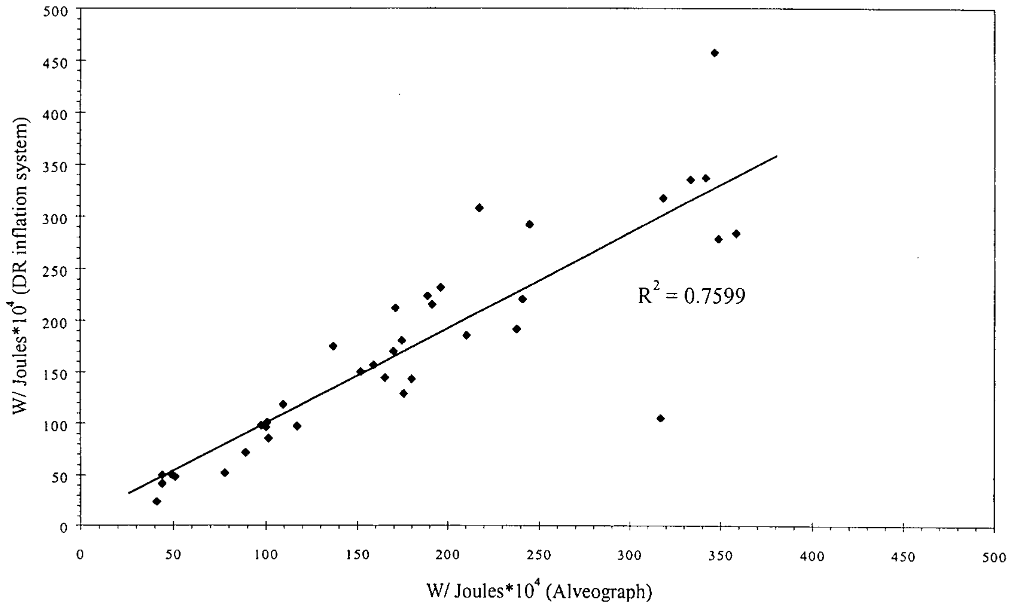


Figure 21 – Comparison of *W* for the Alveograph and D/R dough inflation system



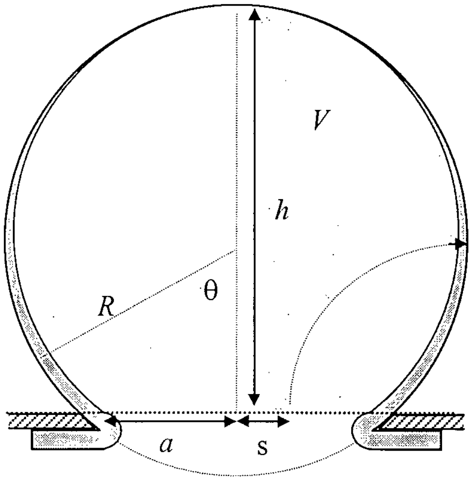
Tests were conducted on several of the flours listed in Tables A.3a and b using doughs prepared with the Alveograph mixer. Figures 19, 20 and 21 show comparisons of *P, L* and *W* measured with the Alveograph and with the D/R dough inflation system. Reasonable agreement was obtained, particularly for *W*, but with a few outliers. For measurements of *P*, as for the Alveograph, a good discrimination could be obtained between samples of group 1 and 2 wheats with values greater than 50mmH_2O, and group 3 and 4 samples which gave values lower than 50mmH_2O. The only exception to this was a sample of Soissons, which gave a low value of *P*=31.34mmH_2O on the D/R system.

3.5.3 Calculation of stress-strain properties of doughs in biaxial extension

One of the novel features of the D/R dough inflation system is the facility to present data in the form of stress-strain curves. Although the formulae necessary to calculate stress and strain from the pressure and volume data of an Alveograph had previously been established (Bloksma, 1957a), these are not widely known among users, and were not provided automatically by previous instruments. In addition to the automatic calculation of stress-strain curves by the D/R system, the automatic recording of Alveograph data in computer readable form using an Alveolink computer provides potential for transforming Alveograph data in the same manner.

Several of the features commonly associated with pressure-volume traces are artefacts of the bubble geometry. By studying dough bubble inflation data in the form of stress-strain curves, it is possible to gain a more direct appreciation of the underlying physics involved in the biaxial extension of dough, and to develop a better understanding of the rheological properties that affect its stability against rupture. To analyse Alveograph data in this way, it is necessary to consider the geometry of the bubble, as shown in Figure 22.

Figure 22 - Geometry of dough bubble blown by the Alveograph



The bubble is inflated by pumping air through an orifice and allowing the dough to expand through an opening of radius, a. Let the volume of the bubble be V, its radius, R, and its height, h.

The shape of the bubble can be approximated as a portion of a sphere, allowing its radius and volume to be calculated as a function of its height (Bloksma, 1957a; Launay *et al.*, 1977):

$$R = \frac{a^2 + h^2}{2h} \tag{20}$$

$$\begin{aligned} V &= \int_{\cos\theta = (h-R)/R}^{\cos\theta = -1} \pi R^3 \sin^3\theta \, d\theta \\ &= \frac{\pi h^2}{3}(3R - h) \\ &= \frac{\pi h}{6}\left(h^2 + 3a^2\right) \end{aligned} \tag{21}$$

This equation can be inverted to calculate h as a function of V. Previous workers (Launay and Buré, 1977) have suggested that this may be done numerically. However, since (21) is a cubic equation in h, an exact analytical solution is possible:

$$h = G - \frac{a^2}{G} \tag{22}$$

where

$$G = \left(k + \sqrt{k^2 + a^6}\right)^{1/3} \tag{23}$$

and

$$k = \frac{3V}{\pi} \tag{24}$$

This calculation is based on the assumption of a spherical bubble, as has been assumed in theoretical analyses by previous workers. At high volumes, Launay *et al.* (1977) observed some flattening of the bubble. This may be a result of the weight of the bubble, since the pressure decreases as the bubble expands, and the weight will therefore become a more dominant component of the forces acting on the dough sheet.

The volume of the bubble is normally assumed to be equal to the volume of air pumped into it, calculated as a function of time on the assumption of a constant flow rate. In early versions of the Alveograph, air delivery was achieved by displacing the air from a column using water. However, this resulted in a non-uniform flow rate, as quantified by Hibberd and Parker (1974). The use of a pump overcomes this problem and achieves a uniform flow rate (Alveograph Handbook). Hibberd and Parker also observed that as the pressure in the Alveograph changes, the volume of the air changes and the increase in volume of the bubble may not be equal to the volume of air delivered. Assuming that the volume of air within the system is primarily represented by that within the bubble, Hlynka and Barth (1955) considered the maximum error in volume to be about 1.5% and therefore negligible. For the original design of Alveograph, utilising water displacement to deliver the air, Hibberd and Parker noted that the volume of air in the total system is, in fact, considerably larger and the volume error is significant. For the modern design using a pump, the volume of the system is smaller and the error is likely to be closer to that deduced by Hlynka and Barth.

If all these factors are considered, the actual time dependence of the volume of the bubble is given by:

$$\left(P(t) + P_{atm}\right)\left(V + V_{system}\right) = P_{atm}V_{system} + \int_0^t (P(t') + P_{atm})Q\,\mathrm{d}t' \tag{25}$$

where Q is the flow rate, $P(t)$ is the pressure difference across the bubble at time t, V is the volume of the bubble and V_{system} is the volume of the remainder of the air in the Alveograph. However, if $P \ll P_{atm}$, and $V_{\text{system}} \ll V$, this reduces to the normally assumed form of:

$$V = Qt \tag{26}$$

For Alveograph instruments incorporating a recording manometer, this was recorded as the length of a trace on a drum rotating at a constant rate, the value at the point of rupture being denoted as L. In modern instruments using the Alveolink computer, this terminology has been retained for consistency. Alternatively, a quantity called the swelling index, G, is defined as:

$$V/\mathrm{ml} = G^2 \tag{27}$$

(Alveograph Handbook; BSI, 1992)

Based on a flow rate of 96 ± 2 l/h (BSI, 1992), a conversion of

$$G = 2.22\sqrt{L / \mathrm{mm}} \qquad \text{(BSI, 1992)} \quad (28)$$

is given, enabling the scaling factor between L and V to be determined:

$$V / \mathrm{ml} = 4.9284 L / \mathrm{mm} \qquad (29)$$

The stress and strain within the dough sheet are dependent on its thickness, which varies with distance from the pole of the bubble. If every particle in the dough sheet moves perpendicularly to the surface of the bubble, and if the dough is assumed to be incompressible, then the thickness, Δ, at a point which was initially at a distance s from the centre of the dough sheet (see Figure 22) is given by:

$$\Delta = \Delta_0 \left\{ \frac{a^4 + s^2 h^2}{a^2 \left(a^2 + h^2 \right)} \right\}^2 \qquad (30)$$

(Bloksma, 1957a)

where Δ_0 is the initial dough thickness. If the excess pressure is P, the thickness is Δ and the tangential stress is σ, a balance of forces gives:

$$\pi R^2 P = 2\pi R \sigma \Delta \qquad (31)$$

$$\therefore \sigma = \frac{PR}{2\Delta} \qquad (32)$$

(Launay and Buré, 1977)

$$= \frac{P}{2\Delta_0} \left(\frac{a^2 + h^2}{2h} \right) \left(\frac{a^2 \left(a^2 + h^2 \right)}{a^4 + s^2 h^2} \right)^2 \qquad (33)$$

The Hencky Strain, ε, can be calculated from the reduction in the thickness of the dough sheet:

$$\therefore \varepsilon = -\frac{1}{2} \ln \frac{\Delta}{\Delta_0} = \ln \left(\frac{a^2 \left(a^2 + h^2 \right)}{a^4 + s^2 h^2} \right) \qquad (34)$$

The maximum stress and strain are at the pole, where $s = 0$, and this is normally the point at which the bubble ruptures. At the pole, equation (33) reduces to

$$\sigma_{pole} = \frac{P}{2\Delta_0} \left(\frac{a^2 + h^2}{2h} \right) \left(1 + \frac{h^2}{a^2} \right)^2$$

$$= \frac{P}{4\Delta_0 h a^4} \left(a^2 + h^2 \right)^3 \qquad (35)$$

Similarly, equation (34) reduces to

$$\varepsilon_{pole} = \ln \left(1 + \frac{h^2}{a^2} \right) \qquad (36)$$

Dough is a viscoelastic material in which stress is dependent not only on strain, but on strain rate. This is given by:

$$\dot{\varepsilon}_{pole} = Q\frac{\mathrm{d}\varepsilon}{\mathrm{d}V} = Q\frac{\mathrm{d}\varepsilon}{\mathrm{d}h}\bigg/\frac{\mathrm{d}V}{\mathrm{d}h} \tag{37}$$

$$= Q\left(\frac{2h}{a^2+h^2}\right)\bigg/\left(\frac{\pi}{2}\left(h^2+a^2\right)\right)$$

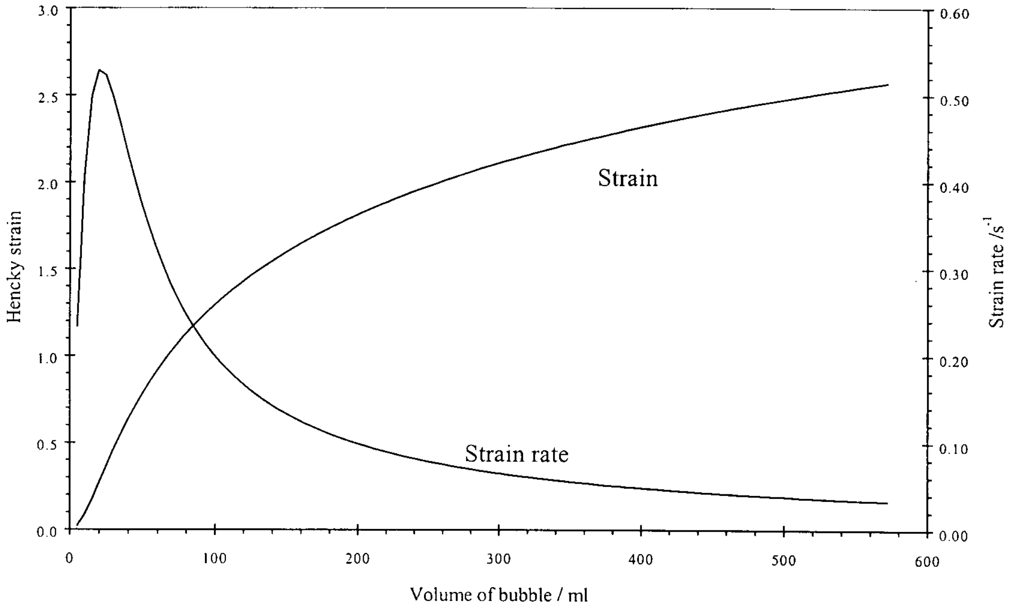
$$= \frac{4Qh}{\pi\left(a^2+h^2\right)^2} \tag{38}$$

which is a special case for $s = 0$ of the more general equation given by Bloksma (1957a):

$$\dot{\varepsilon} = \frac{4}{\pi}\cdot Q\cdot\frac{a^2h\left(a^2-s^2\right)}{\left(a^2+h^2\right)^2\left(a^4+s^2h^2\right)} \tag{39}$$

Combining equations (36) and (38) with equation (22) and using the value for the orifice diameter of $2a = 55.0 \pm 0.1$ mm and the value of Q given previously, the strain and strain rate at the pole can be calculated as direct functions of the bubble volume, or of L or G.

Figure 23 - Strain and strain rate at the pole of an Alveograph bubble as a function of bubble volume



These functions are shown in Figure 23. They are functions only of the bubble geometry and the air flow rate, and are independent of the dough properties. The strain increases continuously as the bubble inflates until the failure strain is reached, thus determining the maximum volume and the value of L conventionally measured. It can be seen that the strain rate increases initially, but subsequently decreases steadily for the majority of the expansion of the bubble. By differentiating equation (38), it can be seen that the maximum strain rate occurs at the point $h=a/\sqrt{3}$, and thus at a volume of $V=5\pi a^3/9\sqrt{3} = 1.008\,a^3 = 21.0$ml (for a value of $a = 27.5$mm). This is in agreement with the value of $V/a^3 = 1.007$ given by Bloksma (1957a), and with the value of 20.7cm^3 given by Launay and Buré (1977), who used a value of $a = 27.4$mm.

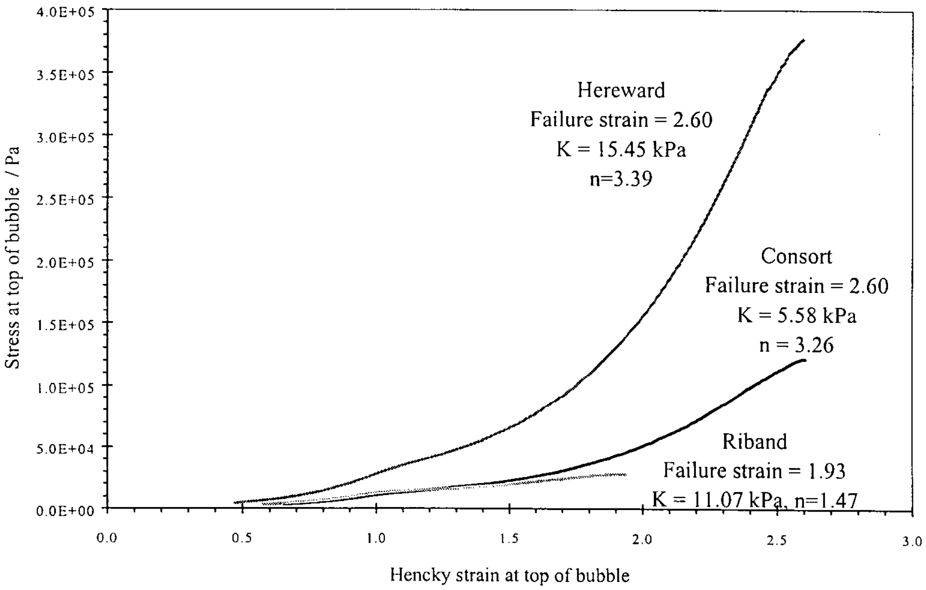
By measuring the pressure P at any given point on an alveogram, the stress can also be calculated from equation (35), using a value of $\Delta_0 = 2.67 \pm 0.01$mm for the initial thickness of the dough piece (BSI, 1992). The Alveograph measures P in units of millimetres of water. This may be converted to units of Pascals by converting the water column height to metres and multiplying by a factor of ρg, where ρ is the density of water, taken as 998kg m^{-3} at 20°C (Kaye and Laby, 1986), and g is the gravitational field strength, taken as 9.81m s^{-2}. It should be noted that Alveograph traces typically start from a non-zero pressure at L=0 (see Figure 10), due to an initial pressurisation performed using a rubber bulb to detach the dough piece from the base plate prior to inflation. To correct for this, the curves have been extrapolated back to determine the intercept, $L_{P=0}$ with the L axis at which P=0, and a shifted scale, L' has been defined with this as its origin:

$$L' = L - L_{P=0} \tag{40}$$

This value has been used in place of L for the purposes of calculating stresses and strains. The magnitude of the offset, $L_{P=0}$ was typically between 5 and 7mm for data collected with the Alveolink, with smaller corrections required for data obtained with a recording manometer.

Figure 24 shows stress-strain curves calculated in this way from the traces shown in Figure 10. The stress-strain curves are likely to be strain rate dependent for a viscoelastic material such as dough. However, despite the variation in strain rate shown in Figure 23, stress-strain curves measured under the controlled flow rate conditions of the Alveograph may still be useful for comparative purposes.

Figure 24 - Stress-strain curves calculated from Alveograph data



Stress-strain curves have been calculated for all of the flour samples measured. The general shape of the curves is consistent with those presented by Van Vliet *et al.* (1992) measured using lubricated test pieces compressed between flat plates, and with those of Dobraszczyk and Roberts (1994) who used a modified Alveograph in which pressure was measured with an electronic transducer and bubble height was measured with a laser ranger. The main variations seen between the behaviour of the different doughs were in their elastic moduli, the curvature of the stress-strain relationships, and the failure stresses and failure strains. It can be seen that the characteristic maximum pressure exhibited by the Alveograph test and normally recorded as one of the main parameters of interest is an artefact of the test geometry and does not correspond to any specific aspect of the dough rheology.

Dobraszczyk and Roberts (1994) modelled the stress-strain curves of doughs as a power law relationship:

$$\sigma = K\varepsilon^{n} \tag{41}$$

For experiments performed with a different geometry, and under conditions of constant strain rate, Van Vliet *et al.* (1992) instead found an exponential relationship:

$$\sigma = A\exp(B\varepsilon) \tag{42}$$

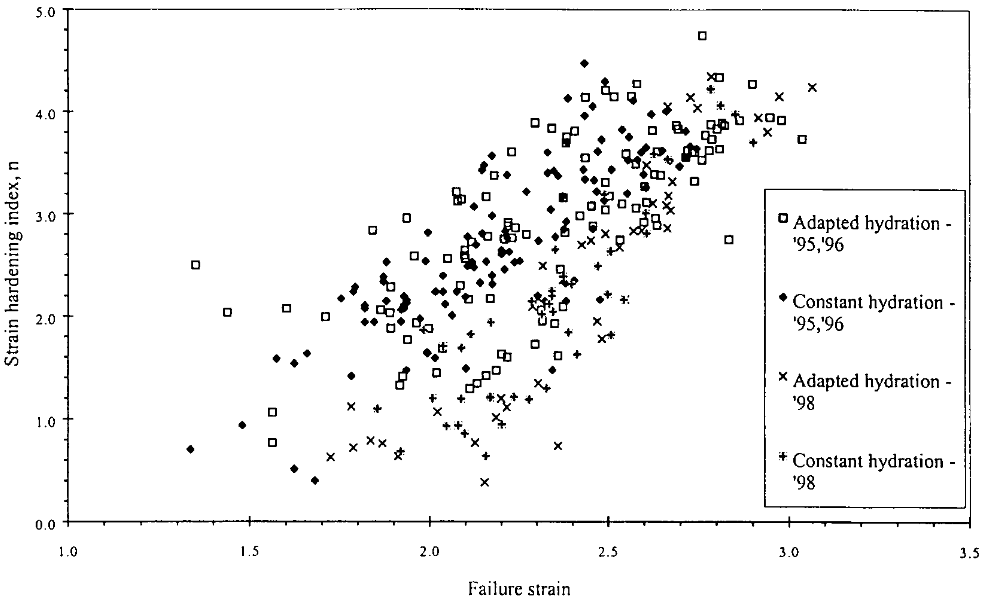
For the data obtained from the Alveograph traces in this project, better agreement was found with the power law (equation 41). Curves were fitted to stress and strain values calculated from the means of replicate Alveograph traces to obtain values of K and n for each sample. Examples are shown alongside the curves in Figure 24. The fitting was performed by minimising the sum of the squares of the deviations between the measured stresses and the fitted values. This seemed to give a closer fit than that obtainable by linear regression of $\ln(\sigma)$ against $\ln(\varepsilon)$, the latter giving a lower weighting to values at high strains and lower values of n than those measured.

The value K is a measure of dough strength and correlates well (R^2=0.815 for the 1995 and 1996 samples) with P. It is equal to the height of the fitted curve at a strain of 1. For example, of the samples shown in Figure 24, the Hereward sample achieved the greatest stress at a strain of 1, which is reflected by its higher value of K. It should be noted, however, that K corresponds to the height of the fitted curve, rather than the actual curve. Thus, the value of K for the Consort example, in particular, is lower than the height of the actual curve, which has a slight bump at a strain of 1.

n is known as the strain hardening index. Dobraszczyk and Roberts (1994) showed that it gives a criterion for the strain at which the dough film will become unstable and showed good agreement with the failure strain, which was confirmed by further data obtained with the D/R dough inflation system (Dobraszczyk, 1997). Van Vliet *et al.* (1992) proposed that the strain hardening may arise from alignment of polymers within the plane of the dough sheet as it is stretched, citing evidence of birefringence in stretched hydrated gluten (Bloksma and Isings, 1957). By theoretical considerations, Van Vliet *et al.* (1992) showed that the strain hardening is important for stabilisation of a dough film under biaxial extension. In simple terms, if a dough sheet develops a localised thin region, the stress becomes concentrated at this point causing the dough to become highly strained, which could lead to rupture. However, strain hardening causes the dough to become stiffer at this point, stabilising it against rupture.

It can be seen from Figure 24 that the examples of Hereward and Consort shown have a large strain hardening index as characterised by their high positive curvature, and that they therefore fail at a higher strain than the example of Riband, which has a lower curvature and, therefore, lower strain hardening. The overall correlation between the strain hardening index and the failure strain is shown in Figure 25. A good correlation was seen, but the relationship was different to that observed by Dobraszczyk and Roberts, who suggested that the strain hardening index should be equal to the failure strain.

Figure 25 – Strain hardening index against failure strain calculated from Alveograph data.



Measurements were made under constant and adapted hydration conditions. For most samples from the 1995 and 1996 harvests, adapted hydration conditions resulted in a greater strain hardening and thus an increased failure strain. However, for the 1998 samples, this effect was generally seen for an increase in water content. Thus, for the samples with low water absorption, adapted hydration represented a reduced water addition and caused a reduction in n and failure strain. Despite these effects, the overall relationship between strain hardening and failure strain was similar for constant and adapted hydration conditions. However, there was a notable difference between the results for the 1995/6 and the 1998 samples, the latter rupturing at higher strains for comparable values of the strain hardening index.

In addition to strain hardening, the dependence of stress on strain rate is also important in determining the stability of dough bubbles against rupture. Modelling the stress-strain behaviour as

$$\ln\sigma = \text{const} + y\cdot\varepsilon_b + z\cdot\dot{\varepsilon}_b \quad , \qquad (43)$$

Vliet *et al.* (1992) gave a criterion of

$$y - 3z > 2 \qquad (44)$$

for stability of a dough film. Dobraszczyk and Roberts (1994) also measured strain rate dependence, based on a series of Alveograph measurements at different inflation rates, and developed an instability criterion including strain hardening and rate hardening. However, although of scientific interest, determination of both factors requires several dough inflation tests for each sample, and is less practical for a routine test. For the normal Alveograph test, the inflation rate is standardised, and it is therefore possible to obtain useful comparative measurements between samples independently of their sensitivity to strain rate. However, inferences about the baking performance of samples may be affected due to the different strain rates used during baking processes.

Dobraszczyk and Roberts showed a good correlation between failure strain of an Alveograph bubble and loaf volume for various doughs made with a commercial CBP flour and a straight-run Buhler milled flour from the soft non-breadmaking variety Apollo. For the wider range of varieties tested in this project, a positive correlation was also seen, but was much weaker. An alternative approach to the development of a predictive parameter has therefore been developed, based on the values of both *K* and *n*.

3.5.4 The use of Alveograph stress-strain data for flour quality prediction

For simplicity of setting wheat and flour quality specifications and for ease of interpretation, it is convenient to represent an Alveograph curve by a small number of parameters. The normal parameters used are *P*, *L* (or *G*) and *W*, as discussed previously.

Figure 26 – *K* and *n* values for a fit of $\sigma=Ke^n$ to Alveograph traces measured under constant hydration conditions

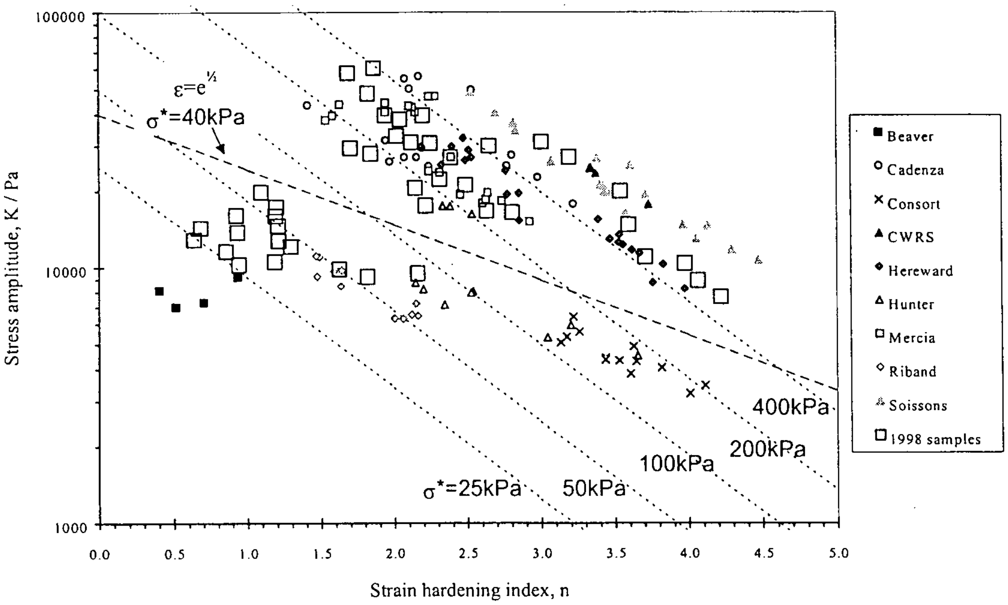
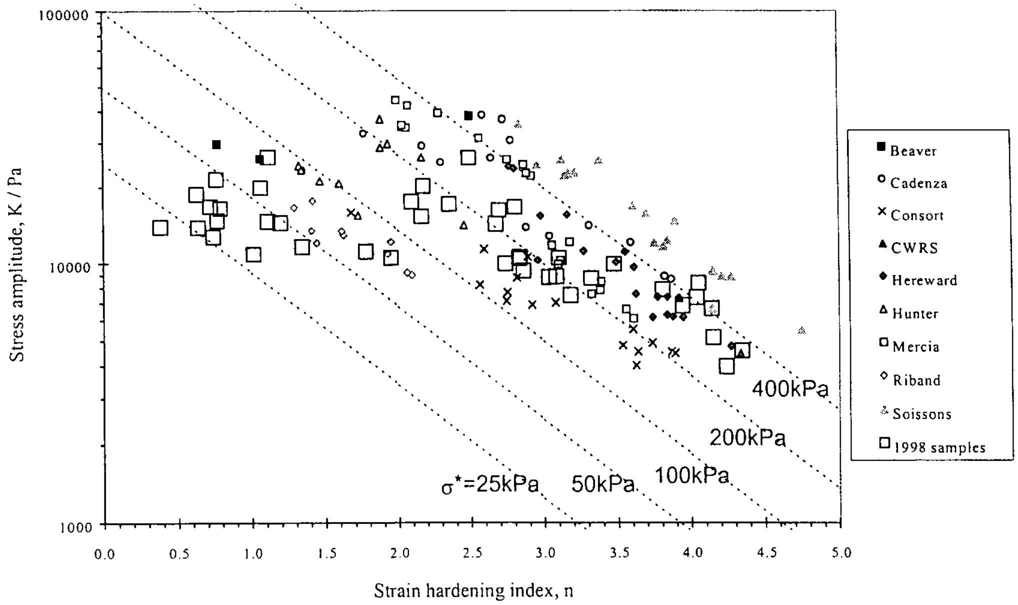


Figure 27 - *K* and *n* values for a fit of $\sigma=Ke^n$ to Alveograph traces measured under adapted hydration conditions



The parameters K and n provide an alternative means of characterising an Alveograph curve which better describe a fit to the entire curve, rather than to specific points. If information is also required about the point of rupture, these could be supplemented with a value for the failure strain (or with L or G, which are directly related to it). It was shown previously in Figures 11 and 12 how the parameterisation of P and L could be used to show a comparison between samples. Figures 26 and 27 show samples plotted on the basis of K and n, in a similar manner for constant and adapted hydration conditions respectively. It can be seen that varieties are well discriminated on this basis, and that when K is plotted on a logarithmic scale, they fall approximately on straight lines.

Taking logarithms of both sides of equation 41 and rearranging yields

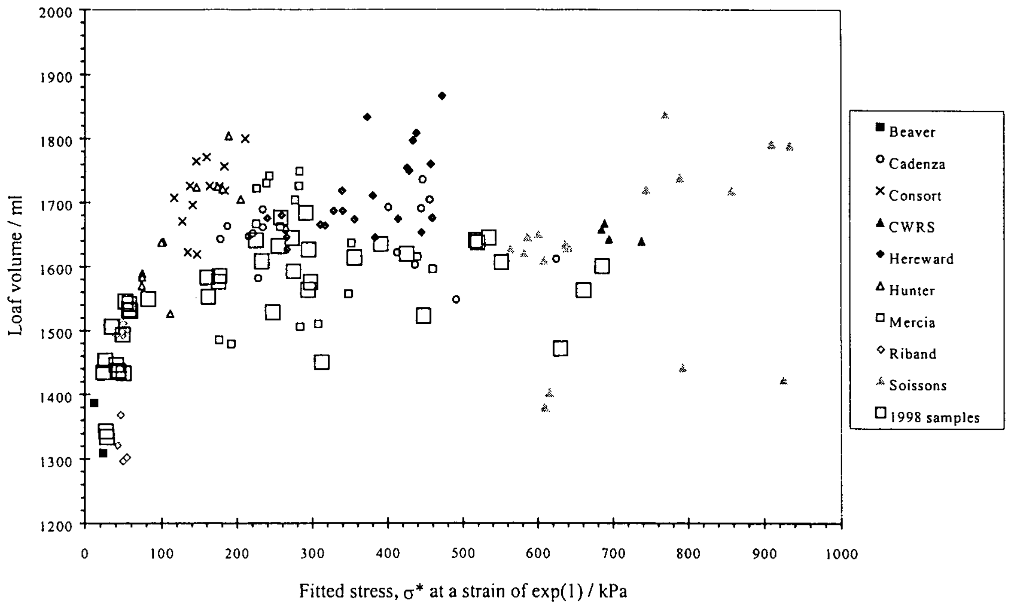
$$\ln K = \ln\sigma - n\ln\varepsilon \qquad (45)$$

which is the equation of a straight line in a plot of $\ln K$ against n, with intercept $\ln\sigma$ and gradient $-\ln\varepsilon$. Thus, straight line contours in Figures 26 and 27 correspond to Alveograph curves with equal stress at a particular strain whose logarithm is minus the gradient of the lines. Visually, the best separation of group 1,2 and group 3,4 wheats is on the basis of lines parallel to the dashed line in Figure 26 with a gradient of $-1/2$, thus corresponding to stress measurements at a strain of $\varepsilon = e^{1/2} = 1.648$, a bubble volume of 161ml and L'=33mm. This only fails to discriminate the 1996 Hunter No. 3 samples, which are the same samples which were not discriminated by P. A more complete varietal separation, however, is obtained for a steeper gradient. Visual inspection suggests that samples of the same variety lie on contours with gradients of about $-\ln(\varepsilon)=-1$, and thus a strain of $\varepsilon = e \approx 2.718$, as represented by the dotted lines on the graphs. This strain corresponds to a bubble volume of 703ml and a modified Alveograph drum distance of L'=143mm. Each contour is marked with the stress achieved by the fitted power law when measured at this strain:

$$\sigma^* = Ke^n \qquad (46)$$

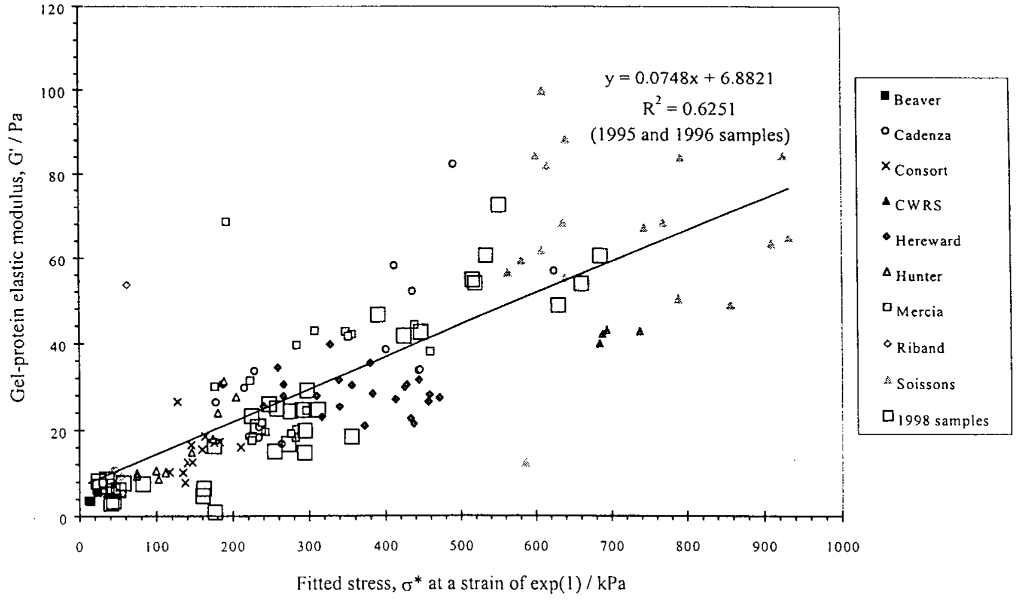
With the exception of two samples of Beaver which gave values of σ^*=265 and 465kPa under adapted hydration conditions, and σ^*=12 and 15kPa respectively for constant hydration (which may be due to underestimation of the appropriate hydration level – c.f. Figure 8), the values of σ^* are fairly similar for adapted and constant hydration conditions. Because of the simpler testing procedure, with no requirement for use of a Consistograph, and because the range is slightly better, the values measured under constant hydration conditions have been chosen for examination of the performance of this variable. Using the values of σ^* derived for these measurements, Figure 28 shows the predictive performance for loaf volume. For the 1995 and 1996 samples, the general trend is a positive correlation between σ^* and volume, although four samples of Soissons (all from 1995 sample No. 2) produced low loaf volumes despite high values of σ^*. It is unclear whether these samples are indicative of a general relationship with maximum loaf volumes for intermediate values of σ^*, or are outliers of a positive correlation. However, it can be seen that the group 1 varieties Hereward and Mercia have intermediate values of 258 to 472kPa and 176 to 459kPa respectively. For the 1998 samples, a similar trend was seen, although the loaf volumes were slightly lower than before. Hereward and Mercia again gave a similar range of values (254 to 294kPa and 232 to 274kPa respectively), and the additional group 1 varieties, Malacca and Spark also gave intermediate values of 160 to 355kPa and 247 to 425kPa respectively. A good discrimination can be made between group 1 and 2 varieties, which generally gave values of σ*>200kPa, and group 3 and 4 varieties, which generally gave lower values. The same criterion also works well for adapted hydration (see Figure 27).

Figure 28 – Loaf volume against σ*, the fitted stress for an Alveograph test at a strain of ε=e.



The ranking of varieties and the appearance of Figure 28 are very similar to those achieved using the Alveograph *W* parameter (see Figure 15), although σ* gave a slightly better discrimination of Soissons from weaker varieties. Comparison of σ* with *W* revealed a correlation of R^2=0.921 for the 1995 and 1996 samples, and R^2=0.968 for the 1998 samples, indicating a close association between these variables.

Figure 29 – Gel-protein elastic modulus against σ*, the fitted stress for an Alveograph test at a strain of ε=e.



The ranking of samples by σ^* is also qualitatively similar to that achieved using gel-protein elastic modulus, G' (see Figure 37, section 3.8.1.3). It is therefore interesting to note the correlation between σ^* and G', as shown in Figure 29, which is $R^2=0.6251$ for the 1995 and 1996 samples. For the 1998 samples, the correlation was even better ($R^2=0.86$). σ^* or W therefore appear to offer favourable alternatives to G' for identification of bread baking potential, and showed similar performance in this study. However, before they could be fully recommended, further work would be necessary to assess their sensitivity to starch damage, and to select a standardised milling protocol if necessary. On the basis of the limited set of samples measured from 1998, for which two starch damage levels were obtained for each wheat, an analysis of covariance suggested that σ^* was highly significantly correlated with starch damage (P=0.001) with a sensitivity of 3.3kPa/Farrand unit.

Since σ^* is measured at a constant strain for a fixed bubble geometry, each stress corresponds directly to a particular value of the pressure. Thus, in principle, the value σ^* could be determined directly from an Alveograph curve by measurement of the pressure at the point L'=143mm. However, in practice, most doughs rupture before such a high value of L' is attained, and it would therefore be necessary to determine the pressure by extrapolation of the curve. Except where rupture occurs at values close to L'=143mm, it is doubtful whether this could be achieved accurately from the raw alveograms, and the power law fitting approach described above would seem more appropriate for reliable results.

Hlynka and Barth (1955) also suggested measuring the pressure achieved with an Alveograph at a fixed drum distance. They suggested a value of L=20mm. For typical curves, this would correspond to an approximate value of L'=25mm, and thus a strain of approximately 1.45. Contours of pressure measured (for a fitted power law) at this point would thus have a gradient of $-\ln(1.45) = -0.37$ on a plot of $\ln K$ against n. Assuming that actual pressures correspond approximately to those obtained from fitting a power law to a stress-strain curve, it is clear from Figure 26 that this would also achieve a reasonable discrimination of groups 1 and 2 from groups 3 and 4, but the discrimination of varieties would not be as optimal as that achieved by σ^*. Hlynka and Barth's choice of measurement has the practical advantage of not requiring extrapolation of the Alveograph curve. However, with computer analysis of data from an Alveolink, this is no longer an essential concern.

Although σ^* provides a discrimination between the varieties tested, it is clear that there is also variation within varieties, represented by a spread in K and n values along the length of the contours in Figures 26 and 27. This can be quantified in a similar manner to that used for σ^* by measuring a stress, $\sigma^\dagger$, with contours perpendicular to those of σ^* in a plot of $\ln K$ against n. Thus, the contours have gradient $-\ln(\varepsilon)=+1$, and:

$$\sigma^\dagger = Ke^{-n} \qquad (47)$$

$\sigma^\dagger$ is therefore the stress attained by the fitted power law curve at a strain of exp(-1) = 1/e = 0.37, corresponding to a bubble volume of 25ml and an offset drum distance of L'=5.1mm. Typically, this represents a value of L very close to zero, and thus corresponds to the stress (or pressure) attained at the start of the Alveograph trace. Since the fit of the power law is often poorest for low strains, a value measured directly from a single point in the raw data may provide a poor approximation to $\sigma^\dagger$, and this is therefore better measured from calculations of K and n as described above. It is not clear whether $\sigma^\dagger$ relates to any functional property of the flour. Comparison of $\sigma^\dagger$ with other measured attributes for the 1995 and 1996 flours showed no clear correlations with starch damage, protein content, bread or biscuit properties, and this value may simply represent random variation within varieties, or experimental error.

3.5.5 Summary

It has been demonstrated that inflation of bubbles in dough sheets is a useful practical method for testing rheological properties in biaxial tension, and can provide some degree of varietal discrimination and prediction of loaf volume potential. The best established instrument is the Chopin Alveograph, although the Stable Microsystems D/R instrument provides a versatile alternative. The maximum pressure attained (*P*) discriminated group 1 and 2 wheats from groups 3 and 4, but is specific to the bubble geometry, and does not identify a fundamental rheological property of the dough. The drum distance, *L*, at rupture is directly related to the failure strain of the bubble and showed some potential for prediction of loaf volume, most notably under adapted hydration conditions. The energy to inflate the bubble to rupture (*W*) showed a better discrimination of individual varieties, and gave a better prediction of overall baking performance. However, the greatest potential for understanding the dough properties comes from a consideration of the fundamental rheological characteristics of the dough as it is strained. The D/R system provides the facility for calculating stress and strain automatically, and it has been shown how these quantities can also be calculated from Alveograph data. By consideration of the data in this way, a new parameter, σ^*, has been developed to provide an optimal discrimination of samples by variety. In practice, σ^* offered little or no improvement in discrimination over *W*, the energy required to inflate a bubble to rupture. However, the method of derivation provides a better rationale for its selection. The same method also allowed an independent contribution, $\sigma^\dagger$, to the shape of Alveograph curves to be identified, although this did not appear to be relevant to flour functionality.

A significant contribution to dough rheology is the hydration level. In the standard Alveograph test, doughs are tested at constant hydration. However, in bread and biscuit production, dough water addition is adapted to the water absorption capacity of the flour. By also testing doughs under adapted hydration conditions, it has been possible to assess differences in rheology which are more likely to be relevant to those in practical baking systems. Differences in *P* appeared to be partially a consequence of hydration, larger values being obtained for flours with higher water absorptions; these differences were less apparent for the parameter, *T*, measured under adapted hydration conditions. *W* was also partially dependent on hydration, and the range of values was reduced for *Fb*, measured under adapted hydration conditions. Similar differences were seen for the newly developed parameter, σ^*. Values of *L* and *A*, however, were similar for the two hydration protocols and therefore appeared to be more reliable indicators of underlying flour properties.

3.6 Extensograph

The tests described above involve the testing of dough to rupture under biaxial strain, which reflects in some respects the mode of strain achieved during proving and baking of bread. The Extensograph instead tests doughs under more uniaxial conditions. It was originally developed to test flours for breadmaking but, with a modified protocol, is also now routinely used for biscuit flours.

Extensograph measurements were made for most of the flours. Results are shown in Tables A.4a, b and c. Figure 30 shows extensibility plotted against resistance for the 1995 and 1996 flours, together with an indication of the ratio $100 \times E/R$. It can be seen that extensibility and resistance were lowest in combination for the biscuit and feed varieties Beaver, Riband and Hunter. These varieties were tested under a different protocol to the other varieties (see section 2.6.5), and would be expected to give an even lower resistance if tested under comparable conditions. The Soissons samples were among those with the highest resistance values, which is consistent with the reputation of this variety for being extra strong. Each of the breadmaking varieties tested gave a wide range of resistance values. With the exception of Cadenza, for which resistance increased with protein content, this parameter showed little relationship with variations in protein content.

Figure 30 – Extensograph measurements for 1995 and 1996 flours

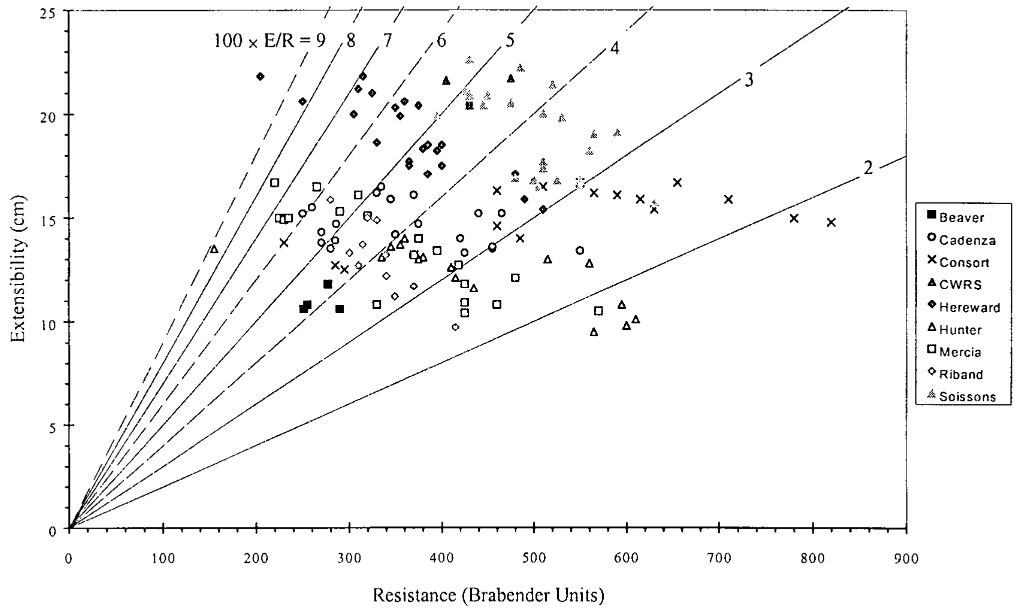
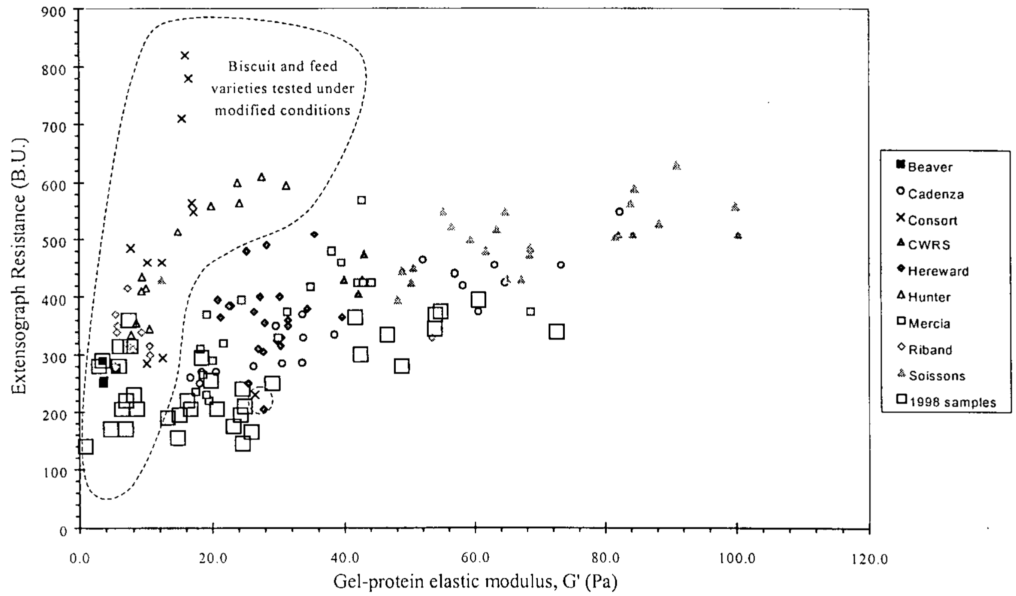


Figure 31 – Extensograph resistance against gel-protein elastic modulus

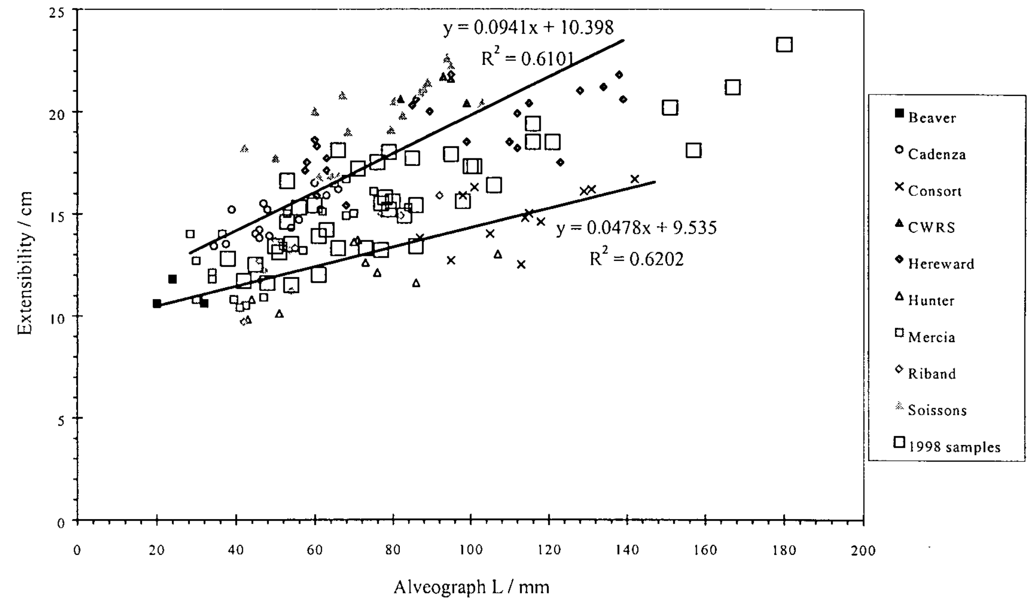


When comparing Extensograph measurements with other measurements of flour quality, it should be borne in mind that the group 3 and 4 varieties were tested under a different protocol to the other flours, and it is therefore appropriate to consider these two sets of flours separately when making comparisons. Resistance is a measure of dough strength, and was correlated with gel-protein elastic modulus (see section

3.8.1.3), which is also a measure of flour strength, as shown in Figure 31. The group 3 and 4 varieties are shown within a dotted line. The Alveograph *P* parameter is also a measure of dough strength, measured under biaxial rather than uniaxial conditions. However, the relationship with this variable was poor.

Extensibility is a measure of the strain that a dough can sustain before rupture, and could therefore be expected to show a better relationship with variables such as Alveograph *L*, which measures a similar property under biaxial conditions. A positive correlation was indeed obtained between these variables, as shown in Figure 32. The extensibility was lower for group 3 and 4 varieties than for groups 1 and 2 due to the modified protocol under which these samples were tested.

Figure 32 – Extensibility against Alveograph *L*



3.7 Test baking

3.7.1 Bread baking

Bread was produced for almost all of the flours and was assessed for volume, crumb texture and colour. Results are shown in Tables A.5a, c and c for bread baked from the 1995, 1996 and 1998 flours respectively. In many cases, replicate bakes were performed and the results represent mean values for all the loaves prepared from each flour. Similar trends in baking performance between varieties were seen for each of the harvest years, although the maximum loaf volumes achieved were smaller for 1998 than for the other two years.

The most popular current U.K. breadmaking variety, Hereward, produced loaves of the highest volume with a good crumb score. Other U.K. varieties used in breadmaking grists (Cadenza, Mercia, Malacca and Spark) produced loaves of slightly lower volume and crumb score. As expected, the poorest bread quality was obtained for loaves baked from group 3 and 4 varieties. The smallest loaves with the poorest crumb scores were obtained from Riband and Beaver. In some cases, for 1995 and 1996, the group 3 and 4 varieties Consort and Hunter produced loaves of comparable volume to the recognised breadmaking varieties, although the crumb texture was poor and the loaves of Hunter had pale crusts and an unattractive break. It is interesting to note that these samples also produced the highest values of Alveograph σ* (section

3.5.4), *W*, and gel-protein *G'* (section 3.8.1.3) among group 3 and 4 varieties, adding confidence in the ability of these tests to predict loaf volume potential. The group 2 variety Soissons, which has a tendency to be extra-strong, produced some loaves of reasonable quality in 1996 and 1998, but the flours milled from wheats No.2 and No.3 from the 1995 harvest produced very poor loaves. Most of the predictive tests assessed in this project did not distinguish the differing performance among the Soissons samples. However, Soissons was consistently identified as extra-strong (for example, by high values of σ^*, *W* and *G'*), and its potential lack of performance at typical work inputs could be identifed on this basis. The Canadian wheat class, CWRS, is generally regarded as having excellent breadmaking quality. In this work, it produced loaves with good crumb scores, but unexceptional volumes. The failure to achieve the expected volumes may be because wheats of this class are stronger than typical U.K. breadmaking wheats. The doughs may therefore have been underdeveloped in the baking process used, which was identical for all flours. As for the Soissons samples, this strength was identifiable by high values of σ^*, *W* and *G'*. The purpose of this project was to identify ways of assessing the potential of wheat varieties in typical U.K. baking systems. As exemplified by CWRS, this does not eliminate the possibility that improved performance may be obtainable by optimisation of the baking process to suit particular flours.

3.7.2 Biscuit Baking

Semi-sweet biscuits were baked for all the flours produced. Results of quality assessments and of the level of water addition as determined by an extrusion test are shown in Tables A.6a, b and c. It should be noted that the oven used for baking was different for the 1995 samples than for the 1996 and 1998 samples. Therefore, a direct comparison of the 1995 results with the others would be inappropriate. Examination of the results reveals that there were actually significant differences in biscuit properties between all three years. For example, the mean values of the biscuit eccentricity were 0.999±0.004, 1.066±0.004 and 0.951±0.008 for the 1995, 1996 and 1998 samples respectively. It is thought that such differences are more likely to reflect a lack of repeatability in the test baking method than actual differences in flour sample properties from each harvest. However, past experience suggests that greater confidence can be placed in comparisons within the set of samples for each harvest year, which were each baked by a single operator within a short space of time. Part of the difficulty in obtaining repeatable results may be due to the absence of sodium metabisulphite (SMS) from the biscuit recipe. In addition to the benefits that this can provide in relaxation of dough rheology, it also assists in providing more uniform dough processing characteristics. One effect that was particularly noticeable at the time of conducting the tests, and which was attributed to the lack of SMS, was a poor repeatability in dough extrusion times, used for determination of water addition.

Of particular interest among the quality data are the biscuit hardnesses. A hardness of 35 seconds has been found to be the maximum level for consumer acceptance of semi-sweet biscuits (Oliver *et al.*, 1995). This criterion was achieved for most examples of the soft varieties Beaver, Consort, Hunter, Riband and Claire, but only for three examples of flours milled from hard varieties. The hardness of biscuits has been previously recognised as being correlated with flour protein content (Wade, 1972). A weak trend was observed for the 1995 and 1996 flours, as can be seen from Figure 33, but did not exist for the 1998 samples. It would appear that any correlation with protein content was a secondary consequence of the difference in hardness between biscuits baked from soft wheat varieties, which tend to have low protein content, and hard varieties which tend to have higher protein content. Within either population, no correlation with protein content was apparent. This bimodal distribution of biscuit hardnesses meant that correlations could also be obtained with other variables which discriminated between these populations, including starch damage, flour water absorption, Alveograph *P* or *W*, and gel-protein elastic modulus. However, no tests were identified which could predict the hardness of biscuits within either population, and it is therefore doubtful whether any of the tests mentioned measured a direct causal effect on biscuit hardness.

Figure 33 - Relationship between flour protein content and biscuit hardness

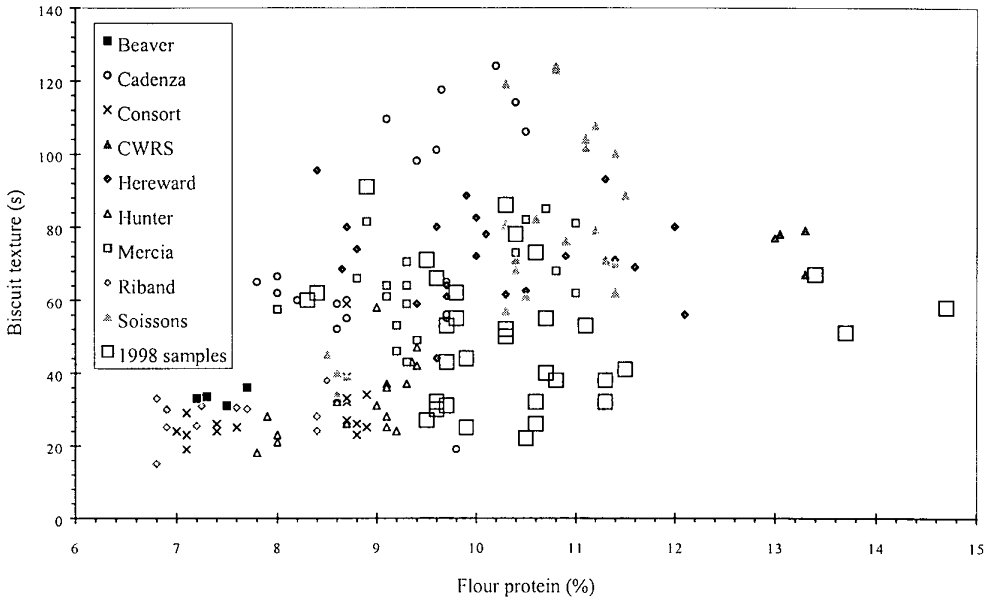
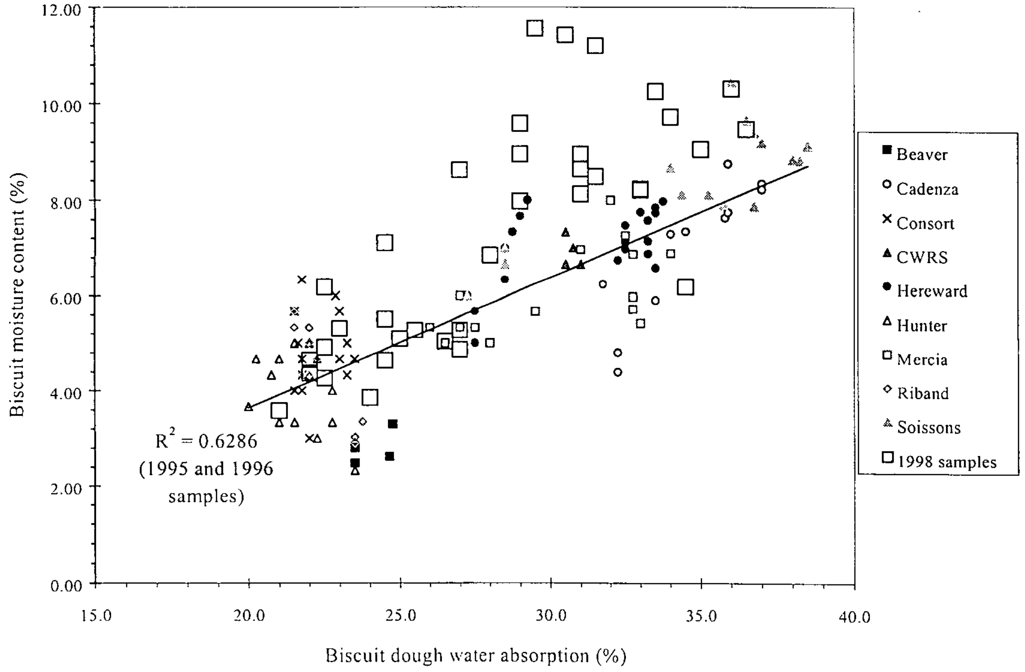


Figure 34 – Biscuit moisture content against flour water absorption



In addition to hardness, the moisture content of the biscuits also differed for soft varieties (2.3 - 7.1%) and hard varieties (3.7 - 11.6%). This was correlated with the water absorption of the flours (20.0-27.0% and 25.5-38.5% for soft and hard varieties respectively) and thus the water content of the dough recipe, as shown in Figure 34.

During baking, water is lost by evaporation in the oven. For high initial moisture content of the dough, it is difficult to achieve sufficient water removal, thus resulting in the high biscuit moisture contents measured for such samples. With increasing moisture content, the biscuits become progressively less crisp. This is not reflected in the texture values measured by the saw test, for which the biscuits with high moisture content can clog the saw blade, resulting in high values.

A high level of checking was observed for many of the biscuits. It was originally thought that some of this may have arisen from the use of the NEFF oven for the baking tests of 1995 samples. However, the same effect was also seen for tests of 1996 samples, which were baked in a Spooner travelling oven. The checking was generally less severe for biscuits baked from hard wheat varieties, due to their higher moisture content which made them less brittle.

3.8 Fundamental rheology measurements

3.8.1 Gel-protein

3.8.1.1 Introduction

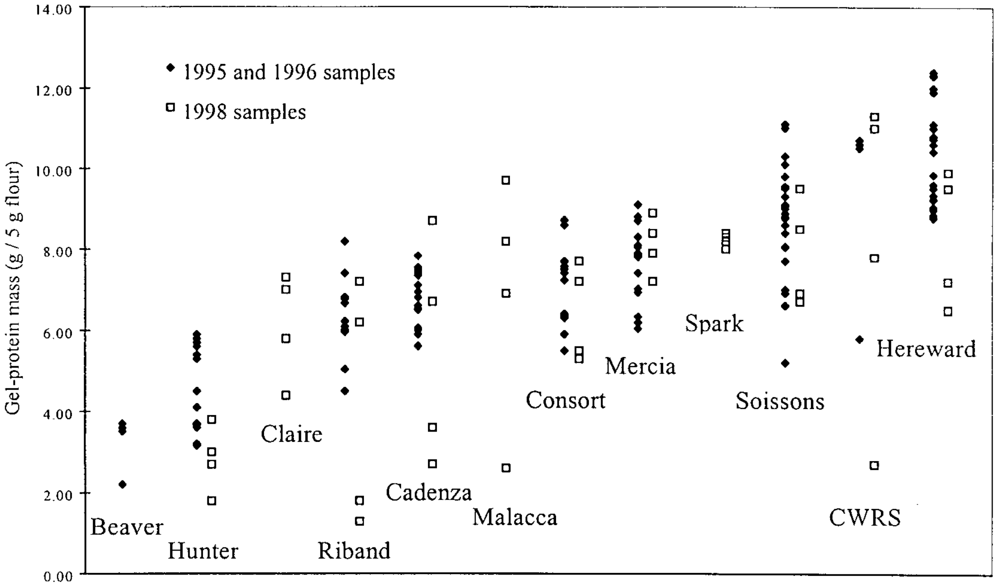
The characteristics of wheat proteins are an important aspect of wheat functionality. Much of the varietal difference in breadmaking quality is thought to be due to the glutenin fraction of wheat proteins (Schofield, 1986). Graveland *et al.* (1982) identified a fraction of glutenin that could be separated as an insoluble gel layer when a mixture of sodium dodecylsulphate (SDS) and de-fatted flour was centrifuged at high speed. This was named gel-protein and was shown to correlate with baking quality. During dough mixing, the aggregated glutenin is de-polymerised and the amount of SDS-insoluble protein recoverable from doughs as gel-protein decreases with mixing time. For stronger varieties, the rate of decrease in gel-protein mass as a function of mixing time ('gel-protein breakdown rate') is lower for stronger varieties, and provided an improved correlation with loaf volume for U.K. wheats (Pritchard and Brock, 1994). Preparation of samples from multiple mixes to determine gel-protein breakdown rate is a time consuming test. However, it has been shown that similar properties can be distinguished by measuring the elastic modulus of gel-protein samples (Oliver and Pritchard, 1993). It was suggested that the higher elastic moduli measured for strong wheat varieties were indicative of greater cross-linking in the gel-protein, which may have resulted in a greater resistance to breakdown. The success of gel-protein elastic modulus as a predictor of breadmaking quality has led to its use as part of the quality assessments carried out within the HGCA/NIAB Recommended List trials in the U.K. Within this project, the capabilities of gel-protein measurements have been re-assessed. Alternative methods have also been considered which would allow these measurements to be made with less costly apparatus and would provide potential for its more widespread use.

3.8.1.2 Gel-protein mass

Tables A.7a, b and c show results for the mass and rheological properties of gel-protein extracted from flours milled from the 1995, 1996 and 1998 harvest wheats. The mass of gel-protein is related to the genetic background of a variety and is a measure of the quantity of functional protein. It is thus capable of distinguishing broad categories of wheat (Pritchard, 1993). Figure 35 shows the masses of gel-protein measured for the flours in this project listed in order of the mean results for the 1995 and 1996 samples. The 1998 samples are shown separately for validation purposes. In cases of varieties not represented among the 1995 and 1996 samples, these have also been placed in order based on the mean 1998 results.

For the 1995 and 1996 results, it can be seen that the group 3 variety Beaver and the group 4 variety Hunter have low quantities of functional protein and that the breadmaking varieties Hereward, CWRS and Soissons have high quantities. In most cases, the results for the 1998 samples were consistent with these values, although much lower results were obtained for two Riband samples, one Cadenza sample and one CWRS sample. Despite the general trend of gel-protein mass with variety and its consistency between the sample sets, this measurement was insufficient to discriminate between several varieties of differing properties which gave values in the middle of the range. For example, the varieties Riband and Consort, which are favoured for biscuitmaking, gave similar results to the varieties Cadenza and Mercia, which are used in breadmaking grists.

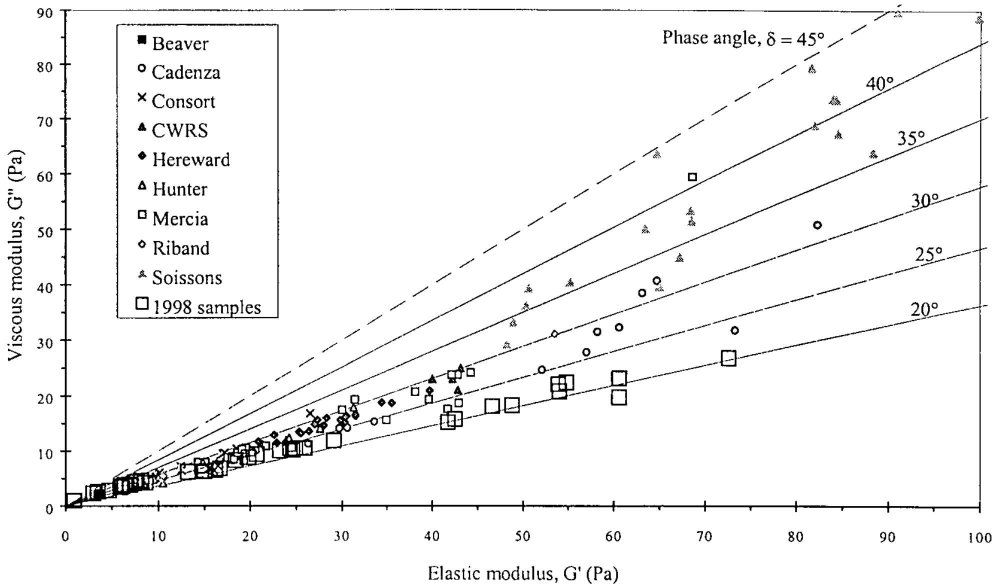
Figure 35 – Gel-protein mass classified by variety



3.8.1.3 Gel-protein rheology using a Bohlin rheometer

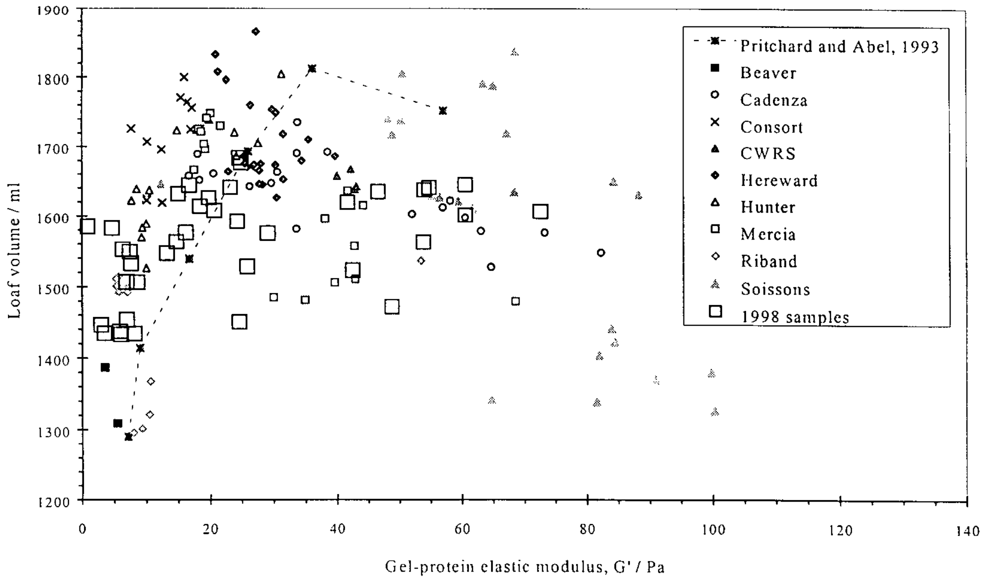
Improved discrimination between varieties of differing breadmaking potential can be obtained from measurements of the rheology of gel-protein, for which results are also shown in Tables A.7a, b and c, measured with a Bohlin VOR rheometer. The discrimination achieved can be seen from Figure 36 in which the viscous (loss) modulus, G" has been plotted against the elastic (storage) modulus, G'. For the 1995 and 1996 samples, many of the wheat varieties tested are well separated with Soissons having the highest modulus, Cadenza the next highest and the biscuit and feed varieties Riband, Hunter, Consort and Beaver having the lowest moduli. Within the Cadenza samples, the higher moduli were measured for the flours with the highest protein contents (e.g. $G' = 26.3$ to 33.6 for sample No. 1, 52.1 to 60.6 for No. 2, and 63.1 to 82.3 for No. 3 in 1995 for which the wheat protein contents were 10.15, 11.70 and 12.60% respectively). For the majority of the samples, the ratio of G'' to G' (i.e. tan δ, where δ is the phase angle) had a relatively narrow range of values (phase angle between 23.3° and 32.2°). However, the Soissons flours yielded gel-proteins with higher phase angles (29.9° to 44.6°), the reason for which is not yet understood. Similar rankings of varieties were obtained for the 1998 samples although, as can be seen from the graph, the phase angles were lower than for the previous samples, with most samples in the range 18.0° to 31.5° and higher values being obtained for only three samples, all with G'<4Pa.

Figure 36 – Gel-protein rheological measurements



Gel-protein rheology is considered to have potential for predicting breadmaking quality and is used for this purpose as part of the National and Recommended List trialling systems. Loaf quality assessments were shown in Tables A.5a and b for bread baking tests made with the flours from the 1995 and 1996 harvests. One parameter of interest is the loaf volume. Figure 37 shows the relationship between loaf volume and gel-protein elastic modulus, *G*'. Optimum breadmaking performance is commonly expected for flours with a *G*' value of approximately 15 to 40Pa. It can be seen that maximum loaf volume was indeed obtained for flours in this range, including in particular the Hereward samples. This is consistent with the observations of Pritchard and Abel (1993) on flours with *G*' in the range of 7.15 to 57.05Pa. Pritchard and Abel saw evidence of a decline in loaf volume for the highest values of *G*' in their study. The results of this study confirm this for higher values of *G*' measured for some examples of Soissons and Cadenza in 1995 and 1996. No such decline was seen for examples of 1998 flours with high *G*'. Nevertheless, it should be concluded that high values of *G*' indicate a risk of poor breadmaking performance.

Figure 37 – Loaf volume against gel-protein elastic modulus, *G*'



3.8.1.4 Gel-protein rheology using a TA CSL$^2{}_{100}$ rheometer

The Bohlin VOR rheometer is an expensive instrument with greater versatility than required for measurement of *G'*. Tests of a simpler rheometer were therefore made to assess whether comparable results could be obtained with cheaper equipment. Figure 38 shows a comparison of typical gel-protein rheology measurements made using the Bohlin VOR and the TA CSL$^2{}_{100}$ rheometers. For each flour, two curves (dashed) are shown representing replicate frequency sweeps for the Bohlin rheometer, and one curve (solid) representing a frequency sweep over the same range for the TA rheometer. In all cases, the elastic and viscous moduli increased with increasing frequency. The measured frequency responses were different for the two rheometers, although reasonable agreement was achieved at some frequencies. The enlarged points on the graph indicate the results obtained at a frequency of 1Hz, which is the same frequency as the method used for the *G'* results reported above.

Figure 38 – Comparison of gel-protein rheology measurements with Bohlin VOR and TA CSL$^2{}_{100}$ rheometers

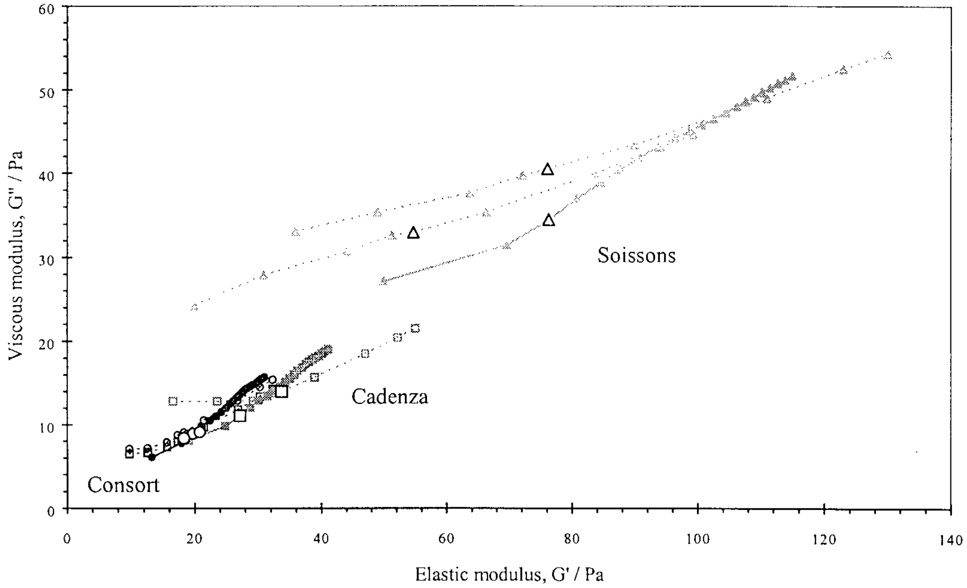


Table 7 – Statistics for replicate measurements of Gel-protein elastic modulus, G', at 1Hz

Sample	TA CSL$^2{}_{100}$ rheometer		Bohlin VOR rheometer	
	Mean (Pa)	Std. dev. (Pa)	Mean (Pa)	Std. Dev. (Pa)
Control	36.7	2.8	39.2	6.0
Cadenza	29.5	4.2	38.1	6.2
Soissons	61.5	10.1	58.1	9.0
Consort	17.0	2.3	21.6	3.2

Replicate gels were prepared for eight subsamples of a control flour and four subsamples each of the Consort, Cadenza and Soissons flours shown in Figure 38. Each gel was subdivided. One half was tested with the TA CSL$^2{}_{100}$ rheometer and the other half was simultaneously tested with the Bohlin VOR. Within the time taken for the TA measurement, two determinations were made with the Bohlin and the mean value was calculated. Table 7 shows the mean and standard deviation of the *G'* values at 1Hz for the replicate gels. It can be seen that the TA rheometer gave similar results to the Bohlin, with the exception of the Cadenza sample for which it gave a lower value. In all but one case, the repeatability was better for the TA rheometer. On the basis of these results, the TA CSL^2_{100} showed good potential for use as a cheaper alternative to the Bohlin VOR rheometer for testing of gel-protein elastic modulus, and offers encouragement that other, simpler rheometers may also be suitable for use in this test. However, before implementation of the test on a second instrument of any type, a more comprehensive calibration would first be necessary.

3.8.1.5 Ultrasound measurements of gel-protein

For many materials, sound propagation characteristics are affected by the density and rheology of the material. Typically, the wave speed increases with increasing elastic modulus and decreasing density, and attenuation is greater for viscous materials than for elastic materials. It was therefore considered that the sound propagation characteristics of gel-protein samples might provide a comparative measurement of their rheological properties, and might be used as the basis of a cheaper alternative to the use of a rheometer. Samples of gel-protein were placed in cuvettes and the time required for ultrasound pulses to pass through them was measured.

Figure 39 – Propagation times for ultrasound through Gel-protein samples and other materials

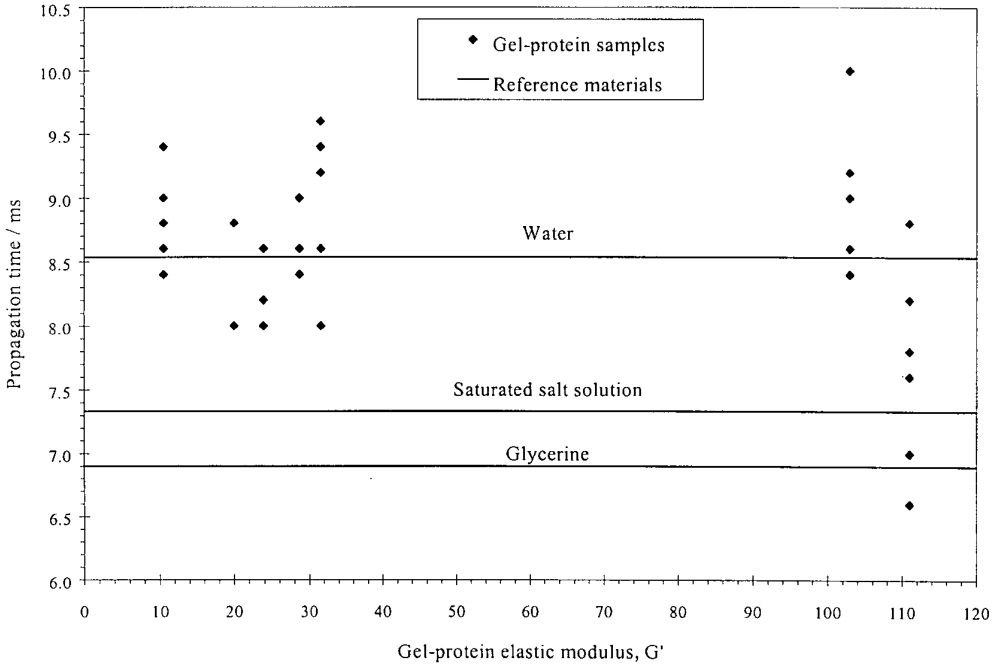


Figure 39 shows replicate determinations of the propagation times for gel-protein samples extracted from seven different flours, compared with the elastic modulus measured for the same gels. The measurements shown were made using separate transmitter and detector transducers for a single passage through the gel-protein sample. For comparison, mean values are shown for three reference materials (distilled water, saturated salt solution and glycerine). These were used to establish the validity and repeatability of the measurement technique, and were well discriminated from one another, giving standard deviations of 0.3s between replicate samples of each material. However, the gel-protein samples were poorly discriminated from one another and, despite a wide range of rheological properties, no effect on the propagation time could be seen. Measurements were also made using a double transit through the sample, and with a range of pulse shapes, but showed no improvement. The failure to establish a relationship between gel-protein elastic modulus and wave speed may be due to variability in the density of the samples, which can also be expected to influence the wave speed. However, it is also possible that the failure to observe an effect arose from inconsistencies in the sample presentation. In particular, it was difficult to achieve a reliable packing of the samples into the cuvettes without trapping air bubbles, and these may have affected the measurements. In contrast, more consistent results were achieved for the reference materials which were all liquids and could be poured into the cuvettes without air bubbles. Subjectively, there appeared to be differences in attenuation of ultrasound between different gel-protein samples and measurement of this might be a possible alternative to measurement of wavespeed. However, even greater care would be required in sample presentation in order to ensure consistent coupling between the transducer(s) and the cuvette, and no systemmatic measurements of attenuation were made. Despite the failure of these experiments to discriminate gel-protein samples on the basis of their sound propagation characteristics, the possibility still remains that such a method may be applicable with better sample presentation.

3.8.2 Oscillatory measurements of doughs

Dough rheology was tested using a Bohlin VOR rheometer for both bread and biscuit doughs. Each dough was subsampled after mixing. The subsamples were first tested in triplicate under oscillatory conditions and were then tested in duplicate under stress relaxation conditions. Results are shown in Tables A.8a,b and A.9a,b for the bread and biscuit doughs respectively, and are plotted in Figures 40 and 41. Measurements were only made for the 1995 and 1996 samples.

A comparison reveals that the modulus of bread doughs was lower than that of biscuit doughs, and that the phase angle was also lower on average, suggesting that bread doughs are primarily elastic in nature, whereas biscuit doughs have a greater viscous component.

For biscuit doughs, the highest modulus values were measured for Riband, the next highest for Beaver and Hunter and the lowest for Soissons, thus reversing the trend seen for the gel-protein extracts. For bread doughs, a similar trend was seen, with the highest moduli being measured for samples of Hunter and the lowest for CWRS. Overall, however, these trends were weak and considerable overlap in moduli was seen between varieties. The lack of a strong effect of flour type on dough modulus may result from the fact that dough water addition is adjusted for each flour in an attempt to achieve a uniform dough consistency (as measured with a Farinograph for breadmaking purposes and an extrusion test for biscuit doughs). Standardisation of the torque developed by a dough during mixing, or of the resistance to extrusion may also result in more consistent torque measurements under low strain conditions or may at least serve to eliminate any differences resulting from variations in flour properties. The reversal of the trend in modulus between gel-protein extracts and doughs may result from the contribution that starch makes to dough properties. The samples with the lowest gel-protein moduli also tend to have low water absorptions, resulting from low starch damage and low protein content. For the large strains used to determine water absorption, the flow characteristics are likely to be strongly affected by the characteristics of the protein, with the starch granules carried as particles in the protein matrix. However, for the small strain properties measured with the Bohlin rheometer, the rheology of the starch granules may contribute to a larger extent, possibly accounting for the high moduli measured for doughs with low water absorption in which fewer hydrated damaged granules are present.

Figure 40 - Bread dough rheology

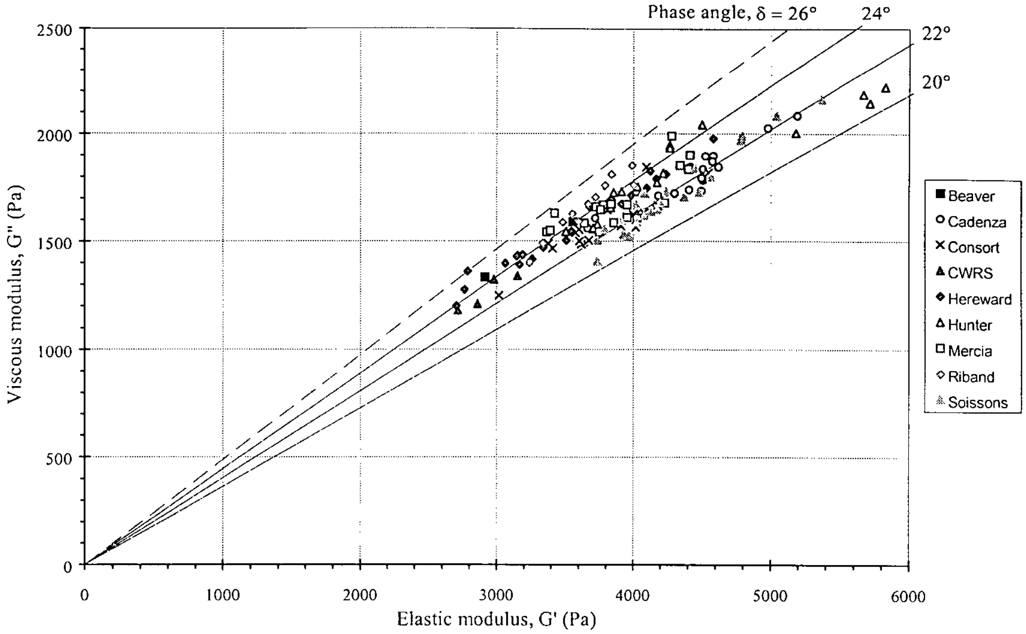
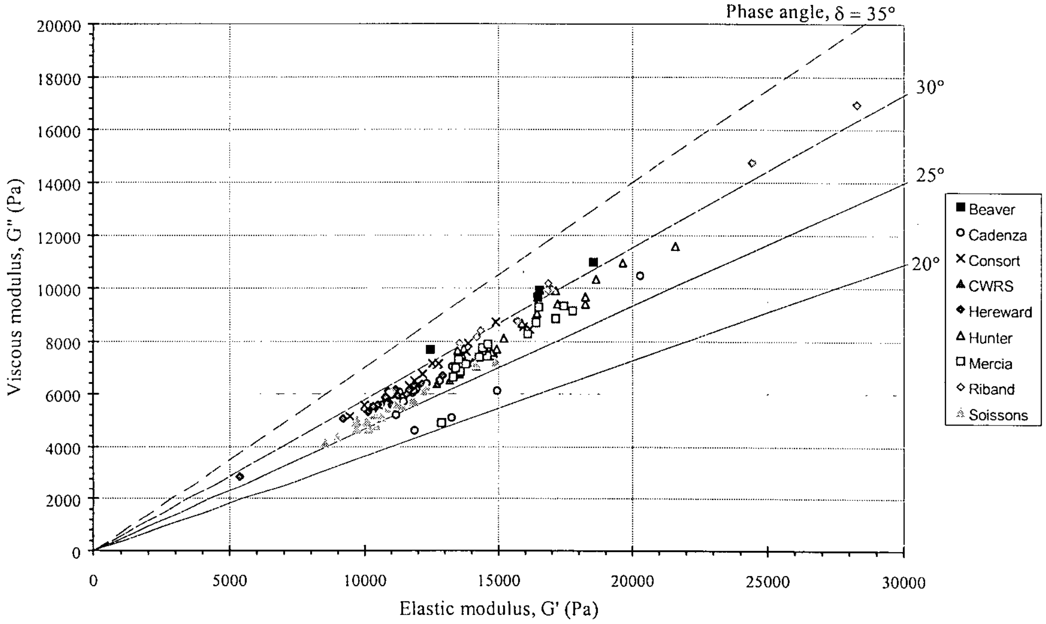
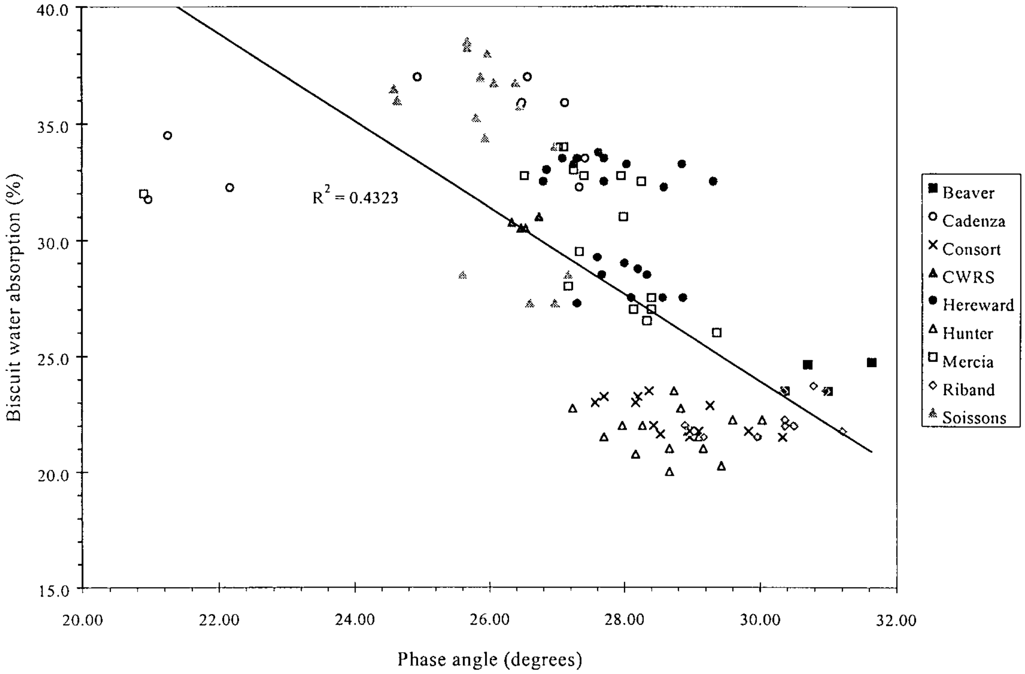


Figure 41 – Biscuit dough rheology



Although dough modulus showed little ability to discriminate flours, phase angle had greater potential. It can be seen from Figures 40 and 41 that there is some grouping of the varieties according to phase angle. For bread doughs, no clear relationship could be detected between the phase angle and the product quality attributes. However, for the biscuit doughs, a correlation of R^2=0.37 was seen between phase angle and biscuit texture. A stronger correlation of R^2=0.43 was seen with biscuit dough water absorption, as shown in Figure 42. It is therefore likely that differences in dough water content are the cause of the differences in dough rheology, and that the correlation with biscuit texture may be a consequence of the previously observed association of hard wheat varieties with high water absorption and with hard biscuit texture. The effect of varying water addition on biscuit dough rheology has been studied previously (Sahi and Guy, 1998). Further results from the same study showed a decrease in phase angle with increasing water content of doughs made from single flour samples (Sahi, private communication). The effect was of similar magnitude to that seen in Figure 42, but the sensitivity of phase angle to water addition varied between samples. It may be concluded that although the phase angle of biscuit doughs is partially influenced by flour properties, much of the variation seen in Figure 42 can be attributed simply to the differing water content of the doughs tested.

Figure 42 – Biscuit water absorption against biscuit dough phase angle



3.8.3 Stress relaxation measurements of doughs

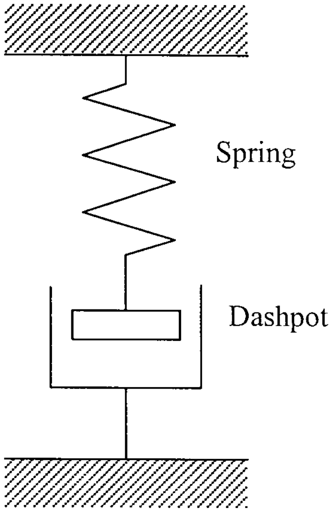
After the oscillatory measurements of doughs had been made, samples were tested under stress relaxation conditions. Due to the time taken for the oscillatory measurements, these measurements were made about 5 to 10 minutes after mixing. Each dough sample was measured twice. A torsional strain was applied and the stress was measured as a function of time. This was normalised by the applied strain and the data were recorded as relaxation modulus values. The data were exported to a spreadsheet for analysis.

The average relaxation modulus for replicate doughs and for the replicate measurements of each dough was calculated at a time of 0.32 s after application of the strain, and is given in Tables A.8a and b for bread doughs, and in Tables A.9a and b for biscuit doughs. As for the moduli measured under oscillatory conditions, the values were higher for biscuit doughs than for bread doughs, indicating that biscuit doughs were stiffer. However, no clear trends could be seen within the data for either dough type and no meaningful varietal discrimination or correlation with final product quality attributes could be discerned.

To assess the potential of stress-relaxation measurements of dough more thoroughly, the full stress-relaxation curves were analysed and attempts were made to fit models to these data.

Many viscoelastic materials can be modelled by a simple linear system consisting of an elastic component (modelled as a spring) for which the stress is proportional to the strain, and a viscous component (modelled as a dashpot) for which the stress is proportional to the rate of change of strain. For stress relaxation conditions, the appropriate configuration is one in which the spring and dashpot are connected in series. This is known as the Maxwell model (Figure 43). The analysis is equally applicable to torsional as well as linear strain.

Figure 43 – The Maxwell model of a linear viscoelastic material



For the spring (elastic element), the stress is given by

$$\sigma = E\varepsilon_{spring} \tag{48}$$

where E is the elastic modulus and ε is the strain.

For the dashpot,

$$\sigma = \eta \frac{d\varepsilon_{dashpot}}{dt} \tag{49}$$

where η is the viscous modulus.

Under stress relaxation conditions, a constant strain is applied, so

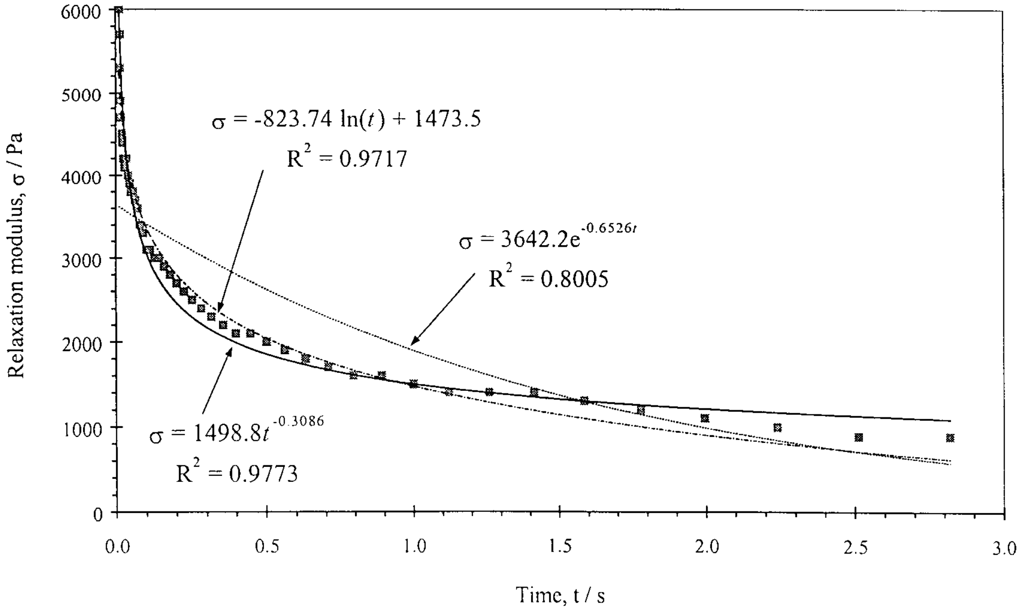
$$\frac{d(\varepsilon_{spring} + \varepsilon_{dashpot})}{dt} = 0 \tag{50}$$

This leads to the following model for the time dependence of the stress:

$$\sigma = \sigma_0 \exp\left(\frac{-Et}{\eta}\right) \tag{51}$$

where σ_0 is the initial stress at t=0. This describes an exponentially decaying stress with a time constant of η/E.

Figure 44 – Fitting of several trends to a bread dough stress relaxation curve.



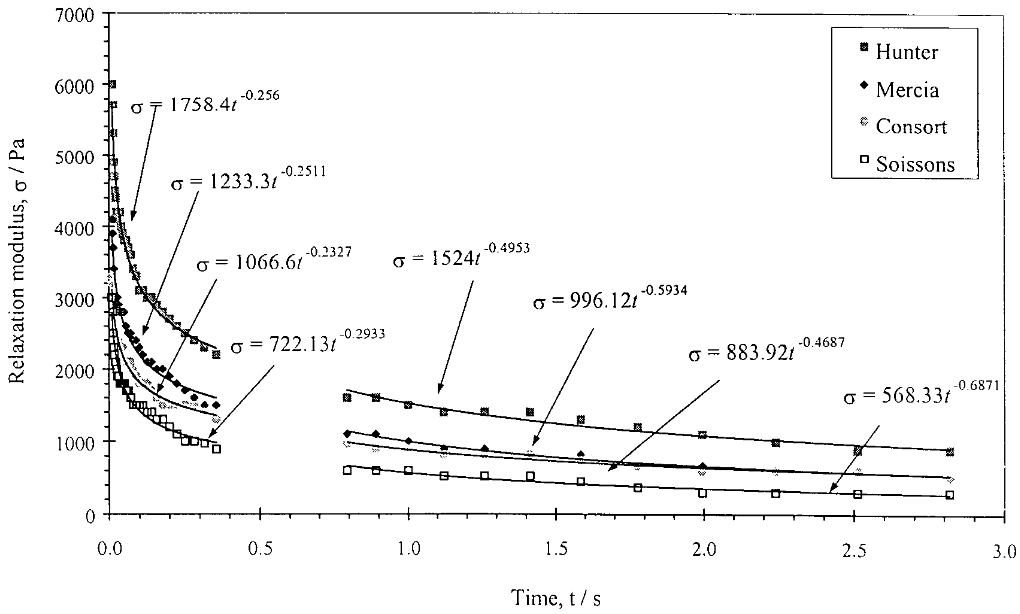
The data obtained from the stress relaxation measurements of dough were analysed to determine whether they could be adequately modelled in this way and whether time constants could be calculated which would provide a useful measurement of the dough properties.

Figure 44 shows several formulae fitted to a typical stress relaxation curve for a bread dough. It can be seen that an exponential relationship is a poor fit to the experimental data, and that better fits were obtained with power law or logarithmic relationships. However, it was apparent from analysis of many datasets that such curves did not provide a satisfactory fit over the full duration of the test, and that different behaviour was seen over short and long time intervals. This is common in many real materials which may contain several components with differing relaxation times. Such materials can often be modelled by several Maxwell elements in parallel, in which case the total stress is the sum of a series of exponentially decaying terms. For the dough measurements, however, fits of a sum of exponential terms provided little improvement over the simpler models shown in Figure 44. Instead, the best fit to the data was found by subdividing each curve into short and long term responses, to which separate power law curves were fitted. The transition between the different responses occurred at about 0.5 s after application of the strain, although the exact timing varied and there was a period of transition between the two responses. To avoid this period, data up to a time of 0.355 s were selected for fitting of a short term response, and data between 0.794 s and 2.818 s (the end of the test) were used to model the long term relaxation, as follows:

$$\begin{aligned} \sigma &= a_{short} t^{-1/b_{short}} && \text{for } 0.000 \le t \le 0.355 \text{ s} \\ \sigma &= a_{long} t^{-1/b_{long}} && \text{for } 0.794 \le t \le 2.818 \text{ s} \qquad (52) \end{aligned}$$

where σ is the relaxation modulus, t is the time in units of seconds and a and b are the power law constants. Figure 45 shows examples of fitting this model to data from samples of four different varieties.

Figure 45 – Power law fits to stress relaxation curves for bread doughs over two time periods.



The values of the constants a_{short}, b_{short}, a_{long} and b_{long} were calculated for each dough sample by least squares regression. Figures 46 to 49 show the range of values obtained for each variety. Although there are some apparent varietal differences, no strong relationships were seen, and the results showed no correlation with final product quality attributes such as loaf volume.

Figure 46 – Variation in the stress relaxation parameter a_{short} for bread doughs

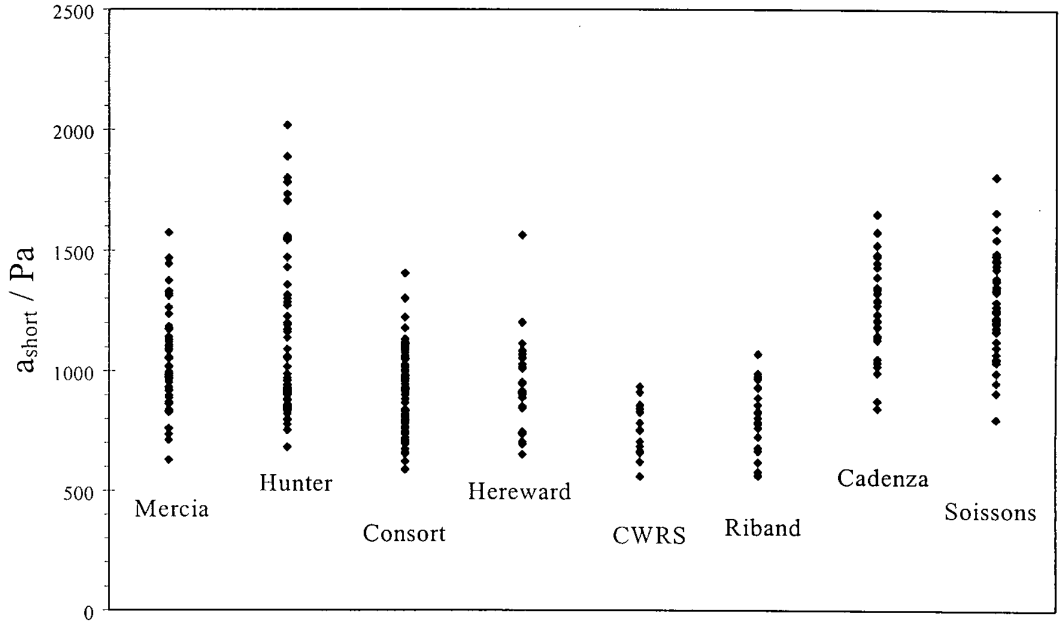


Figure 47 - Variation in the stress relaxation parameter b_{short} for bread doughs

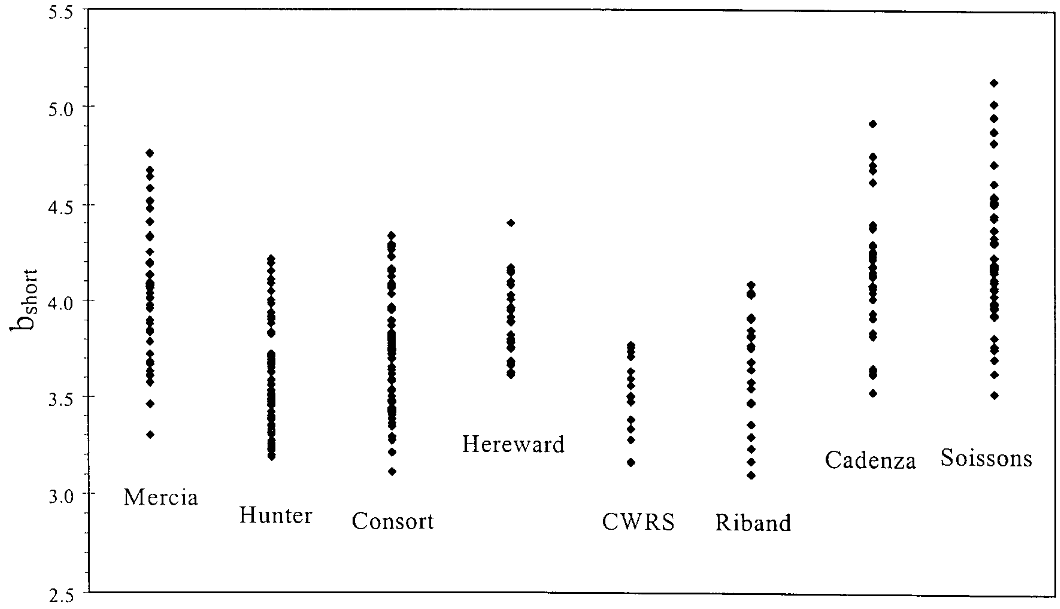


Figure 48 - Variation in the stress relaxation parameter a_{long} for bread doughs

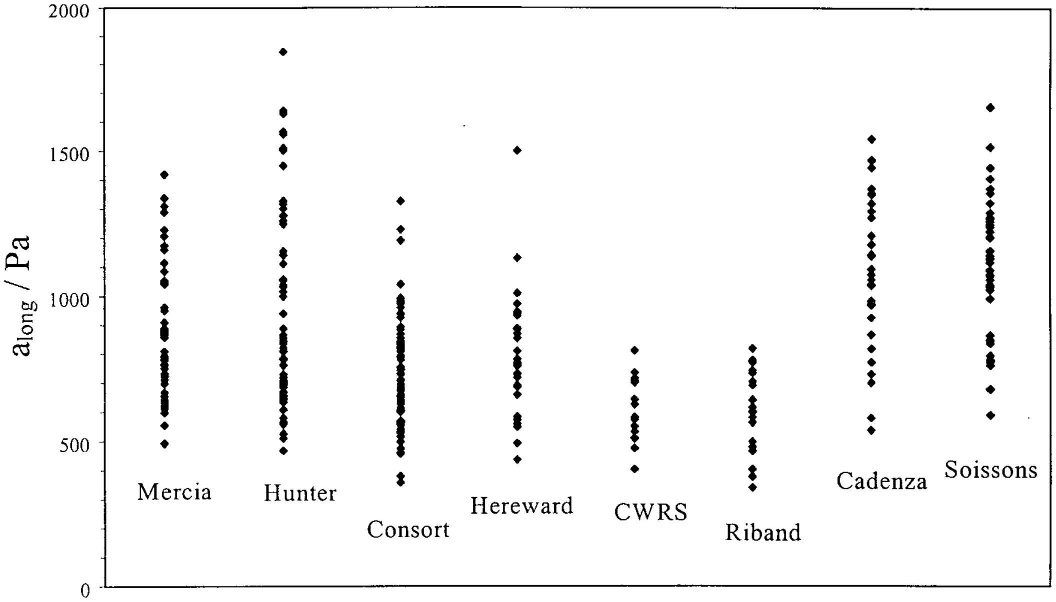
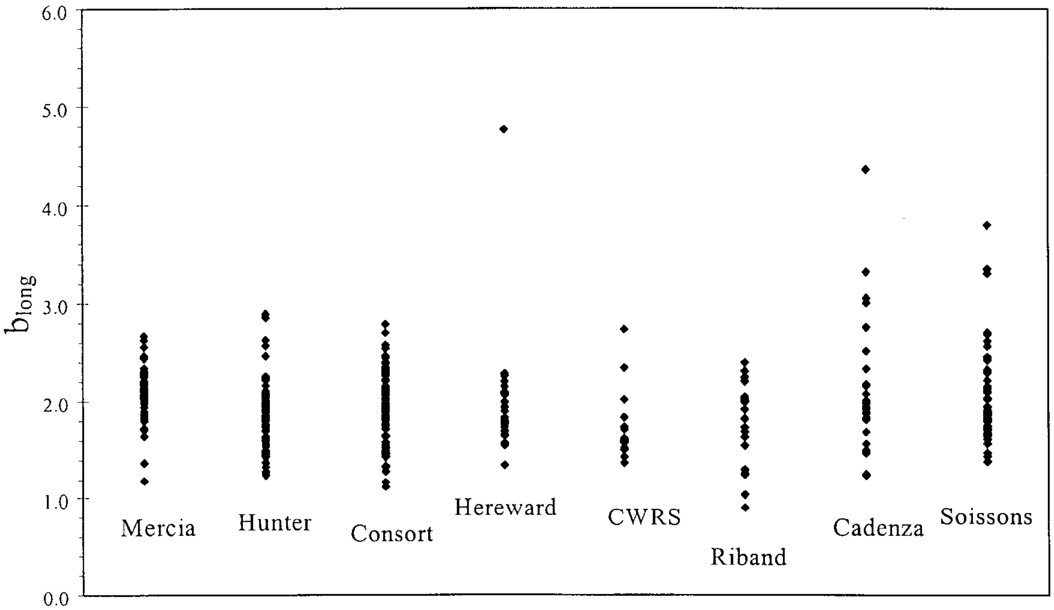


Figure 49 - Variation in the stress relaxation parameter b_{long} for bread doughs



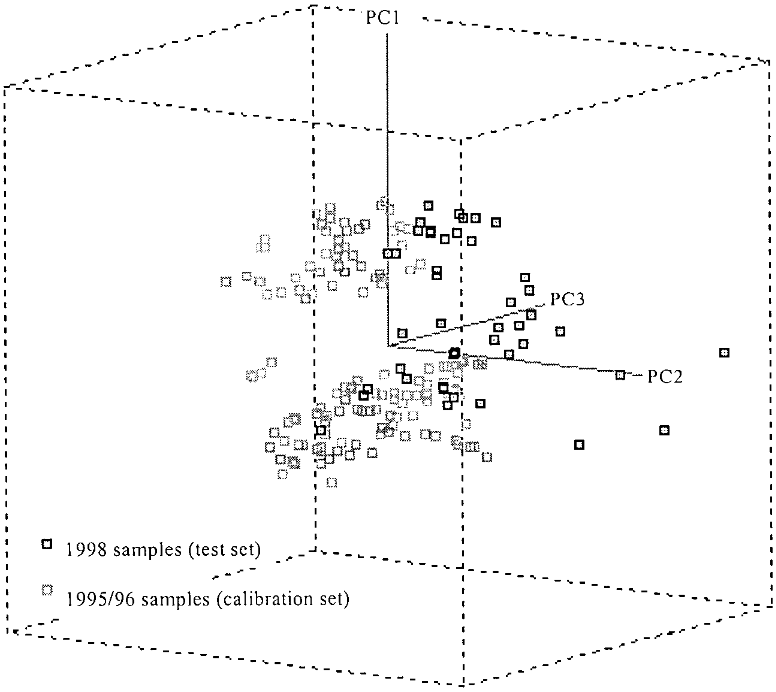
Similar stress relaxation curves were obtained for biscuit doughs, although with higher magnitudes of stress, as previously seen in Figures 40 and 41 as a difference in the moduli of biscuit and bread doughs. The curves for biscuit doughs were analysed in a similar manner. Again, slight differences were seen in the range of fitted parameters for doughs prepared from different varieties, but no trends with established flour properties, or with final product quality were seen.

Overall, small strain rheological measurements of doughs showed little potential for predicting baking performance in either bread or semi-sweet biscuit processes. The measurements showed some dependence on the water content of the doughs, but it is thought that the suitability of different flours for particular baking processes is more strongly dependent on the rheological characteristics of doughs at high strains. Although it is conceivable that some such differences might also influence low strain behaviour, this did not appear to be the case.

3.9 Near infra-red spectroscopy

NIR spectra were obtained for almost all the flour samples, and were used to test the possibility of developing calibrations for several of the flour and product quality attributes. Figure 50 shows a plot of the first three principal components for all the spectra measured. The samples were separated into two distinct populations by the first principal component. The upper group in Figure 50 contained the soft group 3 and 4 varieties, and the lower group contained the hard group 1 and 2 varieties. It can be seen that the 1998 samples were distinctly different in properties from the 1995 and 1996 samples, as quantified by principal components 2 and 3. Variations are often seen between NIR spectra of samples from different harvests, and it is important to include samples with a wide range of properties in calibrations in order that they remain robust when applied to samples from a new crop year. Because of the limited range of samples available in this project, however, the 1995 and 1996 samples were used to develop calibrations and the 1998 samples were used as an independent set of samples to test the calibrations. This demonstrated the potential of NIR for measuring particular flour properties. However, for practical calibrations, a wider range of samples would be appropriate. The four points to the right of Figure 50 with the highest values of principal component 2 were samples of CWRS. These samples are notable as having the highest protein content of all the samples tested. Examination of the spectral loadings for principal component 2 suggested that protein was an influence on this component, and this may therefore explain why these samples have such extreme values on this axis.

Figure 50 – NIR principal component (PC) scores for the calibration spectra (1995/96 samples) and test spectra (1998 samples)



Calibrations were developed and tested for the following measurements:

- Starch damage
- Water absorption (Farinograph)
- Resistance (Extensograph)
- Extensibility (Extensograph)
- Gel-protein mass
- Gel-protein elastic modulus
- Loaf volume
- Bread crumb score (visual)
- Bread crumb colour (Hunterlab)
- Biscuit water absorption (extrusion test)
- Biscuit eccentricity
- Biscuit texture

No attempt was made to test calibrations against flour moisture and protein content, since the capabilities of NIR spectroscopy for these purposes are already well established and since the 'reference' values had themselves been measured by NIR.

On the basis of the first principal component, one sample of Beaver (starch damage level SD1) was grouped among the hard varieties and one sample of Hereward (1995 harvest, wheat No. 1, starch damage level SD1) was grouped among the soft varieties. These samples consistently appeared as outliers in calibrations, and it was therefore suspected that these samples may have become transposed during sampling for NIR scanning. These samples were therefore removed from the calibration set and are not included in the calibration statistics, although they have been included in Figures 51 to 53 below for completeness.

Good correlations with the reference data for the calibration samples were obtained for many of the measurements. However, the only calibrations that also gave good correlations when tested against the prediction sample set were those for starch damage, Farinograph water absorption and biscuit water absorption. Statistics for these calibrations are shown in Table 8. Graphs are shown in Figures 51 to 53 showing comparisons between the values predicted by NIR and the measured values for each of these calibrations. The calibrations generally performed well despite the differences in spectra between the calibration and prediction set shown in Figure 50. For example, although the Farinograph water absorption of several of the prediction samples was higher than the range of calibration values, the calibration still performed well over this extended range. In section 3.3.1, modelling of water absorption as a function of starch damage, moisture and protein content gave inconsistent results for the 1995/96 and the 1998 samples. The fact that an NIR calibration based on the former samples also performed well for the latter suggests that an improved model should be possible, based only on simple properties of the flours likely to be measurable in the NIR spectrum.

Table 8 – Performance statistics for NIR calibrations

Measurement	Calibration set		Prediction set				
	Standard error of calibration (SEC)	**R^2**	**Standard error of prediction (SEP)**	**R^2**	**Bias**	**Slope**	**Standard error of prediction after bias correction (SEP(C))**
Starch damage (Farrand)	3.4405	0.920	5.592	0.710	-1.437	0.973	5.467
Farinograph water absorption (%)	1.1061	0.932	1.809	0.828	-0.457	0.945	1.770
Biscuit water absorption (%) (extrusion test)	1.7935	0.872	2.668	0.793	-1.568	0.841	2.190

Figure 51 – NIR prediction of starch damage against reference values measured by the Farrand method

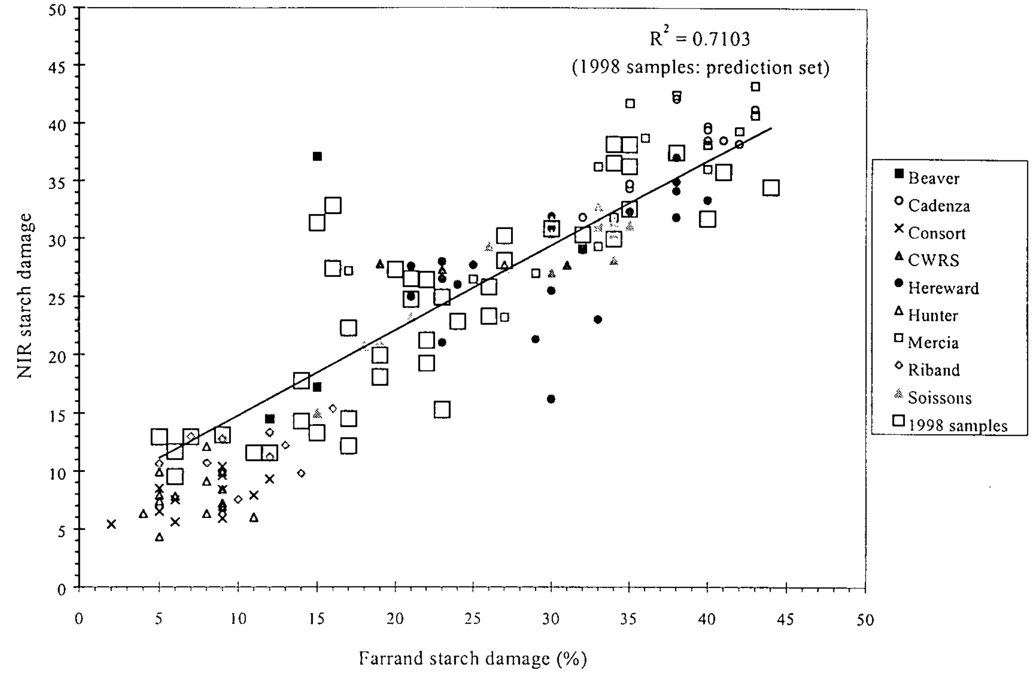


Figure 52 – NIR prediction of water absorption against reference values measured by Farinograph

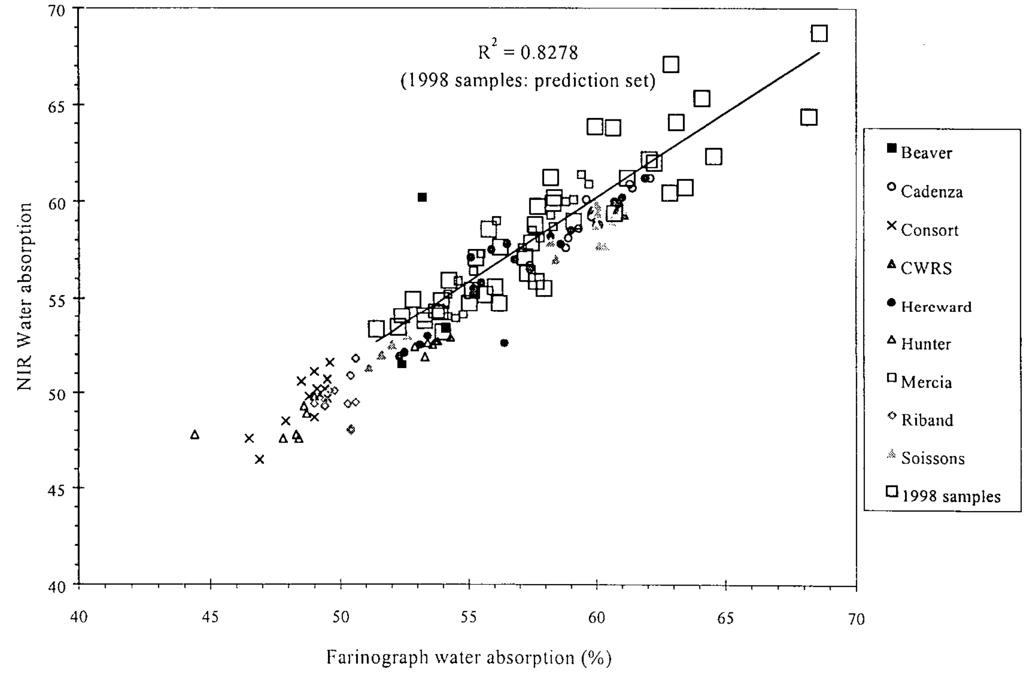
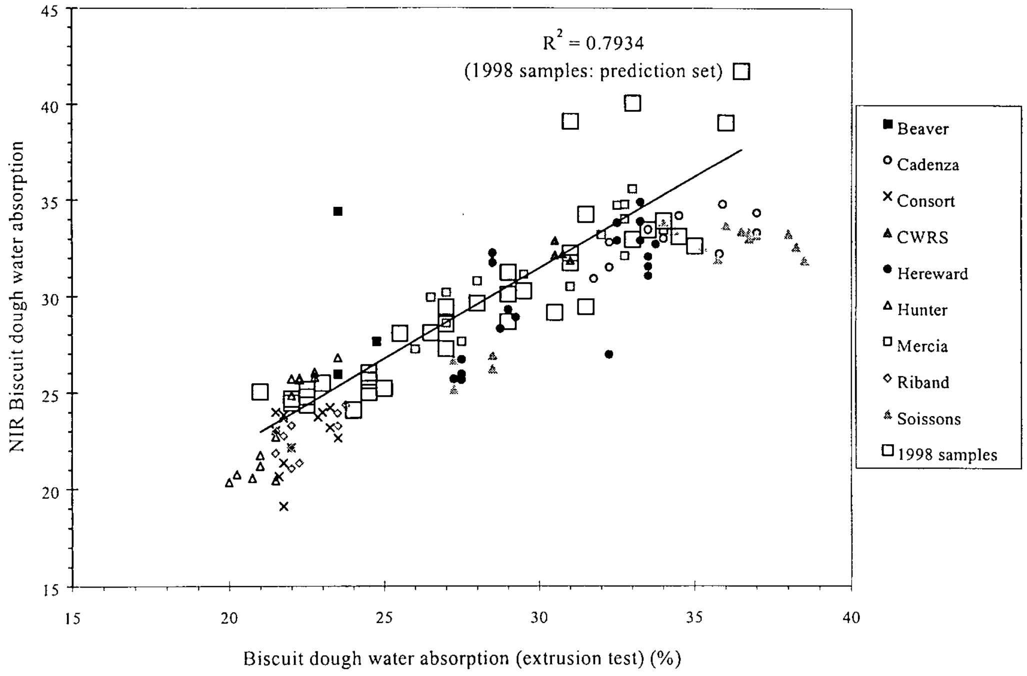


Figure 53 – NIR prediction of biscuit dough water absorption against reference values measured by extrusion



The potential of NIR spectroscopy for prediction of starch damage has been demonstrated previously and calibrations for this have been developed by instrument manufacturers. Moisture content and protein content are the other two major factors which influence water absorption (see section 3.3.1). Since NIR has a good response to both of these, its potential for measuring water absorption is therefore also unsurprising, and calibrations against Farinograph values are in widespread commercial use. Water absorption for biscuits, as measured by the extrusion test, is strongly correlated with Farinograph values, as shown in Figure 9 (section 3.3.3), and therefore also gives a good NIR calibration. To the author's knowledge, NIR is not currently used for this purpose and specifications for biscuit flours are instead based on Farinograph values. However, it can also be seen from Figure 9 that there was a bias (of 2.9%) in the relationship of extrusion and Farinograph values between the 1995/6 and the 1998 samples. Thus, reliance on Farinograph values to determine biscuit water addition could be unreliable. Indeed, application of the regression line from Figure 9 gives a standard error of 3.5% in prediction of biscuit water addition for the 1998 samples. This is greater than the SEP of 2.7% for the NIR calibration, which thus represents an improvement over use of Farinograph values (for this sample set, at least). Flour specifications using calibrations developed specifically for particular biscuit processes may therefore be able to offer improved consistency of flour performance for such applications. For test baking purposes too, NIR may offer benefits. The extrusion test currently used is time consuming, often requires several mixes to be made, and has poor repeatability. An NIR calibration against this test might be a useful rapid, non-destructive alternative. Almost comparable accuracy might be achievable and, if necessary, a single mix could be made to confirm the measurement.

4. Conclusions

Wheat samples of a total of 13 varieties have been collected at several protein contents over three harvest years (1995, 1996 and 1998). Of 66 wheat samples received, 60 have been laboratory Buhler milled to create a total of 186 flours with up to 4 levels of starch damage per wheat. These flours and their parent wheats have been subjected to a wide range of quality tests. Test baking of bread and of semi-sweet biscuits has also been conducted, including rheological testing of the doughs produced for the 1995 and 1996 harvest samples.

The work has demonstrated that many of the flour quality tests in use today have the capability to distinguish the widely differing baking properties of **nabim** group 1 and 2 wheats from those of groups 3 and 4. However, test baking remains the most effective method of discriminating performance within these populations. It was found that water absorption is a significant contribution to results measured by many current methods based on dough rheology at constant hydration. Improvements in the Farrand equation for prediction of Farinograph water absorption were developed. This equation is based on starch damage, protein and moisture content. However, it did not adequately predict an increase in average water absorptions between 1995/96 and 1998, suggesting that additional factors also need to be included. Water absorptions measured by the new Consistograph instrument did not show a simple relationship with Farinograph values, and could not be modelled so effectively in this way. An effective NIR calibration was demonstrated for Farinograph water absorption, and such calibrations are already in use in industry. It was shown that an effective calibration could also be developed against the dough extrusion test used for biscuit water absorption, and that this provided a better prediction of biscuit water absorption than a value based on a Farinograph measurement. The adoption of such a system in biscuit flour specifications might therefore provide an improvement on current practice.

For breadmaking performance, gel-protein rheology remains one of the most useful small-scale tests, but involves expensive equipment. It was shown that a simpler rheometer than the Bohlin VOR currently used could provide comparable results; however, the cost still remains significant. Small-scale rheological tests of doughs showed little potential for prediction of processing performance, and it is appropriate to concentrate attention on large strain tests, which have greater relevance to typical processing conditions. Among such tests, the Alveograph is not widely used in the U.K., but showed promise for measurement of breadmaking potential. The new Stable Micro Systems D/R instrument also provided reasonable agreement with the Alveograph, and offers a promising alternative to it. The Alveograph P value clearly discriminated group 1 and 2 wheats from group 3 and 4 wheats. No such discrimination existed under adapted hydration conditions and this discrimination is therefore probably partially due to differences in water absorption. The L parameter, and its equivalent, A, under adapted hydration showed some correlation with loaf volume. This alone, however, is insufficient since some samples produced loaves of high volume, but which were otherwise of poor quality. A good prediction of overall breadmaking quality was provided by W, which was similar to that provided by gel protein elastic modulus. A more fundamental understanding of dough rheology was obtained by transforming Alveograph data into stress-strain relationships, a calculation which the D/R system performs automatically. Considered on this basis, it was apparent that dough extensibility was determined by the strain hardening properties of the dough. A combination of rheological properties, σ^*, was identified which provided optimal discrimination of flours on a varietal basis. This measurement was very similar to *W* in its predictive capability.

For biscuitmaking performance, samples could be subdivided into two populations: Hard group 1 and 2 wheats had high water absorption and produced biscuits with an unacceptably hard texture and a high moisture content. Soft group 3 and 4 wheats were more suitable for biscuitmaking and produced biscuits with softer texture and lower moisture. Many tests were able to discriminate these two populations. However, no effective prediction of quality within the group 3 and 4 wheats could be found, including methods currently relied on for this purpose. This may reflect the difficulty in obtaining consistent baking quality under small-scale test baking conditions, particularly in the absence of SMS.

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Appendix – Tables of data

Table A.1a - Flour properties for samples from the 1995 harvest

Wheat Variety	Nominal Starch Damage	Falling number (s)	Starch damage (Farrand)	Flour protein (%)	Flour moisture (%)	Total pentosans (%)	Soluble pentosans (%)
Beaver	LOW	312	12	7.2	12.8	1.80	0.62
	SD1	302	15	7.3	12.5	1.87	0.58
	SD2	309	15	7.5	12.4	1.96	0.56
	HIGH	307	15	7.7	12.4	1.92	0.56
Cadenza No. 1	LOW	357	32	7.8	13.2	1.76	0.44
	SD1	358	38	8.0	13.2	1.89	0.38
	SD2	359	40	8.0	13.1	1.83	0.42
	HIGH	357	40	8.2	12.9	1.94	0.43
Cadenza No. 2	LOW	388	35	9.1	13.8	1.74	0.43
	SD1	397	42	9.4	13.7	1.98	0.47
	SD2	396	44	9.7	13.5	1.95	0.44
	HIGH	396	43	9.6	13.5	1.80	0.38
Cadenza No. 3	LOW	429	35	10.1	14.0	1.76	0.47
	SD1	421	41	10.2	13.8	2.02	0.44
	SD2	429	40	10.4	13.7	1.91	0.45
	HIGH	446	38	10.5	13.5	1.78	0.44
Consort No. 1	LOW	324	5	7.6	13.5	1.39	0.46
	SD3	320	6	7.4	13.6	1.37	0.34
	HIGH	328	9	7.4	13.6	1.43	0.38
Consort No. 2	LOW	378	5	8.8	13.6	1.41	0.41
	SD3	395	11	8.9	13.5	1.35	0.33
	HIGH	402	9	8.9	13.5	1.37	0.36
CWRS	LOW	444	31	13.3	14.7	1.63	0.43
	SD1	458	23	13.3	14.8	1.73	0.46
	SD2	454	27	13.0	14.9	1.54	0.45
	HIGH	460	19	13.1	14.9	1.55	0.44
Hereward No. 1	LOW	415	30	8.4	13.4	1.32	0.39
	SD1	393	30	8.7	13.5	1.42	0.40
	SD2	416	32	8.8	13.3	1.41	0.43
	HIGH	424	30	8.7	13.2	1.47	0.40
Hereward No. 2	LOW	374	40	9.6	13.5	1.40	0.44
	SD1	371	38	9.9	13.4	1.55	0.37
	SD2	401	38	10.0	13.2	1.58	0.39
	HIGH	407	38	10.1	13.0	1.50	0.39
Hereward No. 3	LOW	392	30	10.0	13.4	1.39	0.36
	SD1	400	35	10.3	13.1	1.46	0.39
	SD2	325	38	10.5	12.9	1.46	0.42
	HIGH	413	38	10.9	12.9	1.27	0.34
Hunter No. 1	LOW	384	5	9.2	12.8	1.83	0.65
	SD1	377	8	9.1	12.7	1.81	0.60
	SD2	362	9	9.0	12.6	1.86	0.54
	HIGH	380	5	9.0	12.5	1.73	0.73
Hunter No. 2	LOW	405	8	8.6	13.0	1.90	0.54
	SD1	425	5	8.6	12.9	1.73	0.61
	HIGH	413	11	8.7	12.7	1.65	0.55
Mercia No. 1	LOW	379	40	8.9	13.3	1.49	0.43
	SD1	381	42	8.8	13.2	1.48	0.33
	SD2	397	35	8.0	13.3	1.36	0.32
	HIGH	411	43	9.3	13.5	1.49	0.26
Mercia No. 2	LOW	358	32	9.1	14.5	1.49	0.42
	HIGH	377	33	9.1	14.4	1.25	0.40
Mercia No. 3	LOW	395	34	10.4	13.9	1.52	0.30
	SD1	439	40	10.4	13.5	1.56	0.33
	SD2	421	43	10.5	13.6	1.73	0.34
	HIGH	428	38	10.7	13.5	1.65	0.25
Riband No. 2	LOW	303	10	7.2	13.5	1.24	0.37
	SD1	302	14	7.6	13.5	1.36	0.38
	SD2	305	9	7.7	13.4	1.57	0.39
	HIGH	333	16	7.3	13.3	1.35	0.40
Soissons No. 1	LOW	370	30	10.3	13.2	1.11	0.37
	SD1	364	27	10.3	13.3	1.12	0.33
	SD2	400	26	10.6	13.0	1.22	0.33
	HIGH	395	34	10.9	13.1	1.21	0.36
Soissons No. 2	LOW	416	34	10.8	13.0	1.34	0.32
	SD1	434	34	11.1	12.8	1.23	0.37
	SD2	421	30	11.5	12.9	1.33	0.37
	HIGH	438	30	11.3	12.8	1.35	0.37
Soissons No. 3	LOW	389	33	10.8	13.2	1.32	0.29
	SD1	414	35	11.1	13.5	1.28	0.33
	SD2	419	33	11.2	13.3	1.53	0.34
	HIGH	388	33	11.2	13.8	1.30	0.38

Table A.1b - Flour properties for samples from the 1996 harvest

Wheat Variety	Nominal Starch Damage	Falling number (s)	Starch damage (Farrand)	Flour protein (%)	Flour moisture (%)	Total pentosans (%)	Soluble pentosans (%)
Cadenza No. 1	LOW	399	27	9.7	14.5	1.04	0.46
	SD1	377	28	9.7	14.5	1.75	0.73
	SD2	374	30	9.8	14.5	1.81	0.43
	HIGH	376	33	9.7	14.5	1.57	0.48
Cadenza No. 2	LOW	371	29	8.7	14.5	2.21	0.69
	SD1	363	28	8.6	14.5	1.89	0.44
	SD2	359	27	8.7	14.6	1.55	0.38
	HIGH	382	33	8.6	14.6	1.68	0.71
Consort No. 1	LOW	257	9	8.8	13.6	1.29	0.35
	SD1	263	12	8.9	13.7	1.09	0.55
	SD2	240	5	8.7	13.9	1.19	0.56
	HIGH	259	-	8.7	13.9	1.25	0.41
Consort No. 2	LOW	265	2	7.1	14.2	1.30	0.32
	SD1	271	9	7.1	14.1	1.24	0.48
	SD2	251	9	7.1	14.0	1.30	0.49
	HIGH	266	6	7.0	13.8	1.32	0.31
Consort No. 3	LOW	283	5	8.7	14.0	1.35	0.61
	SD1	270	9	8.7	14.0	1.37	0.60
	SD2	276	9	8.7	14.1	1.44	0.37
	HIGH	267	26	8.7	14.1	1.37	0.61
Hereward No. 1	LOW	370	25	11.6	14.6	1.32	0.36
	SD3	369	24	11.4	14.7	1.31	0.34
	HIGH	374	30	11.3	14.8	1.39	0.42
Hereward No. 2	LOW	365	23	12.1	14.4	1.30	0.38
	SD3	364	21	12.0	14.6	1.18	0.41
	HIGH	364	23	11.7	14.8	1.33	0.33
Hereward No. 3	LOW	349	29	9.6	14.8	1.24	0.42
	SD1	368	23	9.7	14.7	1.35	0.45
	SD2	357	33	9.7	14.8	1.39	0.41
	HIGH	359	21	9.4	14.7	1.42	0.63
Hunter No. 1	LOW	312	9	9.1	13.7	1.76	0.66
	SD3	298	5	9.1	13.7	1.71	0.65
	HIGH	315	8	9.1	13.7	1.78	0.72
Hunter No. 2	LOW	260	4	7.8	13.6	2.03	0.70
	SD1	258	9	8.0	13.6	1.69	0.67
	SD2	261	9	7.9	13.6	1.66	0.51
	HIGH	254	6	8.0	13.3	1.65	0.71
Hunter No. 3	LOW	317	5	9.4	13.7	1.10	0.67
	SD1	322	11	9.4	13.8	1.91	0.70
	SD2	315	13	9.3	13.7	1.65	0.75
	HIGH	316	13	9.4	13.7	1.55	0.69
Mercia No. 1	LOW	428	-	11.0	14.5	1.24	0.39
	SD3	424	36	11.0	14.6	1.54	0.37
	HIGH	419	33	10.8	14.6	1.54	0.40
Mercia No. 2	LOW	353	27	9.2	14.7	1.07	0.30
	SD1	329	17	9.4	14.5	1.23	0.33
	SD2	337	25	9.3	14.4	1.02	0.33
	HIGH	364	29	9.3	14.4	1.35	0.34
Mercia No. 3	LOW	322	29	9.3	14.4	1.53	0.31
	SD1	310	30	9.2	14.4	1.43	0.38
	SD2	313	29	9.1	14.4	1.45	0.49
	HIGH	319	40	9.1	14.4	1.27	0.30
Riband No. 1	LOW	195	5	6.9	14.0	1.01	0.36
	SD1	194	8	6.9	14.0	1.10	0.38
	SD2	193	12	6.8	14.0	1.17	0.37
	HIGH	205	9	6.8	13.9	1.33	0.36
Riband No. 2	LOW	258	13	8.4	13.8	1.37	0.30
	SD3	264	7	8.5	13.9	1.27	0.32
	HIGH	250	12	8.4	14.0	1.22	0.37
Soissons No. 1	LOW	330	15	8.6	14.8	1.26	0.31
	SD1	341	18	8.6	14.7	1.26	0.39
	SD2	349	19	8.7	14.6	1.44	0.30
	HIGH	358	21	8.5	14.7	1.38	0.27
Soissons No. 2	LOW	372	20	11.3	14.8	1.39	0.64
	SD1	376	22	11.4	14.7	1.55	0.38
	SD2	357	20	11.4	14.8	1.34	0.33
	HIGH	383	23	11.4	14.8	1.54	0.34
Soissons No. 3	LOW	331	20	10.3	14.5	1.47	0.29
	SD1	362	20	10.4	14.6	1.37	0.36
	SD2	361	26	10.5	14.6	1.43	0.26
	HIGH	354	42	10.4	14.6	1.42	0.29

Table A.1c - Flour properties for samples from the 1998 harvest

Wheat Variety	Nominal Starch Damage	Falling number (s)	Starch damage (Farrand)	Flour protein (%)	Flour moisture (%)
Cadenza	LOW	272	26	7.8	14.4
No. 1	HIGH	275	27	7.9	14.2
Cadenza	LOW	405	22	10.6	14.8
No. 2	HIGH	376	38	10.7	14.1
Claire	LOW	303	7	9.9	12.9
No. 1	HIGH	304	19	9.8	12.7
Claire	LOW	329	9	9.8	13.5
No. 2	HIGH	323	22	9.6	13.2
Consort	LOW	249	11	8.2	13.6
No. 1	HIGH	245	23	8.2	13.4
Consort	LOW	296	12	10.3	13.5
No. 2	HIGH	298	14	10	13.5
CWRS	LOW	459	16	13.7	14.3
No. 1	HIGH	371	35	13.4	13.9
CWRS	LOW	407	15	14.5	13.8
No. 2	HIGH	412	34	14.7	13.7
Hereward	LOW	292	21	9.8	14.3
No. 1	HIGH	303	23	9.7	14.4
Hereward	LOW	266	24	11.3	15.1
No. 2	HIGH	250	44	11.1	14.5
Hunter	LOW	202	17	9.6	13.5
No. 1	HIGH	208	17	9.5	13.5
Hunter	LOW	301	6	9.9	13.2
No. 2	HIGH	307	15	8.9	13.3
Malacca	LOW	347	30	10.8	13.4
No. 1	HIGH	359	35	10.7	13.5
Malacca	LOW	428	20	11.3	13.6
No. 2	HIGH	414	34	11.1	13.6
Mercia	LOW	312	22	10.3	14.4
No. 1	HIGH	314	32	10.3	14.3
Mercia	LOW	316	21	10.6	14.1
No. 2	HIGH	319	41	10.5	13.8
Riband	LOW	226	6	8.4	13.4
No. 1	HIGH	226	19	8.3	13.1
Riband	LOW	275	5	9.5	13.9
No. 2	HIGH	276	14	9.6	13.7
Soissons	LOW	322	19	9.7	14.4
No. 1	HIGH	315	26	9.7	14
Soissons	LOW	328	17	10.8	14.2
No. 2	HIGH	325	40	10.6	13.6
Spark	LOW	296	27	11.5	14.2
No. 1	HIGH	294	35	11.3	13.5
Spark	LOW	384	16	10.3	14.4
No. 2	HIGH	343	34	10.4	13.7

Table A.2a - Farinograph and Consistograph results for 1995 harvest flours

Wheat Variety	Nominal Starch Damage	Farinograph (300g, 600 line)				Consistograph HYDHA (%)
		Water abs. (%)	Dev. time (min)	Stability (min)	Degree of soft. (BU)	
Beaver	LOW	52.4	1.5	1.0	180	43.5
	SD1	53.2	1.5	1.0	185	41.0
	SD2	54.1	1.5	1.0	190	43.0
	HIGH	55.2	1.5	1.0	210	43.0
Cadenza No. 1	LOW	57.4	1.5	1.3	130	-
	SD1	58.8	1.5	1.8	130	52.0
	SD2	59.6	2.0	2.0	140	53.0
	HIGH	60.1	2.0	2.5	125	52.3
Cadenza No. 2	LOW	58.9	2.0	2.0	67	-
	SD1	59.8	2.0	2.0	90	55.1
	SD2	61.4	1.5	2.0	85	-
	HIGH	61.4	2.3	2.9	85	56.7
Cadenza No. 3	LOW	59.3	2.0	2.5	70	-
	SD1	60.7	2.0	2.3	80	55.2
	SD2	61.3	2.5	2.5	75	54.7
	HIGH	62.1	2.5	2.8	80	55.5
Consort No. 1	LOW	49.5	1.5	1.5	190	48.3
	SD3	49.2	1.0	1.5	185	48.0
	HIGH	49.1	1.0	1.5	160	47.0
Consort No. 2	LOW	48.5	1.5	2.5	130	48.5
	SD3	49.0	1.5	2.5	130	49.0
	HIGH	49.6	1.5	3.0	140	49.3
CWRS	LOW	60.7	4.5	8.0	65	57.4
	SD1	60.8	5.0	8.5	75	59.9
	SD2	59.8	5.0	10.0	50	57.8
	HIGH	61.1	5.0	9.0	60	61.1
Hereward No. 1	LOW	55.6	1.8	1.6	115	51.7
	SD1	56.4	1.8	1.7	130	53.7
	SD2	57.4	1.8	1.5	140	52.4
	HIGH	56.8	2.0	1.7	140	53.7
Hereward No. 2	LOW	58.6	2.0	3.6	105	55.8
	SD1	59.0	2.0	3.7	130	56.1
	SD2	60.1	2.0	3.8	110	55.6
	HIGH	61.0	2.4	3.2	135	55.9
Hereward No. 3	LOW	58.2	3.2	3.5	120	-
	SD1	60.0	2.7	3.1	140	55.5
	SD2	60.9	3.0	3.1	130	55.3
	HIGH	61.9	3.3	2.8	140	57.1
Hunter No. 1	LOW	53.3	1.5	2.0	120	-
	SD1	53.6	1.5	1.5	140	47.5
	SD2	53.4	2.0	2.0	140	47.5
	HIGH	54.3	1.5	2.0	135	47.5
Hunter No. 2	LOW	53.8	1.5	1.5	140	47.4
	SD1	53.7	1.5	1.5	140	46.8
	HIGH	52.9	1.5	1.5	140	47.2
Mercia No. 1	LOW	58.3	1.5	0.8	100	50.7
	SD1	58.2	1.5	1.2	100	51.5
	SD2	59.1	1.7	1.4	115	53.3
	HIGH	59.7	1.8	1.6	115	53.7
Mercia No. 2	LOW	54.6	2.0	2.5	100	54.6
	HIGH	55.2	2.0	2.0	130	-
Mercia No. 3	LOW	55.5	1.6	2.2	42	-
	SD1	56.1	1.6	2.8	50	52.3
	SD2	58.8	2.0	1.8	70	52.9
	HIGH	59.4	2.2	2.3	55	55.6
Riband No. 2	LOW	49.0	1.0	1.2	190	49.1
	SD1	49.8	1.0	1.0	200	48.0
	SD2	50.4	1.5	1.3	200	-
	HIGH	50.6	1.0	1.3	190	47.0
Soissons No. 1	LOW	58.4	9.7	21.5	15	57.1
	SD1	58.2	1.8	11.0	40	56.8
	SD2	60.0	2.0	7.5	60	56.4
	HIGH	60.0	2.5	10.2	45	57.0
Soissons No. 2	LOW	60.1	2.2	2.1	65	54.2
	SD1	60.0	2.0	2.3	85	55.2
	SD2	60.0	2.5	2.6	65	56.2
	HIGH	59.9	2.0	2.3	95	56.1
Soissons No. 3	LOW	60.3	2.0	1.9	80	57.0
	SD1	60.6	2.0	2.2	75	57.2
	SD2	60.4	2.0	2.4	75	57.2
	HIGH	60.0	2.0	2.6	85	57.8

Table A.2b - Farinograph and Consistograph results for 1996 harvest flours

Wheat Variety	Nominal Starch Damage	Farinograph (300g, 600 line)				Consistograph HYDHA (%)
		Water abs. (%)	Dev. Time (min)	Stability (min)	Degree of soft. (BU)	
Cadenza No. 1	LOW	55.7	2.0	3.0	85	55.1
	SD1	56.8	2.0	2.5	90	55.4
	SD2	57.1	2.0	3.0	95	55.5
	HIGH	58.0	2.0	3.0	85	55.3
Cadenza No. 2	LOW	56.1	2.0	4.5	105	55.9
	SD1	57.0	2.0	4.0	105	56.2
	SD2	56.9	2.0	4.5	95	56.1
	HIGH	57.2	2.0	4.0	110	56.1
Consort No. 1	LOW	49.5	1.5	2.0	190	48.7
	SD1	49.5	1.5	2.0	175	49.3
	SD2	49.4	1.5	2.0	200	50.1
	HIGH	48.8	1.5	2.5	160	49.4
Consort No. 2	LOW	46.5	1.0	1.0	180	47.6
	SD1	46.9	1.0	1.5	170	48.1
	SD2	47.9	1.0	1.0	190	48.0
	HIGH	49.0	1.5	1.5	180	48.3
Consort No. 3	LOW	48.4	1.5	3.5	150	48.9
	SD1	48.6	1.5	4.0	140	49.0
	SD2	49.0	1.5	3.5	140	48.3
	HIGH	49.1	1.5	3.5	140	49.5
Hereward No. 1	LOW	55.5	3.5	4.5	105	54.9
	SD3	55.2	3.5	4.5	100	54.9
	HIGH	55.2	3.5	4.5	100	55.5
Hereward No. 2	LOW	56.5	4.0	4.5	110	53.6
	SD3	55.9	4.0	4.5	120	55.9
	HIGH	55.1	4.0	4.0	130	55.1
Hereward No. 3	LOW	52.3	1.5	4.0	90	52.9
	SD1	52.5	2.0	3.5	100	54.9
	SD2	53.1	2.0	5.5	90	54.1
	HIGH	53.4	2.0	5.0	95	54.8
Hunter No. 1	LOW	49.0	-	-	-	48.0
	SD3	48.7	1.5	3.0	120	44.6
	HIGH	48.6	1.5	2.0	140	45.8
Hunter No. 2	LOW	47.8	1.5	1.5	135	-
	SD1	48.4	1.5	1.0	150	-
	SD2	48.3	1.5	1.5	150	-
	HIGH	44.4	1.5	1.0	150	-
Hunter No. 3	LOW	50.4	1.5	2.0	100	48.8
	SD1	51.3	1.5	1.5	120	48.0
	SD2	51.9	1.5	1.5	130	49.5
	HIGH	52.4	1.5	2.0	125	48.6
Mercia No. 1	LOW	57.1	2.0	3.5	70	54.9
	SD3	57.8	2.0	2.5	60	55.6
	HIGH	57.5	2.0	2.5	80	54.1
Mercia No. 2	LOW	54.2	2.0	3.0	130	53.9
	SD1	54.2	2.0	3.5	115	-
	SD2	54.5	2.0	3.0	125	56.1
	HIGH	54.8	2.0	3.0	130	54.1
Mercia No. 3	LOW	55.1	2.0	4.0	115	54.2
	SD1	55.2	2.5	4.5	120	54.5
	SD2	55.7	2.0	3.5	115	55.7
	HIGH	55.7	2.0	4.5	105	54.0
Riband No. 1	LOW	50.4	1.0	1.0	195	48.7
	SD1	50.3	1.0	1.0	200	49.0
	SD2	50.4	1.0	1.0	205	48.8
	HIGH	50.6	1.0	1.0	180	48.9
Riband No. 2	LOW	49.6	1.5	1.5	180	47.4
	SD3	49.4	1.5	1.5	190	48.5
	HIGH	49.4	1.5	1.5	180	49.4
Soissons No. 1	LOW	51.1	1.5	4.0	75	53.0
	SD1	51.6	1.5	2.5	100	-
	SD2	52.0	1.5	2.5	95	53.2
	HIGH	52.6	1.5	2.5	105	53.1
Soissons No. 2	LOW	54.8	9.0	18.0	40	55.9
	SD1	54.6	2.0	16.5	35	56.2
	SD2	54.3	2.0	17.0	30	56.5
	HIGH	55.3	2.0	16.5	30	57.6
Soissons No. 3	LOW	53.9	11.5	21.0	45	54.3
	SD1	54.1	1.5	22.0	20	54.6
	SD2	54.2	1.5	20.0	25	55.5
	HIGH	54.1	2.0	22.0	20	54.6

Table A.2c - Farinograph and Consistograph results for 1998 harvest flours

Wheat Variety	Nominal Starch Damage	Farinograph (300g, 600 line)				Consistograph HYDHA (%)
		Water abs. (%)	Dev. Time (min)	Stability (min)	Degree of soft. (BU)	
Cadenza No. 1	LOW	55.3	1.5	2.0	150	54.3
	HIGH	57.6	2.0	2.0	150	54.0
Cadenza No. 2	LOW	58.2	2.5	5.5	95	57.2
	HIGH	63.1	2.5	4.5	100	58.3
Claire No. 1	LOW	55.1	1.5	1.0	210	51.0
	HIGH	57.7	1.5	1.0	215	51.4
Claire No. 2	LOW	53.3	1.5	1.0	200	50.0
	HIGH	58.0	1.5	1.0	205	51.4
Consort No. 1	LOW	51.4	1.5	1.5	210	50.4
	HIGH	53.9	1.5	1.5	200	50.0
Consort No. 2	LOW	52.9	2.0	2.0	185	49.6
	HIGH	54.0	2.0	2.0	175	51.0
CWRS No. 1	LOW	60.0	4.5	5.0	110	58.9
	HIGH	64.1	5.0	6.0	105	59.5
CWRS No. 2	LOW	62.9	5.0	4.5	115	58.2
	HIGH	68.6	5.0	5.0	120	60.5
Hereward No. 1	LOW	56.1	2.0	2.5	175	56.3
	HIGH	57.3	2.0	3.0	160	55.7
Hereward No. 2	LOW	57.5	3.5	3.0	150	56.3
	HIGH	63.5	3.0	3.0	175	60.0
Hunter No. 1	LOW	53.3	2.0	1.5	210	48.4
	HIGH	54.0	2.0	1.5	200	47.2
Hunter No. 2	LOW	53.8	2.0	2.0	165	48.7
	HIGH	56.2	2.0	2.5	160	50.9
Malacca No. 1	LOW	60.7	3.0	2.5	140	56.1
	HIGH	62.3	3.0	3.0	125	56.5
Malacca No. 2	LOW	58.4	3.5	4.0	115	55.8
	HIGH	60.7	3.0	4.5	115	56.4
Mercia No. 1	LOW	56.3	2.5	3.5	140	55.2
	HIGH	59.1	2.5	3.5	155	55.1
Mercia No. 2	LOW	58.3	2.5	3.5	140	55.1
	HIGH	62.1	2.0	3.5	150	56.7
Riband No. 1	LOW	52.3	1.5	1.5	220	48.0
	HIGH	55.7	1.5	1.5	230	49.5
Riband No. 2	LOW	52.4	1.5	1.5	185	49.5
	HIGH	55.2	1.5	2.0	200	52.3
Soissons No. 1	LOW	54.3	2.0	3.0	100	55.8
	HIGH	57.2	2.0	2.0	105	56.1
Soissons No. 2	LOW	55.8	2.0	7.0	75	55.6
	HIGH	62.9	1.5	2.5	105	57.9
Spark No. 1	LOW	61.2	3.0	3.5	125	58.4
	HIGH	68.2	3.0	3.0	150	59.8
Spark No. 2	LOW	57.7	2.0	6.0	80	56.8
	HIGH	64.6	2.5	7.0	75	58.3

Table A.3a - Alveograph data for 1995 flours

Wheat Variety	Nominal Starch Damage	P (mm H_2O)	L (mm)	G	W (J x 10^{-4})	T (mm H_2O)	A (mm)	Ex	Fb (J x 10^{-4})
Beaver	LOW	35.86	24	10.8	33.09	79	24	10.9	75
	SD1	33.3	20	9.9	25.9	110	16	9	82
	SD2	32.8	30.5	12.2	28.1	98	19	9.7	86
	HIGH	36.5	32	12.5	33.5	93	24	11	86
Cadenza No. 1	LOW	88.99	46	14.81	147.15	-	-	-	-
	SD1	83.8	56	16.6	156.2	89	61	17.4	175
	SD2	82.7	48.5	15.4	138.84	81	71	18.8	176
	HIGH	112.5	37.5	13.6	166.15	87	43	14.6	136
Cadenza No. 2	LOW	140	39	13.84	236.09	-	-	-	-
	SD1	130.57	45	14.8	239	103	60	17.3	232
	SD2	>154	-	-	-	-	-	-	-
	HIGH	121.6	61.5	17.36	324.97	87	55	16.5	179
Cadenza No. 3	LOW	144.1	34.5	12.96	219.87	-	-	-	-
	SD1	>154	-	-	-	114	45	14.9	216
	SD2	>154	-	-	-	118	56	16.6	258
	HIGH	>154	-	-	-	107	59	17.1	240
Consort No. 1	LOW	23.1	101	22.38	69.7	37	114	23.8	93
	SD3	24	118	24.22	75.34	35	103	22.6	82
	HIGH	26.62	105	22.72	75.08	48	50	15.8	74
Consort No. 2	LOW	29.7	114	23.7	100.2	40	159	28.1	143
	SD3	29	115	23.8	89	40	151	27.4	137
	HIGH	33	98	21.96	94.24	31	143	26.6	103
CWRS	LOW	110	95	21.7	365.78	61	139	26.2	264
	SD1	103.8	99	22.02	353.42	45	202	31.6	245
	SD2	109.12	82	20.08	321.1	64	124	24.8	246
	HIGH	113.52	93	21.4	372.3	42	156	27.8	191
Hereward No. 1	LOW	92.9	68	18	214.8	85	67	18.2	201
	SD1	101.3	60.5	17.2	208.3	69	82	20.2	189
	SD2	86.09	63	17.52	191.6	86	71	18.8	209
	HIGH	88.2	57.5	16.78	180.3	64	88	20.9	176
Hereward No. 2	LOW	99	63	17.5	214	65	91	21.2	188
	SD1	96.14	58	16.96	197.64	59	122	24.6	205
	SD2	89.95	60	17.2	178.9	61	112	23.5	190
	HIGH	85.14	60.5	17.2	170.7	59	115	23.9	183
Hereward No. 3	LOW	79.5	85	20.4	208.8	-	-	-	-
	SD1	72.7	89.5	20.95	188.7	50	155	27.7	188
	SD2	72.82	86	20.54	182.1	53	138	26.1	181
	HIGH	75.4	95	21.6	180.1	47	121	24.5	139
Hunter No. 1	LOW	-	-	-	-	-	-	-	-
	SD1	-	-	-	-	64	63	17.7	102
	SD2	-	-	-	-	51	74	19.2	89
	HIGH	-	-	-	-	69	42	14.5	93
Hunter No. 2	LOW	-	-	-	-	-	-	-	-
	SD1	36.74	70	18.52	67.36	68	58	17	104
	HIGH	36.52	71	18.74	66.8	63	66	18.1	107
Mercia No. 1	LOW	107.7	28.5	11.8	137.5	119	30	12.1	153
	SD1	113.2	36.5	13.3	156.6	116	25	11.2	127
	SD2	105.1	30	12	127.9	94	38	13.7	143
	HIGH	115.4	30	12.2	153.95	97	40	14.1	152
Mercia No. 2	LOW	83.82	57	16.68	171.1	59	100	22.2	170
	HIGH	88.22	52	16.04	168.5	-	-	-	-
Mercia No. 3	LOW	111.3	39.5	13.8	184.3	-	-	-	-
	SD1	114	42.5	14.4	204.7	96	51	15.9	192
	SD2	121.4	47	15.2	228.3	109	40	14.1	180
	HIGH	118.54	41	14.2	200.73	84	65	18	199
Riband No. 2	LOW	29.77	53.5	16.2	43.1	35	75	19.3	62
	SD1	31.1	50	15.6	45.58	45	75	19.3	79
	SD2	29.2	55	16.4	41.22	-	-	-	-
	HIGH	30.6	46	14.92	39.67	53	60	17.2	82
Soissons No. 1	LOW	129.3	60	17.1	306.2	64	79	19.7	211
	SD1	96.1	82.5	20.2	298.7	64	109	23.3	260
	SD2	96.3	80.4	20.2	299.6	66	86	20.7	217
	HIGH	119.47	67	18.2	305.35	46	94	21.6	167
Soissons No. 2	LOW	137	42.2	14.4	266.57	103	62	17.5	270
	SD1	116.3	50	15.6	256.56	83	53	16.2	195
	SD2	117.6	79.5	19.7	380.6	78	67	18.2	219
	HIGH	110.77	68.5	18.36	317	76	74	19.1	243
Soissons No. 3	LOW	>154	-	-	-	-	-	-	-
	SD1	>154	-	-	-	106	37	13.6	184
	SD2	>154	-	-	-	89	53	16.2	207
	HIGH	-	-	-	-	80	54	16.4	187

Table A.3b - Alveograph data for 1996 flours

Wheat Variety	Nominal Starch Damage	P (mm H_2O)	L (mm)	G	W (J x 10^{-4})	T (mm H_2O)	A (mm)	Ex	Fb (J x 10^{-4})
Cadenza No. 1	LOW	82.94	75	19.2	221.05	62	131	25.5	234
	SD1	94.6	60	17.1	210.6	64	119	24.3	220
	SD2	95.9	66	18.1	229.7	72	99	22.1	214
	HIGH	105.6	63	17.5	242.9	72	108	23.1	235
Cadenza No. 2	LOW	85.8	54	16.4	159.05	58	85	20.5	143
	SD1	89.76	48	15.4	165.2	62	93	21.5	160
	SD2	100.8	47	15.2	174.7	67	55	16.4	123
	HIGH	97.24	46	15.04	169.91	63	99	22.1	169
Consort No. 1	LOW	-	-	-	-	35	145	26.8	112
	SD1	25.3	131	25.4	93.1	27	161	28.3	95
	SD2	25.7	142	26.4	116.2	31	149	27.2	101
	HIGH	25.1	147	26.9	101.6	33	156	27.8	116
Consort No. 2	LOW	23.8	113	23.6	84.24	37	93	21.5	92
	SD1	-	-	-	-	41	58	17	75
	SD2	24.6	95	21.62	74.75	41	82	20.2	92
	HIGH	32.78	87	20.7	77.7	45	50	15.7	74
Consort No. 3	LOW	-	-	-	-	39	139	26.2	131
	SD1	-	-	-	-	38	157	27.9	141
	SD2	28.6	129	25.2	109.74	46	121	24.5	137
	HIGH	-	-	-	-	41	151	27.3	147
Hereward No. 1	LOW	67	128	25.2	254	53	171	29.1	236
	SD3	72	112	23.5	253	49	180	29.9	220
	HIGH	74	115	23.8	265	56	118	24.2	200
Hereward No. 2	LOW	65	134	25.7	254	59	102	22.4	185
	SD3	67	139	26.2	269	40	220	33	194
	HIGH	66	138	26	262	47	193	30.9	220
Hereward No. 3	LOW	58.7	112	23.5	203.92	51	148	27.1	199
	SD1	63.8	123	24.6	238	48	97	22	148
	SD2	69.3	110	23.2	249.17	52	132	25.6	195
	HIGH	73.3	99	22.1	228.7	52	109	23.3	170
Hunter No. 1	LOW	31.7	120	24.3	97.51	52	62	17.5	97
	SD3	-	-	-	-	75	47	15.3	117
	HIGH	32	107	22.9	89	56	81	20.1	120
Hunter No. 2	LOW	30	76	19.4	60	-	-	-	-
	SD1	29	73	18.9	56	-	-	-	-
	SD2	28	86	20.6	59	-	-	-	-
	HIGH	29.92	82	20.14	65.53	-	-	-	-
Hunter No. 3	LOW	59.2	44	14.7	109.6	81	56	16.7	151
	SD1	58.7	43	14.6	100.72	100	40	14.1	153
	SD2	60.3	51	15.8	117.26	79	47	15.3	131
	HIGH	-	-	-	-	86	45	14.9	138
Mercia No. 1	LOW	118.4	39	13.8	196.3	91	65	17.9	210
	SD3	127	34	13	189	86	66	18.1	202
	HIGH	127	34	13	187	-	-	-	-
Mercia No. 2	LOW	68	75	19.2	164	-	-	-	-
	SD1	62	84	20.3	163	-	-	-	-
	SD2	63	65	17.9	137	63	99	22.1	169
	HIGH	72	62	17.5	152	48	124	24.7	148
Mercia No. 3	LOW	69.52	68	18.32	153.95	53	116	24	155
	SD1	72.16	70	18.5	166.57	52	105	22.8	141
	SD2	77	68	18.3	175.66	52	121	24.5	159
	HIGH	82.9	53	16.02	165.33	-	-	-	-
Riband No. 1	LOW	28	47	15.3	41	41	64	17.8	67
	SD1	31	54	16.4	49	34	47	15.2	49
	SD2	30	46	15.1	43	41	42	14.5	54
	HIGH	32	42	14.5	44	48	56	16.7	71
Riband No. 2	LOW	23	92	21.3	48	42	81	20	75
	SD3	24	77	19.5	44	39	80	19.9	71
	HIGH	25	82	20.1	51	34	82	20.1	64
Soissons No. 1	LOW	78.98	66	18.1	217.52	80	84	20.4	260
	SD1	87.34	64	17.72	241.13	-	-	-	-
	SD2	89.3	64.5	17.8	244.86	67	84	20.5	213
	HIGH	97.02	61	17.3	244.6	84	60	17.2	209
Soissons No. 2	LOW	88.7	94	21.52	341.91	62	97	21.9	244
	SD1	88.22	95	21.66	333.54	57	146	26.9	304
	SD2	93.1	89	20.9	346.62	63	72	18.9	199
	HIGH	-	-	-	-	60	98	22.1	236
Soissons No. 3	LOW	101.42	88	20.7	348.84	63	101	22.4	245
	SD1	87.3	87	21.82	318.5	76	77	19.5	240
	SD2	88	103	22.5	358.56	64	111	23.5	272
	HIGH	-	-	-	-	77	84	20.4	258

Table A.3c - Alveograph data for 1998 flours

Wheat Variety	Nominal Starch Damage	P (mm H_2O)	L (mm)	G	W ($J \times 10^{-4}$)	T (mm H_2O)	A (mm)	Ex	Fb ($J \times 10^{-4}$)
Cadenza No. 1	LOW	70	73	19.0	139	49	93	21.4	109
	HIGH	83	50	15.8	133	60	73	19.0	116
Cadenza No. 2	LOW	98	78	19.7	219	52	129	25.3	162
	HIGH	124	56	16.6	230	68	90	21.1	164
Claire No. 1	LOW	33	71	18.7	48	32	62	17.5	45
	HIGH	40	53	16.2	53	37	59	17.1	48
Claire No. 2	LOW	29	63	17.7	41	33	81	20.0	51
	HIGH	42	60	17.3	57	40	41	14.2	47
Consort No. 1	LOW	32	86	20.7	57	34	74	19.1	55
	HIGH	38	66	18.1	57	44	64	17.8	65
Consort No. 2	LOW	33	100	22.2	62	40	97	21.9	75
	HIGH	38	106	22.9	79	39	94	21.6	75
CWRS No. 1	LOW	84	167	28.8	358	41	199	31.4	216
	HIGH	114	127	25.1	413	57	143	26.6	237
CWRS No. 2	LOW	79	180	29.8	321	42	229	33.7	208
	HIGH	129	116	23.9	415	57	190	30.7	254
Hereward No. 1	LOW	75	116	24.0	204	42	126	25.0	122
	HIGH	81	95	21.7	195	50	110	23.4	129
Hereward No. 2	LOW	-	-	-	-	-	-	-	-
	HIGH	109	79	19.8	240	49	128	25.2	137
Hunter No. 1	LOW	45	61	17.4	65	57	49	15.5	78
	HIGH	51	48	15.4	69	75	34	12.9	89
Hunter No. 2	LOW	48	54	16.3	67	62	39	13.8	74
	HIGH	57	38	13.7	70	57	32	12.5	60
Malacca No. 1	LOW	86	85	20.5	174	56	106	22.9	125
	HIGH	104	66	18.0	195	65	99	22.2	144
Malacca No. 2	LOW	92	83	20.3	215	57	120	24.3	162
	HIGH	117	79	19.8	270	72	99	22.1	189
Mercia No. 1	LOW	71	101	22.3	175	46	128	25.1	129
	HIGH	97	77	19.6	206	65	104	22.7	158
Mercia No. 2	LOW	78	86	20.6	175	52	114	23.8	135
	HIGH	109	61	17.4	210	62	83	20.3	137
Riband No. 1	LOW	33	54	16.3	43	50	37	13.6	56
	HIGH	45	42	14.5	50	51	34	13.0	55
Riband No. 2	LOW	37	77	19.5	59	44	66	18.1	64
	HIGH	47	51	15.9	62	41	57	16.8	56
Soissons No. 1	LOW	75	151	27.4	304	44	151	27.3	194
	HIGH	92	121	24.4	311	57	139	26.2	230
Soissons No. 2	LOW	75	157	27.9	316	48	184	30.2	230
	HIGH	123	98	22.0	371	68	127	25.1	255
Spark No. 1	LOW	98	76	19.4	206	49	126	25.0	139
	HIGH	138	53	16.3	247	68	75	19.2	140
Spark No. 2	LOW	108	80	19.9	265	60	117	24.1	190
	HIGH	149	45	14.9	252	89	76	19.3	206

Table A.4a - Extensograph measurements of 1995 harvest samples

Wheat Variety	Nominal Starch Damage	Water added (%)	Resistance, R (Brabender Units)	Extensibility, E (cm)	100 x E / R
Beaver	LOW	49.0	277	11.8	4.26
	SD1	49.2	290	10.6	3.66
	SD2	49.8	255	10.8	4.24
	HIGH	51.4	251	10.6	4.22
Cadenza No. 1	LOW	57.4	350	14.2	4.06
	SD1	58.2	286	14.7	5.14
	SD2	59.6	285	13.9	4.88
	HIGH	60.2	280	13.5	4.82
Cadenza No. 2	LOW	58.9	465	15.2	3.27
	SD1	59.8	420	14.0	3.33
	SD2	61.4	375	14.7	3.92
	HIGH	61.4	440	15.2	3.45
Cadenza No. 3	LOW	59.3	550	13.4	2.44
	SD1	60.7	425	13.3	3.13
	SD2	61.3	455	13.5	2.97
	HIGH	62.1	455	13.6	2.99
Consort No. 1	LOW	47.5	460	16.3	3.54
	SD3	47.9	460	14.6	3.17
	HIGH	47.8	485	14.0	2.89
Consort No. 2	LOW	46.0	820	14.8	1.80
	SD3	46.6	780	15.0	1.92
	HIGH	48.0	710	15.9	2.24
CWRS	LOW	58.9	405	21.6	5.33
	SD1	59.8	430	20.4	4.74
	SD2	59.8	430	20.6	4.79
	HIGH	59.7	475	21.7	4.57
Hereward No. 1	LOW	55.6	510	15.4	3.02
	SD1	56.4	490	15.9	3.24
	SD2	56.7	480	17.1	3.56
	HIGH	56.8	385	17.1	4.44
Hereward No. 2	LOW	58.6	365	17.7	4.85
	SD1	59.0	400	17.5	4.38
	SD2	60.1	330	18.6	5.64
	HIGH	61.0	380	18.3	4.82
Hereward No. 3	LOW	58.2	350	20.3	5.80
	SD1	59.6	305	20.0	6.56
	SD2	61.0	250	20.6	8.24
	HIGH	61.9	205	21.8	10.63
Hunter No. 1	LOW	50.3	380	13.1	3.45
	SD1	50.6	360	14.0	3.89
	SD2	50.4	375	13.0	3.47
	HIGH	54.3	155	13.5	8.71
Hunter No. 2	LOW	51.3	335	13.1	3.91
	SD1	50.6	345	13.6	3.94
	HIGH	50.1	355	13.7	3.86
Mercia No. 1	LOW	55.6	375	14.0	3.73
	SD1	55.6	375	14.0	3.73
	SD2	59.1	330	10.8	3.27
	HIGH	57.0	418	12.7	3.04
Mercia No. 2	LOW	54.6	370	13.2	3.57
	HIGH	55.3	395	13.4	3.39
Mercia No. 3	LOW	55.5	460	10.8	2.35
	SD1	56.5	570	10.5	1.84
	SD2	57.2	425	10.9	2.56
	HIGH	59.4	425	10.4	2.45
Riband No. 2	LOW	47.8	340	13.2	3.88
	SD1	49.2	315	13.7	4.35
	SD2	49.8	300	13.3	4.43
	HIGH	49.4	310	12.7	4.10
Soissons No. 1	LOW	58.4	510	20.0	3.92
	SD1	58.2	530	19.8	3.74
	SD2	60.0	475	20.5	4.32
	HIGH	60.0	430	20.8	4.84
Soissons No. 2	LOW	60.1	560	18.2	3.25
	SD1	60.0	510	17.7	3.47
	SD2	60.0	590	19.1	3.24
	HIGH	59.9	565	19.0	3.36
Soissons No. 3	LOW	60.3	630	15.7	2.49
	SD1	60.6	505	16.5	3.27
	SD2	60.4	550	16.8	3.05
	HIGH	61.0	510	17.4	3.41

Table A.4b - Extensograph measurements of 1996 harvest samples

Wheat Variety	Nominal Starch Damage	Water added (%)	Resistance, R (Brabender Units)	Extensibility, E (cm)	100 x E / R
Cadenza No. 1	LOW	55.7	370	16.1	4.35
	SD1	56.8	335	16.5	4.93
	SD2	57.1	330	16.2	4.91
	HIGH	58.0	345	15.9	4.61
Cadenza No. 2	LOW	56.1	270	14.3	5.30
	SD1	57.0	250	15.2	6.08
	SD2	56.9	260	15.5	5.96
	HIGH	57.2	270	13.8	5.11
Consort No. 1	LOW	47.7	510	16.5	3.24
	SD1	47.7	565	16.2	2.87
	SD2	47.5	550	16.7	3.04
	HIGH	-	-	-	-
Consort No. 2	LOW	46.5	295	12.5	4.24
	SD1	46.9	285	12.7	4.46
	SD2	47.9	285	12.7	4.46
	HIGH	49.0	230	13.8	6.00
Consort No. 3	LOW	46.2	655	16.7	2.55
	SD1	46.1	630	15.4	2.44
	SD2	46.8	590	16.1	2.73
	HIGH	46.8	615	15.9	2.59
Hereward No. 1	LOW	55.5	325	21.0	6.46
	SD3	55.2	355	19.9	5.61
	HIGH	55.2	375	20.4	5.44
Hereward No. 2	LOW	56.5	310	21.2	6.84
	SD3	55.0	360	20.6	5.72
	HIGH	55.1	315	21.8	6.92
Hereward No. 3	LOW	52.0	395	18.2	4.61
	SD1	52.5	365	17.5	4.79
	SD2	52.9	400	18.5	4.63
	HIGH	53.6	385	18.5	4.81
Hunter No. 1	LOW	-	-	-	-
	SD3	45.5	560	12.8	2.29
	HIGH	45.6	515	13.0	2.52
Hunter No. 2	LOW	46.0	415	12.1	2.92
	SD1	45.4	410	12.6	3.07
	SD2	46.0	435	11.6	2.67
	HIGH	-	-	-	-
Hunter No. 3	LOW	49.0	595	10.8	1.82
	SD1	48.4	600	9.8	1.63
	SD2	48.9	610	10.1	1.66
	HIGH	49.4	565	9.5	1.68
Mercia No. 1	LOW	-	-	-	-
	SD3	56.9	480	12.1	2.52
	HIGH	57.5	425	11.8	2.78
Mercia No. 2	LOW	53.7	310	16.1	5.19
	SD1	54.2	290	15.3	5.28
	SD2	54.3	265	16.5	6.23
	HIGH	54.4	320	15.1	4.72
Mercia No. 3	LOW	55.1	220	16.7	7.59
	SD1	55.2	225	15.0	6.67
	SD2	55.7	230	14.9	6.48
	HIGH	55.7	235	15.0	6.38
Riband No. 1	LOW	47.7	340	12.2	3.59
	SD1	48.1	350	11.2	3.20
	SD2	47.4	370	11.7	3.16
	HIGH	46.4	415	9.7	2.34
Riband No. 2	LOW	47.7	280	15.9	5.68
	SD3	47.8	320	15.0	4.69
	HIGH	47.6	330	14.9	4.52
Soissons No. 1	LOW	51.9	500	16.8	3.36
	SD1	52.2	480	16.9	3.52
	SD2	52.0	550	16.6	3.02
	HIGH	52.6	525	16.8	3.20
Soissons No. 2	LOW	54.8	430	22.6	5.26
	SD1	54.6	485	22.2	4.58
	SD2	54.3	520	21.4	4.12
	HIGH	55.2	450	20.9	4.64
Soissons No. 3	LOW	53.9	425	21.1	4.96
	SD1	54.1	430	20.9	4.86
	SD2	54.2	445	20.4	4.58
	HIGH	54.9	395	19.9	5.04

Table A.4c - Extensograph measurements of 1998 harvest samples

Wheat Variety	Nominal Starch Damage	Water Added (%)	Resistance, R (Brabender Units)	Extensibility, E (cm)	100 x E / R
Cadenza	LOW	54.6	220	13.3	6.05
No. 1	HIGH	56.6	205	13.4	6.54
Cadenza	LOW	58.3	240	15.8	6.58
No. 2	HIGH	63.4	250	15.3	6.12
Claire	LOW	51.9	170	17.2	10.12
No. 1	HIGH	53.9	205	16.6	8.10
Claire	LOW	49.7	220	14.2	6.45
No. 2	HIGH	53.6	230	15.4	6.70
Consort	LOW	48.4	315	13.4	4.25
No. 1	HIGH	50.6	280	13.3	4.75
Consort	LOW	49.6	315	17.3	5.49
No. 2	HIGH	50.9	360	16.4	4.56
CWRS	LOW	58.4	340	21.2	6.24
No. 1	HIGH	-	-	-	-
CWRS	LOW	60.4	300	23.3	7.77
No. 2	HIGH	65.2	280	19.4	6.93
Hereward	LOW	55.9	205	18.5	9.02
No. 1	HIGH	57.4	195	17.9	9.18
Hereward	LOW	57.3	190	20.1	10.58
No. 2	HIGH	64.1	155	18.0	11.61
Hunter	LOW	50.1	280	12.0	4.29
No. 1	HIGH	50.7	290	11.6	4.00
Hunter	LOW	50.9	300	11.5	3.83
No. 2	HIGH	53.0	300	12.8	4.27
Malacca	LOW	60.5	140	17.7	12.64
No. 1	HIGH	62.5	170	18.1	10.65
Malacca	LOW	58.4	255	14.9	5.84
No. 2	HIGH	60.7	295	15.2	5.15
Mercia	LOW	56.1	205	17.3	8.44
No. 1	HIGH	58.6	210	15.5	7.38
Mercia	LOW	58.1	175	15.4	8.80
No. 2	HIGH	62.2	195	13.9	7.13
Riband	LOW	49.8	220	13.5	6.14
No. 1	HIGH	52.0	225	11.7	5.20
Riband	LOW	49.3	290	13.2	4.55
No. 2	HIGH	51.6	280	13.1	4.68
Soissons	LOW	54.6	370	20.2	5.46
No. 1	HIGH	57.2	395	18.5	4.68
Soissons	LOW	55.6	375	18.1	4.83
No. 2	HIGH	62.3	345	15.6	4.52
Spark	LOW	61.3	165	17.5	10.61
No. 1	HIGH	67.8	145	14.6	10.07
Spark	LOW	58.4	365	15.6	4.27
No. 2	HIGH	64.7	335	12.5	3.73

Table A.5a – Bread quality data for 1995 samples

Wheat Variety	Nominal Starch Damage	Mean loaf volume (ml)	Mean specific volume (ml/g)	Mean crumb score	Mean Hunterlab Y value	Oven spring (cm)
Beaver	LOW	1309	3.36	4.0	55.45	1.55
	SD1	-	-	-	-	-
	SD2	-	-	-	-	-
	HIGH	1387	3.56	4.0	51.40	1.40
Cadenza No. 1	LOW	1647	4.27	7.0	-	4.35
	SD1	1581	4.14	6.5	-	4.00
	SD2	1663	4.32	6.0	-	4.25
	HIGH	1643	4.25	6.5	-	4.15
Cadenza No. 2	LOW	1602	4.17	7.0	-	4.20
	SD1	1621	4.25	7.0	-	4.35
	SD2	1597	4.16	6.5	-	4.30
	HIGH	1612	4.17	7.0	-	4.45
Cadenza No. 3	LOW	1548	4.05	7.0	-	4.20
	SD1	1527	3.98	6.0	-	3.85
	SD2	1578	4.12	6.5	-	4.25
	HIGH	1576	4.08	7.0	-	4.30
Consort No. 1	LOW	1707	4.28	7.0	59.41	4.70
	SD3	1696	4.22	7.5	59.25	4.80
	HIGH	1726	4.32	7.0	61.33	5.00
Consort No. 2	LOW	1800	4.49	7.5	59.98	5.35
	SD3	1765	4.42	7.5	57.90	5.25
	HIGH	1771	4.39	7.5	57.10	5.35
CWRS	LOW	1667	4.14	8.0	59.16	4.25
	SD1	1639	4.06	8.0	59.41	3.90
	SD2	1658	4.16	8.0	59.04	3.90
	HIGH	1642	4.12	8.0	59.70	3.70
Hereward No. 1	LOW	1711	4.40	7.0	61.49	4.85
	SD1	1645	4.25	7.5	61.82	4.35
	SD2	1686	4.33	7.0	61.44	4.80
	HIGH	1684	4.29	7.0	60.36	4.97
Hereward No. 2	LOW	1686	4.37	7.5	62.01	4.60
	SD1	1673	4.38	7.5	61.46	4.30
	SD2	1626	4.21	7.5	61.97	4.20
	HIGH	1680	4.31	7.0	60.41	4.30
Hereward No. 3	LOW	1718	4.42	7.0	60.48	4.25
	SD1	1665	4.33	7.5	59.50	4.15
	SD2	1675	4.37	7.0	58.23	4.05
	HIGH	1646	4.28	7.0	57.25	3.70
Hunter No. 1	LOW	1650	4.08	6.0	58.42	3.90
	SD1	1643	4.10	6.0	58.28	3.75
	SD2	1612	3.98	6.5	58.44	3.40
	HIGH	1628	4.05	6.0	58.89	3.60
Hunter No. 2	LOW	1622	4.08	6.0	55.00	4.00
	ISD3	1637	4.09	7.0	56.00	4.00
	HIGH	1639	4.07	7.0	57.00	4.00
Mercia No. 1	LOW	1479	3.80	6.0	61.00	3.60
	SD1	-	-	-	-	-
	SD2	1485	3.84	7.0	59.92	3.55
	HIGH	1481	3.84	7.0	59.85	3.65
Mercia No. 2	LOW	1696	4.30	8.0	60.00	4.00
	HIGH	-	-	-	-	-
Mercia No. 3	LOW	1506	3.87	7.0	63.21	4.05
	SD1	1557	4.00	6.5	62.33	4.15
	SD2	-	-	-	-	-
	HIGH	1511	3.84	7.0	61.16	4.00
Riband No. 2	LOW	1302	3.33	4.0	61.00	1.80
	SD1	1321	3.39	4.5	59.74	1.85
	SD2	1368	3.54	4.5	59.55	1.80
	HIGH	1296	3.31	4.0	58.75	1.80
Soissons No. 1	LOW	1650	4.23	7.0	61.64	4.75
	SD1	1630	4.26	7.0	61.83	4.65
	SD2	1634	4.28	7.0	61.98	4.65
	HIGH	1646	4.30	7.0	60.53	4.70
Soissons No. 2	LOW	1379	3.52	6.0	56.94	2.40
	SD1	1403	3.60	6.0	58.13	2.80
	SD2	1422	3.62	6.0	59.50	2.80
	HIGH	1441	3.72	6.0	58.17	2.95
Soissons No. 3	LOW	1370	3.47	6.0	57.85	2.30
	SD1	1339	3.46	6.0	58.82	2.75
	SD2	1341	3.47	5.5	60.06	3.00
	HIGH	1326	3.41	6.5	58.28	3.15

Table A.5b – Bread quality data for 1996 samples

Wheat Variety	Nominal Starch Damage	Mean loaf volume (ml)	Mean specific volume (ml/g)	Mean crumb score	Mean Hunterlab Y value	Oven spring (cm)
Cadenza No. 1	LOW	1690	4.20	8.0	62.33	4.85
	SD1	1692	4.25	8.0	61.77	5.00
	SD2	1735	4.31	8.0	61.82	5.15
	HIGH	1704	4.29	8.5	62.08	4.80
Cadenza No. 2	LOW	1661	4.12	7.5	61.26	4.60
	SD1	1689	4.22	7.5	61.34	4.65
	SD2	1658	4.11	7.0	61.85	4.65
	HIGH	1651	4.12	7.5	61.42	4.50
Consort No. 1	LOW	1771	4.39	7.0	57.30	5.10
	SD1	1725	4.31	7.0	57.11	4.40
	SD2	1756	4.33	7.5	57.07	4.85
	HIGH	1726	4.32	7.0	57.90	4.80
Consort No. 2	LOW	1619	4.14	7.5	61.55	4.10
	SD1	1625	4.13	8.0	61.29	4.00
	SD2	1622	4.13	7.5	60.09	4.30
	HIGH	1671	4.23	7.5	59.33	4.65
Consort No. 3	LOW	1713	4.23	7.5	57.54	4.80
	SD1	1713	4.28	7.5	56.85	4.85
	SD2	1718	4.29	7.5	56.33	4.55
	HIGH	1731	4.29	7.0	56.40	5.00
Hereward No. 1	LOW	1754	4.45	9.0	57.10	4.50
	SD3	1675	4.24	8.0	57.81	4.00
	HIGH	1760	4.38	8.0	57.97	4.70
Hereward No. 2	LOW	1674	4.09	8.0	56.85	3.80
	SD3	1653	4.20	8.0	57.93	3.80
	HIGH	1749	4.41	9.0	57.67	4.20
Hereward No. 3	LOW	1833	4.60	8.0	61.71	5.90
	SD1	1808	4.57	8.0	60.93	5.40
	SD2	1866	4.67	8.0	61.37	5.95
	HIGH	1796	4.52	8.0	60.99	5.40
Hunter No. 1	LOW	1725	4.32	7.5	60.53	5.10
	SD3	1739	4.38	7.5	60.40	5.05
	HIGH	1724	4.26	8.0	60.99	3.55
Hunter No. 2	LOW	1589	3.93	7.0	56.07	3.90
	SD1	1570	3.90	7.0	56.61	3.30
	SD2	1583	3.89	7.0	56.07	3.20
	HIGH	1526	3.73	6.0	55.69	3.00
Hunter No. 3	LOW	1804	4.48	7.0	57.51	5.15
	SD1	1721	4.38	7.0	56.43	5.15
	SD2	1705	4.29	7.5	56.30	4.90
	HIGH	1687	4.25	7.5	56.49	4.80
Mercia No. 1	LOW	1637	4.12	8.0	62.34	4.35
	ISD3	1596	4.02	7.5	62.51	4.50
	HIGH	1615	4.03	8.0	62.82	4.55
Mercia No. 2	LOW	1726	4.39	8.0	59.96	4.60
	SD1	1749	4.37	8.0	59.85	5.30
	SD2	1722	4.35	8.0	58.13	4.70
	HIGH	1730	4.39	7.5	58.98	4.70
Mercia No. 3	LOW	1742	4.41	7.5	58.15	4.05
	SD1	1662	4.22	6.5	58.07	4.10
	SD2	1704	4.31	7.5	58.11	4.20
	HIGH	1667	4.24	7.5	58.27	4.15
Riband No. 1	LOW	1514	3.71	6.0	55.96	2.80
	SD1	1492	3.75	6.0	56.29	2.50
	SD2	1511	3.73	6.0	56.55	2.60
	HIGH	1499	3.74	6.0	56.72	2.40
Riband No. 2	LOW	1501	3.74	6.0	59.00	2.55
	SD3	1493	3.71	6.0	59.10	2.30
	HIGH	1536	3.80	6.0	58.79	3.50
Soissons No. 1	LOW	1620	4.07	8.0	61.51	4.55
	SD1	1609	4.06	8.5	61.36	4.60
	SD2	1628	4.09	8.5	60.85	4.55
	HIGH	1626	4.12	7.5	60.61	4.50
Soissons No. 2	LOW	1788	4.43	8.5	60.11	5.55
	SD1	1837	4.58	8.5	58.78	5.65
	SD2	1791	4.43	8.0	59.06	5.50
	HIGH	1805	4.52	8.0	58.20	5.35
Soissons No. 3	LOW	1738	4.39	6.5	59.59	4.95
	SD1	1720	4.33	8.5	59.38	4.80
	SD2	1718	4.33	6.5	59.90	5.00
	HIGH	1740	4.36	8.0	58.70	4.85

Table A.5c – Bread quality data for 1998 samples

Wheat Variety	Nominal Starch Damage	Mean loaf volume (ml)	Mean specific volume (ml/g)	Mean crumb score	Mean Hunterlab Y value	Oven spring (cm)
Cadenza	LOW	1576	3.99	7.5	56.97	4.2
No. 1	HIGH	1553	3.94	7.0	52.44	3.6
Cadenza	LOW	1684	4.26	7.5	53.38	4.9
No. 2	HIGH	1575	4.02	6.5	50.50	3.9
Claire	LOW	1507	3.81	5.0	46.88	2.3
No. 1	HIGH	1506	3.85	5.0	44.87	2.4
Claire	LOW	1454	3.66	5.5	49.91	2.2
No. 2	HIGH	1434	3.65	5.0	46.11	2.0
Consort	LOW	1433	3.62	5.0	51.01	2.2
No. 1	HIGH	1437	3.64	5.0	49.19	2.3
Consort	LOW	1533	3.87	6.0	45.03	2.7
No. 2	HIGH	1549	3.95	6.5	45.46	2.9
CWRS	LOW	1606	4.07	8.5	55.65	3.7
No. 1	HIGH	1601	4.12	7.0	55.31	3.8
CWRS	LOW	1523	3.81	7.0	50.65	2.7
No. 2	HIGH	1472	3.76	6.5	49.14	2.5
Hereward	LOW	1644	4.23	8.0	53.31	3.8
No. 1	HIGH	1632	4.22	7.5	50.87	3.8
Hereward	LOW	1547	3.94	7.0	52.68	2.9
No. 2	HIGH	1563	3.98	6.5	45.19	3.0
Hunter	LOW	1494	3.83	5.0	45.51	2.0
No. 1	HIGH	1542	3.89	5.5	44.82	2.4
Hunter	LOW	1545	3.94	6.0	47.79	2.6
No. 2	HIGH	1531	3.90	6.0	49.65	3.0
Malacca	LOW	1585	4.06	6.5	49.72	3.7
No. 1	HIGH	1583	4.06	6.5	49.35	3.8
Malacca	LOW	1626	4.21	7.0	52.98	4.4
No. 2	HIGH	1614	4.17	7.5	51.57	4.3
Mercia	LOW	1608	4.13	8.0	53.07	4.0
No. 1	HIGH	1676	4.25	7.0	52.57	4.1
Mercia	LOW	1641	4.20	7.5	56.51	4.0
No. 2	HIGH	1592	4.08	8.0	56.35	4.2
Riband	LOW	1343	3.30	4.5	46.57	1.3
No. 1	HIGH	1334	3.30	4.0	44.84	1.4
Riband	LOW	1434	3.57	5.0	48.06	2.0
No. 2	HIGH	1446	3.63	5.0	47.70	2.1
Soissons	LOW	1637	4.15	8.5	58.84	4.7
No. 1	HIGH	1645	4.17	8.0	55.96	4.8
Soissons	LOW	1640	4.14	8.0	55.81	4.7
No. 2	HIGH	1562	4.06	7.0	50.94	3.9
Spark	LOW	1528	3.91	6.5	48.28	2.8
No. 1	HIGH	1450	3.95	6.0	45.43	2.6
Spark	LOW	1620	4.12	8.5	54.95	4.7
No. 2	HIGH	1635	4.20	7.5	50.77	4.5

Table A.6a - Biscuit properties for 1995 samples.

Wheat Variety	Nominal Starch Damage	Dough water (%)	Biscuit length (mm)	Biscuit width (mm)	Biscuit thickness (mm)	Biscuit weight (g)	Biscuit moisture (%)	Biscuit hardness (s)	Biscuit checking (%)
Beaver	LOW	23.5	64.8	64.8	5.0	6.97	2.81	33	40
	SD1	23.5	64.5	63.9	4.9	6.74	2.49	34	15
	SD2	24.8	65.0	64.6	-	6.89	3.30	31	10
	HIGH	24.7	64.0	64.1	4.8	6.83	2.63	36	20
Cadenza No. 1	LOW	31.8	63.1	64.1	5.4	7.60	6.24	65	95
	SD1	32.3	62.6	63.6	5.1	7.35	4.40	62	90
	SD2	33.5	63.8	64.3	5.4	7.67	5.90	67	80
	HIGH	32.3	62.4	64.6	5.1	7.31	4.81	60	95
Cadenza No. 2	LOW	35.8	63.5	64.2	5.7	7.93	7.63	110	0
	SD1	34.0	62.7	64.0	5.7	7.94	7.29	98	5
	SD2	35.9	62.8	64.1	5.4	7.54	7.75	118	0
	HIGH	34.5	62.7	64.2	5.7	7.64	7.35	101	10
Cadenza No. 3	LOW	-	-	-	-	-	-	-	-
	SD1	37.0	64.0	63.9	6.0	8.13	8.34	124	0
	SD2	37.0	62.9	64.0	5.8	7.97	8.22	114	45
	HIGH	35.9	62.4	64.0	5.7	7.71	8.75	106	0
Consort No. 1	LOW	21.5	61.3	57.5	7.2	6.99	5.67	25	90
	SD3	21.8	61.4	58.6	7.4	7.11	4.67	24	100
	HIGH	21.5	60.8	58.6	7.8	7.81	4.00	26	100
Consort No. 2	LOW	22.9	62.2	56.8	8.4	7.80	6.00	26	60
	SD3	21.8	61.6	59.0	7.4	7.72	6.33	34	60
	HIGH	23.3	62.4	59.0	7.6	7.60	5.00	34	70
CWRS	LOW	30.5	61.0	56.8	8.4	7.86	6.67	79	0
	SD1	30.5	61.1	56.8	8.6	7.40	7.33	67	40
	SD2	30.8	61.2	57.4	8.5	7.50	7.00	77	0
	HIGH	31.0	60.6	58.0	9.1	7.55	6.67	78	30
Hereward No. 1	LOW	33.0	63.0	64.0	5.9	8.19	7.75	96	0
	SD1	32.3	62.7	64.5	5.8	7.92	6.75	69	70
	SD2	33.5	63.7	64.6	5.7	8.15	7.73	74	15
	HIGH	33.5	63.0	65.2	5.7	8.00	7.85	80	25
Hereward No. 2	LOW	33.5	63.4	64.5	5.9	7.97	6.59	80	35
	SD1	33.8	63.6	64.9	5.9	8.07	7.97	89	15
	SD2	32.5	63.0	64.0	5.9	7.94	7.47	83	30
	HIGH	33.3	63.0	64.4	5.9	7.91	6.88	78	30
Hereward No. 3	LOW	32.5	63.3	64.8	6.1	7.92	6.98	72	20
	SD1	33.3	63.8	65.3	6.0	7.95	7.14	62	40
	SD2	32.5	63.2	65.3	6.3	8.10	7.12	63	10
	HIGH	33.3	63.5	64.6	6.6	8.32	7.58	72	30
Hunter No. 1	LOW	22.0	61.3	60.0	7.4	7.26	5.00	24	80
	SD1	22.0	61.4	58.4	7.1	7.01	4.33	25	50
	SD2	22.8	60.8	58.8	6.8	6.80	4.00	31	30
	HIGH	23.5	61.3	60.8	4.9	6.24	2.33	58	0
Hunter No. 2	LOW	22.3	61.7	59.5	6.7	6.79	4.67	26	20
	SD3	22.8	60.5	60.6	5.8	6.52	3.33	33	10
	HIGH	22.3	60.8	61.6	5.5	6.54	3.00	32	0
Mercia No. 1	LOW	34.0	63.5	64.6	5.2	7.69	6.89	82	65
	SD1	32.8	62.8	64.3	5.3	7.50	5.98	66	100
	SD2	32.8	62.3	64.9	5.4	7.39	5.72	58	100
	HIGH	33.0	62.2	64.5	5.3	7.64	5.43	71	50
Mercia No. 2	LOW	-	-	-	-	-	-	-	-
	HIGH	-	-	-	-	-	-	-	-
Mercia No. 3	LOW	31.0	63.1	64.9	5.9	7.73	6.97	73	10
	SD1	32.8	62.8	64.9	5.9	8.05	6.87	73	65
	SD2	32.0	63.1	64.5	6.1	8.28	8.00	82	0
	HIGH	32.5	62.3	65.0	5.9	7.96	7.26	85	10
Riband No. 2	LOW	23.5	63.9	64.5	5.6	7.49	2.91	26	85
	SD1	23.5	63.0	64.3	5.5	7.26	3.04	31	20
	SD2	23.8	62.1	64.5	5.8	7.66	3.35	30	95
	HIGH	-	63.2	64.5	6.0		3.24	31	55
Soissons No. 1	LOW	35.8	64.0	64.3	5.8	8.09	7.90	119	15
	SD1	35.3	63.9	64.8	6.2	8.05	8.11	81	0
	SD2	34.4	63.7	64.7	6.3	8.03	8.12	82	0
	HIGH	34.0	64.2	64.9	6.6	8.58	8.67	76	0
Soissons No. 2	LOW	38.5	63.5	64.4	5.9	8.08	9.12	123	0
	SD1	38.0	63.1	64.7	6.0	8.15	8.83	104	0
	SD2	36.5	63.7	64.1	6.5	8.49	9.65	89	0
	HIGH	36.0	65.0	64.1	6.9	9.15	10.44	71	0
Soissons No. 3	LOW	38.3	63.8	64.0	5.9	8.21	8.81	124	0
	SD1	36.8	64.8	63.9	6.7	8.77	9.39	102	0
	SD2	37.0	64.5	64.5	6.4	8.24	9.18	79	0
	HIGH	36.8	64.6	64.2	5.9	8.19	7.87	108	0

Table A.6b - Biscuit properties for 1996 samples.

Wheat Variety	Nominal Starch Damage	Dough water (%)	Biscuit length (mm)	Biscuit width (mm)	Biscuit thickness (mm)	Biscuit weight (g)	Biscuit moisture (%)	Biscuit hardness (s)	Biscuit checking (%)
Cadenza No. 1	LOW	28.5	60.9	56.1	7.1	7.30	5.67	55	80
	SD1	29.3	61.0	58.0	7.4	7.10	4.00	65	80
	SD2	29.8	61.1	57.1	7.8	7.02	5.00	19	80
	HIGH	29.8	60.7	58.4	7.6	7.07	5.33	56	100
Cadenza No. 2	LOW	28.3	61.4	57.5	6.1	6.30	4.67	60	40
	SD1	28.3	61.0	58.0	5.9	6.36	3.67	59	10
	SD2	28.5	61.0	59.8	6.6	6.67	4.67	55	80
	HIGH	28.3	61.3	59.4	6.1	6.64	5.00	52	20
Consort No. 1	LOW	23.0	61.1	56.1	7.5	7.30	4.67	23	100
	SD1	23.0	61.4	54.8	8.2	7.16	5.67	25	60
	SD2	23.3	62.4	56.6	7.9	7.19	4.33	59	20
	HIGH	23.5	62.4	56.0	7.9	7.19	4.67	32	60
Consort No. 2	LOW	21.6	61.1	57.2	6.9	7.16	5.00	29	80
	SD1	21.8	62.0	56.5	7.9	7.29	4.00	19	100
	SD2	21.8	61.1	56.5	8.2	7.55	4.33	23	100
	HIGH	22.0	61.1	58.2	7.3	7.10	3.00	24	100
Consort No. 3	LOW	22.8	62.2	56.2	7.8	7.15	5.67	39	50
	SD1	23.0	61.7	59.2	7.3	7.41	5.67	33	60
	SD2	23.0	62.5	55.4	7.8	7.21	5.67	39	60
	HIGH	23.5	62.3	57.3	7.6	7.09	5.33	27	70
Hereward No. 1	LOW	29.0	60.9	54.5	8.5	7.73	7.67	69	0
	SD3	28.8	60.8	54.6	7.7	7.71	7.33	71	0
	HIGH	29.3	60.9	55.4	8.1	7.74	8.00	93	0
Hereward No. 2	LOW	28.5	62.0	57.2	8.3	7.76	6.33	56	60
	SD3	28.5	60.0	57.5	8.3	7.92	7.00	80	30
	HIGH	-	-	-	-	-	-	-	-
Hereward No. 3	LOW	27.5	61.0	55.7	7.5	7.50	5.67	44	100
	SD1	27.3	58.9	55.9	8.6	7.47	6.00	64	100
	SD2	27.5	60.0	56.5	7.6	7.70	5.67	61	100
	HIGH	27.5	61.2	54.8	6.6	6.76	5.00	59	100
Hunter No. 1	LOW	21.5	62.0	58.9	7.5	7.62	5.00	37	100
	SD3	21.0	61.3	61.3	6.4	6.83	3.33	36	60
	HIGH	21.0	61.1	59.0	7.6	7.36	4.67	28	100
Hunter No. 2	LOW	20.8	61.0	60.0	6.8	6.92	4.33	18	90
	SD1	20.0	61.6	59.6	6.6	6.60	3.67	23	80
	SD2	20.3	61.0	59.0	6.7	6.59	4.67	28	0
	HIGH	21.5	61.0	59.0	6.7	6.59	3.33	21	50
Hunter No. 3	LOW	25.0	61.7	58.7	6.4	6.60	4.67	42	80
	SD1	24.8	61.9	58.3	7.1	6.70	5.00	43	70
	SD2	24.8	61.8	57.6	6.4	6.39	4.00	37	100
	HIGH	25.0	60.0	58.0	6.6	6.60	4.67	47	90
Mercia No. 1	LOW	27.0	60.8	57.0	7.0	7.28	5.33	81	70
	SD3	28.0	60.3	57.6	7.0	7.30	5.00	62	90
	HIGH	29.5	60.0	56.8	7.5	6.96	5.67	68	90
Mercia No. 2	LOW	27.0	61.2	56.7	7.0	7.02	6.00	53	60
	SD1	26.5	60.1	57.1	6.4	7.04	5.00	49	60
	SD2	26.0	60.0	58.9	6.9	7.21	5.33	43	90
	HIGH	27.5	58.9	57.8	6.5	6.85	5.33	59	80
Mercia No. 3	LOW	27.5	59.0	56.5	6.6	7.07	4.33	64	80
	SD1	28.0	61.7	57.4	6.7	6.83	4.67	46	80
	SD2	28.3	61.5	58.2	6.4	6.72	4.00	61	80
	HIGH	28.8	61.3	58.1	6.5	6.80	4.00	64	90
Riband No. 1	LOW	22.0	61.1	59.8	6.8	6.95	4.33	25	60
	SD1	21.8	61.8	60.4	7.0	6.92	4.33	30	60
	SD2	22.3	62.0	60.3	6.6	7.29	4.67	33	80
	HIGH	22.0	62.5	59.6	6.8	7.42	5.33	15	80
Riband No. 2	LOW	21.5	61.0	59.5	7.1	7.12	5.67	28	100
	SD3	22.0	60.7	58.6	7.7	7.47	5.00	38	10
	HIGH	21.5	62.0	59.1	6.7	6.97	5.33	24	80
Soissons No. 1	LOW	27.3	61.1	56.0	7.9	7.53	6.00	34	100
	SD1	28.5	61.1	58.7	7.9	7.68	6.67	40	80
	SD2	27.3	61.1	57.9	8.3	7.36	6.00	39	100
	HIGH	28.5	61.2	55.5	8.3	7.70	7.00	45	90
Soissons No. 2	LOW	30.5	59.1	53.7	9.4	8.12	9.00	71	0
	SD1	30.8	61.3	56.2	8.0	7.56	7.67	62	0
	SD2	30.8	61.2	55.6	8.9	7.58	8.33	70	0
	HIGH	31.0	61.4	54.8	8.4	7.73	8.33	100	0
Soissons No. 3	LOW	29.3	60.8	56.4	7.5	7.05	6.33	57	0
	SD1	29.5	60.8	55.2	8.6	8.13	6.33	68	0
	SD2	29.5	60.5	54.5	8.3	7.72	7.67	61	10
	HIGH	30.0	59.3	56.6	8.0	7.73	6.33	71	0

Table A.6c - Biscuit properties for 1998 samples.

Wheat Variety	Nominal Starch Damage	Dough water (%)	Biscuit length (mm)	Biscuit width (mm)	Biscuit thickness (mm)	Biscuit weight (g)	Biscuit moisture (%)	Biscuit hardness (s)	Biscuit checking
Cadenza No. 1	LOW	25.5	62.0	61.0	7.1	7.85	5.27	55	Slight
	HIGH	27.0	61.0	63.0	7.1	8.25	5.27	53	Slight
Cadenza No. 2	LOW	-	-	-	-	-	-	-	-
	HIGH	-	-	-	-	-	-	-	-
Claire No. 1	LOW	24.0	56.8	61.9	7.2	6.92	3.86	31	Slight
	HIGH	27.0	57.7	61.5	6.9	6.92	4.87	43	Severe
Claire No. 2	LOW	23.0	58.7	63.0	7.4	7.80	5.31	25	Slight
	HIGH	26.5	64.0	64.0	7.8	7.25	5.04	62	Severe
Consort No. 1	LOW	22.0	61.1	61.6	8.3	7.81	4.65	32	None
	HIGH	24.5	62.2	62.8	8.2	8.15	5.51	27	Slight
Consort No. 2	LOW	-	-	-	-	-	-	-	-
	HIGH	-	-	--	-	-	-	-	-
CWRS No. 1	LOW	31.0	56.7	64.0	7.7	7.41	8.13	51	None
	HIGH	36.0	54.9	62.3	7.8	7.33	10.30	67	None
CWRS No. 2	LOW	33.0	53.9	63.2	7.9	7.30	8.23	62	None
	HIGH	36.5	59.1	60.1	8.4	7.39	9.47	60	None
Hereward No. 1	LOW	27.0	56.8	61.4	8.3	8.04	8.63	38	None
	HIGH	29.0	58.3	60.9	7.8	7.99	7.98	55	None
Hereward No. 2	LOW	28.0	57.6	61.4	8.0	7.36	6.85	50	None
	HIGH	31.5	61.3	65.4	8.3	8.20	11.20	52	None
Hunter No. 1	LOW	21.0	62.1	60.8	6.5	7.79	3.58	41	Slight
	HIGH	22.0	61.6	61.4	6.7	7.75	4.37	32	Slight
Hunter No. 2	LOW	22.5	60.6	61.3	11.1	8.20	6.18	26	Slight
	HIGH	24.5	60.4	61.7	6.1	7.43	4.64	40	Slight
Malacca No. 1	LOW	-	-	-	-	-	-	-	-
	HIGH	-	-	-	-	-	-	-	-
Malacca No. 2	LOW	33.0	57.5	60.7	7.5	7.37	8.21	86	None
	HIGH	34.5	56.9	60.6	8.5	7.92	6.18	78	None
Mercia No. 1	LOW	29.0	59.5	61.1	8.8	8.09	8.95	44	None
	HIGH	31.0	59.8	61.2	7.6	7.92	8.95	91	None
Mercia No. 2	LOW	31.5	56.8	60.8	7.7	7.41	8.49	71	None
	HIGH	33.5	60.8	60.9	9.0	8.49	10.24	66	None
Riband No. 1	LOW	22.5	60.5	62.5	6.9	7.35	4.91	-	Severe
	HIGH	25.0	60.0	60.0	7.1	7.85	5.10	58	Slight
Riband No. 2	LOW	22.5	61.6	63.0	6.0	8.05	4.27	32	Slight
	HIGH	24.5	61.6	61.4	9.0	8.15	7.11	22	None
Soissons No. 1	LOW	29.0	58.3	61.1	9.0	8.00	9.59	-	None
	HIGH	30.5	57.9	61.5	7.5	7.78	11.42	73	None
Soissons No. 2	LOW	29.5	55.5	64.2	7.6	8.80	11.56	38	None
	HIGH	35.0	55.0	62.1	10.9	8.01	9.05	53	None
Spark No. 1	LOW	-	-	-	-	-	-	-	-
	HIGH	-	-	-	-	-	-	-	-
Spark No. 2	LOW	31.0	53.8	64.5	8.0	7.66	8.65	62	None
	HIGH	34.0	56.0	59.8	14.2	8.52	9.72	30	None

Table A.7a – Gel-protein data for 1995 harvest samples

Wheat Variety	Nominal Starch Damage	Mass of gel-protein, g	Elastic modulus G', Pa	Viscous modulus G", Pa	Phase angle (degrees)
Beaver	LOW	3.70	5.5	3.0	28.5
	SD1	3.59	3.5	2.1	30.5
	SD2	3.51	3.7	2.3	32.0
	HIGH	2.20	3.6	2.2	31.4
Cadenza No. 1	LOW	6.00	29.7	14.1	25.4
	SD1	6.06	33.6	15.3	24.5
	SD2	5.61	30.6	14.2	24.9
	HIGH	6.50	26.3	11.3	23.3
Cadenza No. 2	LOW	7.34	52.1	24.7	25.4
	SD1	7.54	58.2	31.5	28.4
	SD2	7.49	60.6	32.3	28.1
	HIGH	6.53	57.0	27.8	26.0
Cadenza No. 3	LOW	6.94	82.3	50.8	31.7
	SD1	7.49	64.7	40.7	32.2
	SD2	7.83	63.1	38.5	31.4
	HIGH	7.44	73.3	31.8	23.5
Consort No. 1	LOW	6.36	10.2	4.9	25.5
	SD3	7.40	12.4	7.2	30.1
	HIGH	7.23	7.7	3.8	26.1
Consort No. 2	LOW	8.72	16.0	6.6	22.4
	SD3	7.69	16.5	7.3	23.7
	HIGH	7.57	15.5	6.8	23.7
CWRS	LOW	10.70	42.2	23.0	27.9
	SD1	10.60	42.8	21.0	26.1
	SD2	5.80	40.0	23.0	29.9
	HIGH	10.50	43.1	25.0	30.2
Hereward No. 1	LOW	8.85	35.5	18.7	27.8
	SD1	8.78	28.3	16.0	29.5
	SD2	9.34	25.3	13.5	28.1
	HIGH	9.84	22.9	11.5	26.7
Hereward No. 2	LOW	9.22	39.7	20.9	27.8
	SD1	8.98	30.3	15.2	26.6
	SD2	9.04	30.5	16.3	28.1
	HIGH	9.24	34.4	18.8	28.7
Hereward No. 3	LOW	10.42	31.5	16.3	27.4
	SD1	10.73	27.8	14.3	27.2
	SD2	10.79	25.5	13.2	27.4
	HIGH	11.10	27.8	14.4	27.4
Hunter No. 1	LOW	-	-	-	-
	SD1	-	-	-	-
	SD2	-	-	-	-
	HIGH	-	-	-	-
Hunter No. 2	LOW	3.20	7.8	3.5	24.2
	SD1	3.15	10.5	4.2	21.7
	HIGH	3.67	8.5	3.8	23.8
Mercia No. 1	LOW	9.10	68.6	59.4	40.9
	SD1	6.19	31.4	19.3	31.6
	SD2	6.33	30.0	17.5	30.3
	HIGH	6.04	34.9	15.6	24.1
Mercia No. 2	LOW	7.88	19.3	8.3	23.2
	HIGH	6.92	24.5	10.6	23.4
Mercia No. 3	LOW	7.40	39.6	19.3	26.0
	SD1	7.83	42.8	23.8	29.1
	SD2	8.05	42.1	23.8	29.5
	HIGH	7.84	42.9	18.7	23.6
Riband No. 2	LOW	6.22	9.3	4.6	26.3
	SD1	6.66	10.5	4.9	24.8
	SD2	6.81	10.6	5.5	27.4
	HIGH	6.77	8.0	4.3	28.3
Soissons No. 1	LOW	9.80	84.3	73.4	40.9
	SD1	8.76	88.3	63.8	35.8
	SD2	8.40	68.4	53.3	37.9
	HIGH	5.20	12.3	7.1	29.9
Soissons No. 2	LOW	8.80	99.9	88.7	41.6
	SD1	8.88	82.0	68.8	40.0
	SD2	9.07	84.5	67.3	38.5
	HIGH	9.54	84.0	73.5	41.2
Soissons No. 3	LOW	9.10	91.0	89.7	44.6
	SD1	8.05	81.6	79.3	44.2
	SD2	8.06	64.7	63.6	44.5
	HIGH	9.55	100.3	89.3	41.7

Table A.7b – Gel-protein data for 1996 harvest samples

Wheat Variety	Nominal Starch Damage	Mass of gel-protein, g	Elastic modulus G', Pa	Viscous modulus G", Pa	Phase angle (degrees)
Cadenza No. 1	LOW	7.4	33.7	-	-
	SD1	5.9	38.5	-	-
	SD2	6.0	33.8	-	-
	HIGH	-	-	-	-
Cadenza No. 2	LOW	7.1	20.6	10.1	26.3
	SD1	6.8	18.1	8.3	24.5
	SD2	6.6	16.7	8.3	26.3
	HIGH	6.8	18.4	8.9	25.8
Consort No. 1	LOW	-	-	-	-
	SD1	7.5	17.0	9.5	29.0
	SD2	7.7	17.2	9.7	29.8
	HIGH	8.6	18.5	10.4	29.3
Consort No. 2	LOW	6.3	12.5	6.5	27.4
	SD1	6.4	10.1	5.7	29.5
	SD2	5.5	10.1	6.1	31.1
	HIGH	5.9	26.5	16.8	32.3
Consort No. 3	LOW	-	-	-	-
	SD1	-	-	-	-
	SD2	-	-	-	-
	HIGH	-	-	-	-
Hereward No. 1	LOW	11.9	29.8	15.6	27.6
	SD3	12.3	28.0	14.6	27.6
	HIGH	12.0	26.4	13.6	27.4
Hereward No. 2	LOW	11.0	27.0	14.8	28.7
	SD3	12.3	31.5	16.6	27.8
	HIGH	12.4	30.4	16.2	29.0
Hereward No. 3	LOW	10.8	20.9	11.7	29.2
	SD1	10.6	21.3	11.2	27.8
	SD2	9.6	27.3	15.6	29.8
	HIGH	9.5	22.6	12.9	29.5
Hunter No. 1	LOW	5.8	17.9	8.8	26.0
	SD3	5.6	19.9	9.8	26.3
	HIGH	5.7	14.8	8.0	28.3
Hunter No. 2	LOW	3.7	10.0	5.7	29.5
	SD1	4.1	9.3	4.8	27.5
	SD2	3.6	9.4	5.4	30.0
	HIGH	4.5	10.0	5.3	28.0
Hunter No. 3	LOW	5.4	31.3	17.9	29.6
	SD1	4.5	23.9	12.0	26.7
	SD2	5.3	27.6	14.1	27.1
	HIGH	5.9	24.2	12.4	27.2
Mercia No. 1	LOW	7.0	41.7	17.6	23.0
	SD1	6.2	38.1	20.7	28.4
	HIGH	7.9	44.2	24.2	28.7
Mercia No. 2	LOW	7.8	18.2	8.5	25.0
	SD1	8.3	20.1	9.8	26.1
	SD2	7.9	18.6	9.7	27.5
	HIGH	8.1	21.7	10.9	26.1
Mercia No. 3	LOW	8.7	19.5	10.6	28.4
	SD1	-	-	-	-
	SD2	8.8	19.1	10.3	28.5
	HIGH	7.8	17.5	8.8	26.7
Riband No. 1	LOW	6.0	5.6	3.2	29.5
	SD1	6.1	5.7	3.4	30.3
	SD2	6.0	5.4	3.1	30.1
	HIGH	5.0	7.2	3.7	27.2
Riband No. 2	LOW	4.5	5.4	3.4	32.1
	SD3	8.2	7.1	3.9	28.6
	HIGH	7.4	53.5	31.1	30.2
Soissons No. 1	LOW	6.6	59.4	-	-
	SD1	7.0	61.7	-	-
	SD2	6.9	55.2	40.4	35.7
	HIGH	7.7	56.5	-	-
Soissons No. 2	LOW	10.3	65.0	39.6	31.4
	SD1	11.0	68.5	51.4	37.0
	SD2	11.1	63.4	50.0	38.3
	HIGH	10.1	50.6	39.3	37.9
Soissons No. 3	LOW	9.5	50.3	36.2	35.8
	SD1	9.3	67.2	44.9	33.8
	SD2	8.6	48.9	33.2	34.2
	HIGH	9.0	48.2	29.2	31.2

Table A.7c – Gel-protein data for 1998 harvest samples

Wheat Variety	Nominal Starch Damage	Mass of gel-protein, g	Elastic modulus G', Pa	Viscous modulus G", Pa	Phase angle (degrees)
Cadenza No. 1	LOW	3.6	16.2	6.5	21.9
	HIGH	2.7	6.4	3.9	31.5
Cadenza No. 2	LOW	8.7	24.6	10.2	22.5
	HIGH	6.7	29.1	11.9	22.2
Claire No. 1	LOW	5.8	6.9	3.9	29.5
	HIGH	4.4	8.5	4.2	26.3
Claire No. 2	LOW	7.3	7.0	3.8	28.7
	HIGH	7.0	8.1	4.7	29.9
Consort No. 1	LOW	5.5	6.1	3.6	30.6
	HIGH	5.3	5.9	3.5	30.4
Consort No. 2	LOW	7.2	7.7	4.4	29.8
	HIGH	7.7	7.5	4.4	30.7
CWRS No. 1	LOW	2.7	72.6	26.8	20.3
	HIGH	7.8	60.6	19.7	18.0
CWRS No. 2	LOW	11.3	42.5	15.8	20.4
	HIGH	11.0	48.8	18.3	20.6
Hereward No. 1	LOW	6.5	16.7	6.9	22.5
	HIGH	7.2	15.0	6.4	23.1
Hereward No. 2	LOW	9.9	13.2	6.3	25.3
	HIGH	9.5	14.7	7.4	26.7
Hunter No. 1	LOW	3.0		Insufficient sample	
	HIGH	1.8		Insufficient sample	
Hunter No. 2	LOW	2.7		Insufficient sample	
	HIGH	3.8		Insufficient sample	
Malacca No. 1	LOW	2.6	0.9	0.9	46.6
	HIGH	6.9	4.7	2.8	31.3
Malacca No. 2	LOW	9.7	19.8	8.9	24.1
	HIGH	8.2	18.4	8.4	24.5
Mercia No. 1	LOW	8.4	20.7	9.5	24.6
	HIGH	8.9	24.9	10.5	22.9
Mercia No. 2	LOW	7.2	23.2	10.1	23.6
	HIGH	7.9	24.3	10.5	23.4
Riband No. 1	LOW	1.8		Insufficient sample	
	HIGH	1.3		Insufficient sample	
Riband No. 2	LOW	6.2	3.5	2.6	37.0
	HIGH	7.2	3.0	2.3	37.6
Soissons No. 1	LOW	6.9	54.0	20.8	21.1
	HIGH	6.7	60.6	23.1	20.8
Soissons No. 2	LOW	9.5	54.8	22.4	22.3
	HIGH	8.5	53.9	22.1	22.3
Spark No. 1	LOW	8.3	25.9	10.5	22.0
	HIGH	8.4	24.6	10.2	22.5
Spark No. 2	LOW	8.0	41.7	15.2	20.0
	HIGH	8.2	46.6	18.1	21.2

Table A.8a - Bread dough rheology for 1995 samples.

Wheat Variety	Nominal Starch Damage	Phase angle (degrees)	Complex viscosity (Pa)	Elastic modulus, G' (Pa)	Viscous modulus, G" (Pa)	Relaxation modulus (Pa)	Rel. mod. (filtered) (Pa)
Beaver	LOW	24.05	620	3557	1590	3293	2905
	SD1	-	-	-	-	-	-
	SD2	-	-	-	-	-	-
	HIGH	24.55	510	2913	1332	3238	3105
Cadenza No. 1	LOW	23.08	634	3663	1560	3298	3338
	SD1	23.43	659	3802	1647	3373	3000
	SD2	23.28	697	4022	1728	-	-
	HIGH	23.35	645	3720	1607	3318	2875
Cadenza No. 2	LOW	22.45	790	4583	1730	4103	3518
	SD1	22.15	774	4507	1833	4470	3920
	SD2	22.68	781	4525	1895	4423	3893
	HIGH	22.13	856	4980	2027	4550	3950
Cadenza No. 3	LOW	22.27	787	4577	1870	4180	3550
	SD1	21.92	890	5192	2083	5278	4650
	SD2	21.78	792	4620	1843	4420	3888
	HIGH	22.67	762	4417	1843	4235	3650
Consort No. 1	LOW	23.32	620	3575	1540	2052	2094
	SD3	22.45	519	3015	1248	1790	1832
	HIGH	24.23	714	4093	1843	2309	2356
Consort No. 2	LOW	22.28	687	3997	1625	2335	2370
	SD3	22.28	623	3618	1485	2260	2298
	HIGH	21.92	670	3907	1570	2368	2421
CWRS	LOW	23.05	546	3152	1338	1997	2073
	SD1	22.97	410	2858	1210	2038	2121
	SD2	23.90	519	2978	1322	1907	1970
	HIGH	23.48	472	2715	1180	1900	1963
Hereward No. 1	LOW	23.87	718	4123	1825	4270	3950
	SD1	23.17	734	4237	1812	3900	3620
	SD2	23.10	709	4097	1747	3898	3490
	HIGH	23.29	794	4582	1978	4042	3533
Hereward No. 2	LOW	24.65	589	3367	1542	3085	2718
	SD1	23.62	616	3545	1547	3290	2748
	SD2	23.25	690	3982	1712	3595	3095
	HIGH	23.20	608	3508	1503	3130	2915
Hereward No. 3	LOW	24.43	551	3152	1433	2775	2513
	SD1	24.50	550	3147	1430	2898	2593
	SD2	24.27	557	3190	1437	2790	2598
	HIGH	24.82	485	2763	1275	2840	2223
Hunter No. 1	LOW	24.15	672	3853	1725	2562	2616
	SD1	56.28	646	3735	1578	2445	2530
	SD2	23.87	681	3912	1730	2507	2561
	HIGH	23.80	610	3505	1545	2337	2410
Hunter No. 2	LOW	23.00	640	3705	1562	2444	2479
	SD3	23.00	640	3705	1557	2348	2433
	HIGH	23.00	665	3832	1657	2426	2528
Mercia No. 1	LOW	22.47	645	3748	1543	2810	2515
	SD1	-	-	-	-	-	-
	SD2	21.65	725	4230	1678	3753	3478
	HIGH	21.80	690	4027	1608	3505	3038
Mercia No. 2	LOW	23.00	683	3952	1670	2409	2621
	HIGH	-	-	-	-	-	-
Mercia No. 3	LOW	22.40	663	3853	1587	3353	3000
	SD1	23.10	751	4340	1852	4138	3625
	SD2	-	-	-	-	-	-
	HIGH	22.18	679	3952	1610	3465	3073
Riband No. 2	LOW	23.87	627	3600	1593	3165	2758
	SD1	24.03	582	3338	1490	3403	2905
	SD2	24.60	652	3720	1702	3168	2790
	HIGH	23.37	562	3240	1400	3093	2770
Soissons No. 1	LOW	22.22	672	3912	1595	2925	2633
	SD1	21.07	764	4480	1727	4038	3598
	SD2	21.57	714	4173	1648	3645	3268
	HIGH	22.37	651	3785	1557	3243	2943
Soissons No. 2	LOW	20.63	635	3733	1407	3073	2698
	SD1	21.03	676	3963	1523	3273	2913
	SD2	21.27	670	3923	1530	3618	3198
	HIGH	21.52	688	4022	1588	3373	2948
Soissons No. 3	LOW	21.93	641	3733	1505	3258	2833
	SD1	21.83	720	4195	1680	4098	3433
	SD2	21.33	747	4370	1705	3943	3430
	HIGH	21.60	720	4078	1620	3393	3033

Table A.8b - Bread dough rheology for 1996 samples.

Wheat Variety	Nominal Starch Damage	Phase angle (degrees)	Complex viscosity (Pa)	Elastic modulus, G' (Pa)	Viscous modulus, G" (Pa)	Relaxation modulus (Pa)	Rel. mod. (filtered) (Pa)
Cadenza No. 1	LOW	22.30	719	4182	1710	2984	3003
	SD1	21.82	700	4083	1633	2869	2914
	SD2	21.58	772	4508	1783	2944	2995
	HIGH	22.67	703	4052	1623	2794	2843
Cadenza No. 2	LOW	21.53	754	4407	1738	2888	2911
	SD1	21.83	737	4300	1722	2552	2613
	SD2	21.75	771	4497	1793	2626	2696
	HIGH	21.08	767	4497	1733	2795	2860
Consort No. 1	LOW	23.30	591	3408	1465	1938	1989
	SD1	23.82	588	3378	1488	1828	1836
	SD2	23.37	625	3602	1555	2045	2055
	HIGH	23.32	661	3808	1645	2285	2331
Consort No. 2	LOW	21.62	713	4167	1652	2328	2357
	SD1	21.78	780	4548	1818	2421	2487
	SD2	21.73	716	4180	1665	2067	2122
	HIGH	22.60	621	3603	1500	1862	1915
Consort No. 3	LOW	21.33	686	4017	1565	2535	2580
	SD1	21.77	698	4075	1633	2720	2761
	SD2	22.25	632	3673	1503	2403	2446
	HIGH	22.23	679	3950	1615	2215	2309
Hereward No. 1	LOW	24.53	536	3063	1397	1974	1993
	SD3	23.77	550	3167	1390	1974	2007
	HIGH	23.57	566	3260	1417	2235	2248
Hereward No. 2	LOW	23.87	471	2703	1200	1639	1650
	SD3	23.73	581	3340	1470	2011	2077
	HIGH	26.03	494	2787	1360	1826	1840
Hereward No. 3	LOW	23.25	722	4167	1790	2571	2568
	SD1	23.13	677	3910	1673	2458	2465
	SD2	24.25	642	3678	1660	2257	2315
	HIGH	23.78	668	3837	1693	2608	2694
Hunter No. 1	LOW	23.35	731	4218	1815	2814	2893
	SD3	23.50	700	4032	1752	2645	2654
	HIGH	23.07	721	4172	1772	2365	2515
Hunter No. 2	LOW	24.53	747	4267	1947	2832	2884
	SD1	24.40	787	4500	2043	2497	2522
	SD2	24.37	746	4267	1933	2348	2392
	HIGH	23.80	117	6737	2970	3990	4033
Hunter No. 3	LOW	20.83	992	5827	2218	4102	4134
	SD1	21.07	967	5668	2185	3748	3836
	SD2	20.68	967	5715	2145	3991	4081
	HIGH	21.13	884	5182	2003	3373	3501
Mercia No. 1	LOW	25.38	753	4280	1990	2514	2558
	SD3	22.60	759	4402	1835	2738	2758
	HIGH	23.40	766	4413	1900	2702	2736
Mercia No. 2	LOW	25.43	603	3423	1630	2048	2128
	SD1	24.57	590	3367	1543	2160	2167
	SD2	24.47	594	3390	1550	2086	2068
	HIGH	23.68	657	3775	1668	2365	2421
Mercia No. 3	LOW	24.05	649	3725	1660	2309	2339
	SD1	23.68	653	3757	1647	2328	2354
	SD2	23.48	632	3638	1583	2626	2639
	HIGH	23.57	666	3833	1672	2383	2375
Riband No. 1	LOW	24.57	621	3553	1627	2011	2052
	SD1	25.23	676	3840	1810	1937	1964
	SD2	24.97	700	3990	1850	2385	2394
	HIGH	24.80	665	3790	1757	2086	2148
Riband No. 2	LOW	24.50	609	3483	1588	2067	2064
	SD3	24.55	641	3665	1672	1955	1954
	HIGH	23.75	697	4003	1758	2086	2119
Soissons No. 1	LOW	22.37	824	4783	1972	2925	2960
	SD1	22.60	826	4790	1992	2833	2889
	SD2	22.28	908	5367	2163	2982	3037
	HIGH	22.48	868	5042	2083	2944	3045
Soissons No. 2	LOW	22.60	692	4018	1668	2591	2623
	SD1	22.85	706	4085	1722	2647	2695
	SD2	22.45	766	4448	1838	2852	2867
	HIGH	23.02	703	4063	1723	2664	2681
Soissons No. 3	LOW	22.65	684	3967	3987	2926	2907
	SD1	22.22	729	4240	1728	2740	2818
	SD2	21.67	707	4128	1640	2684	2722
	HIGH	21.60	781	4562	1798	2682	2719

Table A.9a - Biscuit dough rheology for 1995 samples.

Wheat Variety	Nominal Starch Damage	Phase angle (degrees)	Complex viscosity (Pa)	Elastic modulus, G' (Pa)	Viscous modulus, G" (Pa)	Relaxation modulus (Pa)	Rel. mod. (filtered) (Pa)
Beaver	LOW	31.00	3067	16533	9925	37425	35800
	SD1	30.37	3038	16467	9660	33925	31875
	SD2	31.63	2330	12450	7685	27750	24825
	HIGH	30.70	3428	18533	11000	36700	34725
Cadenza No. 1	LOW	20.97	2262	13250	5093	28125	26200
	SD1	27.33	3630	20283	10475	36825	35075
	SD2	27.42	2208	12317	6397	23200	21400
	HIGH	22.17	2567	14950	6110	30825	29425
Cadenza No. 2	LOW	26.47	2038	11467	5712	20150	19300
	SD1	27.03		15600			27875
	SD2	27.12	5292	11800	6038	21625	20175
	HIGH	21.25	2028	11867	4610	24425	23250
Cadenza No. 3	LOW	-	-	-	-	-	-
	SD1	24.93	1967	11183	5197	17675	16300
	SD2	26.57	2640	14817	7425	25200	23025
	HIGH	26.48	2377	13350	6657	24300	22250
Consort No. 1	LOW	28.97	2217	12167	6753	16370	16610
	SD3	29.83	2540	13867	7930	16990	18320
	HIGH	30.33	2747	14900	8727	20735	21240
Consort No. 2	LOW	29.27	2313	12700	7107	17045	17710
	SD3	28.93	2503	13800	7610	22315	22745
	HIGH	28.20	2877	15933	8550	26445	26965
CWRS	LOW	26.47	2517	14167	7057	20505	20560
	SD1	26.53	2407	13533	6747	17040	17600
	SD2	26.33	2337	13167	6507	16270	16000
	HIGH	26.73	2260	12700	6383	17505	17405
Hereward No. 1	LOW	26.85	1965	11017	5573	19400	18200
	SD1	28.58	1950	10763	5865	18500	17475
	SD2	27.08	1963	10978	5602	19975	18175
	HIGH	27.70	1823	10128	5315	18550	17225
Hereward No. 2	LOW	27.30	2313	12917	6698	24550	22825
	SD1	27.62	1947	10842	5660	17700	16725
	SD2	26.80	2417	13550	6840	25025	22800
	HIGH	27.25	2190	12217	6297	22200	20300
Hereward No. 3	LOW	27.70	2097	11667	6128	21400	20400
	SD1	28.85	1673	9192	5063	16725	15125
	SD2	29.32	1985	10883	6098	18500	17925
	HIGH	28.03	2133	11850	6298	23125	21225
Hunter No. 1	LOW	28.27	3907	21600	11600	36860	37085
	SD1	27.97	3283	18233	9667	24330	25410
	SD2	27.23	3263	18233	9397	30535	30930
	HIGH	28.73	2473	13633	7483	18445	18740
Hunter No. 2	LOW	29.60	2470	13467	7653	19035	20140
	SD3	28.83	2990	16433	9050	26925	27635
	HIGH	30.03	3150	17133	9897	27430	27680
Mercia No. 1	LOW	27.10	2603	14567	7448	25425	23950
	SD1	26.52	2368	13300	6640	24650	23250
	SD2	27.40	2472	13767	7128	26050	24850
	HIGH	27.25	2880	16083	8278	30275	28275
Mercia No. 2	LOW	-	-	-	-	-	-
	HIGH	-	-	-	-	-	-
Mercia No. 3	LOW	27.98	2590	14383	7635	24825	23000
	SD1	27.95	2435	13500	7157	24200	23275
	SD2	20.90	2192	12867	4908	28125	27175
	HIGH	28.25	-	15433	-	-	25600
Riband No. 2	LOW	30.35	3137	16983	9958	33500	31525
	SD1	30.97	4542	24433	14750	48725	45900
	SD2	30.78	5250	28283	16967	62025	58300
	HIGH	31.23	-	19600	-	-	41067
Soissons No. 1	LOW	26.45	1983	11133	5547	18400	17925
	SD1	25.80	1505	8525	4117	14450	13675
	SD2	25.93	2012	11372	5517	21975	20800
	HIGH	26.97	-	11380	-	-	21400
Soissons No. 2	LOW	25.67	1712	9702	4655	16625	15125
	SD1	25.97	2017	11383	5548	18800	18175
	SD2	24.58	1825	10438	4767	19800	18600
	HIGH	24.63	1780	10162	4653	19125	17475
Soissons No. 3	LOW	25.67	2092	11850	5692	17700	17200
	SD1	26.07	1788	10088	4937	15900	15800
	SD2	25.87	1587	8970	4353	14125	12850
	HIGH	26.38	1987	11167	5543	20300	17650

Table A.9b - Biscuit dough rheology for 1996 samples.

Wheat Variety	Nominal Starch Damage	Phase angle (degrees)	Complex viscosity (Pa)	Elastic modulus, G' (Pa)	Viscous modulus, G" (Pa)	Relaxation modulus (Pa)	Rel. mod. (filtered) (Pa)
Cadenza No. 1	LOW	27.63	1913	10663	5583	15810	16120
	SD1	28.20	2040	11300	6070	14630	14740
	SD2	26.93	2280	12800	6493	15960	16505
	HIGH	27.37	2137	11933	6157	15040	15065
Cadenza No. 2	LOW	28.60	1983	10933	5953	12545	13140
	SD1	27.37	2123	11833	6127	14595	14790
	SD2	27.87	2397	13267	7040	17455	18350
	HIGH	26.90	2407	13467	6837	17450	17465
Consort No. 1	LOW	27.57	2907	16167	8463	24830	25535
	SD1	28.17	1967	10900	5837	15225	14715
	SD2	27.70	1950	10863	5697	13980	14665
	HIGH	28.37	1830	10093	5473	12660	13050
Consort No. 2	LOW	28.53	1713	9450	5147	11695	11835
	SD1	28.97	1820	10013	5537	11765	12400
	SD2	29.10	1827	9997	5570	11799	12135
	HIGH	28.43	2027	11167	6060	15135	16815
Consort No. 3	LOW	29.70	2297	12533	7157	16890	17680
	SD1	28.37	2113	11667	6307	15640	15620
	SD2	29.30	2327	12767	7153	15640	17480
	HIGH	28.70	2153	11867	6493	15225	16635
Hereward No. 1	LOW	28.00	1890	10500	5580	11770	12635
	SD3	28.20	9687	5373	2877	4851	5027
	HIGH	27.60	1863	10380	5437	10540	11090
Hereward No. 2	LOW	28.33	2003	11067	5967	16320	15700
	SD3	27.67	2183	12133	6377	15090	15830
	HIGH	27.87	2020	11233	5930	13395	13470
Hereward No. 3	LOW	28.10	1867	10317	5520	13030	12860
	SD1	27.30	2073	11567	5973	14540	14420
	SD2	28.57	1953	10800	5870	14460	14700
	HIGH	28.87	2030	11167	6157	12920	14030
Hunter No. 1	LOW	29.10	3390	18633	10330	26025	26560
	SD3	29.17	3587	19633	10967	31820	32460
	HIGH	28.67	3120	17200	9400	19850	20490
Hunter No. 2	LOW	28.17	2737	15200	8117	24445	24665
	SD1	28.67	2873	15867	8673	23620	24525
	SD2	29.43	2507	13700	7733	22455	22645
	HIGH	27.70	2630	14633	7683	21970	22305
Hunter No. 3	LOW	27.77	2613	14533	7647	19150	20235
	SD1	27.27	2640	14733	7593	22105	22080
	SD2	27.10	2507	14033	7197	20800	21490
	HIGH	27.27	2677	14933	7710	20325	21090
Mercia No. 1	LOW	28.13	3147	17433	9323	24445	25455
	SD3	27.17	3183	17767	9143	25205	26250
	HIGH	27.33	3070	17133	8853	22390	22295
Mercia No. 2	LOW	28.40	2443	13500	7310	18160	18800
	SD1	28.33	2600	14400	7760	17400	18735
	SD2	29.37	3013	16500	9280	18975	21075
	HIGH	28.40	2643	14600	7897	17395	18460
Mercia No. 3	LOW	26.80	2417	13567	6850	17300	18610
	SD1	27.53	2400	13400	6980	19325	18960
	SD2	27.90	2957	16400	8697	21415	22475
	HIGH	27.43	2557	14267	7400	18085	18645
Riband No. 1	LOW	30.50	3110	16833	9930	23425	24390
	SD1	31.20	3130	16867	10180	27015	26610
	SD2	30.37	2643	14333	8413	23010	23995
	HIGH	30.37	2493	13533	7913	19270	19795
Riband No. 2	LOW	29.97	2603	14167	8163	17915	19670
	SD3	28.90	2000	11000	6057	16545	16555
	HIGH	29.17	2867	15700	8760	20325	20855
Soissons No. 1	LOW	26.97	1727	9667	4917	14055	14335
	SD1	27.17	1733	9703	4980	12955	13300
	SD2	26.60	2167	12167	6097	14630	16015
	HIGH	25.60	1883	10633	5120	14500	14220
Soissons No. 2	LOW	26.67	1843	10337	5197	13980	13880
	SD1	26.47	1880	10567	5263	15225	14245
	SD2	26.80	1930	10800	5463	14395	13720
	HIGH	25.83	2073	11733	5687	14810	15220
Soissons No. 3	LOW	27.07	2197	12300	6283	15640	15815
	SD1	26.53	2520	14167	7077	17150	17255
	SD2	26.73	2517	14133	7120	17670	18425
	HIGH	25.87	2630	14900	7210	17200	18355