HGCA

PROJECT REPORT No. 160

EFFECTS OF SEASONAL AND SHORT-TERM CHANGES DURING STORAGE ON THE BREADMAKING PERFORMANCE OF HOME-GROWN WHEAT

APRIL 1998

Price £10.00

PROJECT REPORT No. 160

EFFECTS OF SEASONAL AND SHORT-TERM CHANGES DURING STORAGE ON THE BREADMAKING PERFORMANCE OF HOME-GROWN WHEAT

by

S E SALMON

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

This is the final report of a three year project which commenced on 1 July 1991. The work was carried out by the Campden and Chorleywood Food Research Association and was supported by a grant of £412,700 from the Home-Grown Cereals Authority (project no 0020/1/91).

CONTENTS

4.3 Effects on dough rheology

ABSTRACT

Breadmaking wheat varieties, representing different protein quality classes, were milled as soon as possible after harvest before being stored at -18°C (control flour) or under controlled conditions of 15-20°C and ~50% relative humidity (stored flour). The remaining wheat was held under an equivalent storage regime to the stored flour and at pre-determined time-points samples were removed for comparison of milling and breadmaking quality potential. This protocol was devised to permit separation of the effects of wheat storage after harvest and normal flour storage over the same period (~8 months) on end-use quality.

Post-harvest changes in wheat quality have been documented since the beginning of the century, but seasonal differences in fundamental quality due to growing or harvesting conditions may also be responsible for observed variability in processing performance of home-grown wheat at crop changeover. The magnitude and biochemical basis of this variability required investigation to provide end-users, millers and bakers, with the necessary information to optimise product consistency.

Optimum milling performance in a laboratory Bühler mill was generally not achieved until wheat had been subjected to a period of storage prior to milling. In particular, the endosperm appeared to be easier to separate from the bran and a slight increase in flour particle size was observed after storage. Sieving problems have been perceived by millers when using new crop wheat and increased granularity would be expected to improve flour flow characteristics. Unfortunately, the Instron method used to test ease of flour movement and potential for bridging proved too imprecise to enable a firm conclusion to be made on this point. Effects on milling performance were generally overcome by storage for approximately six weeks, confirming the value of blending old and new crop wheat at harvest changeover.

Storage, as wheat or flour, had no significant effect on basic chemical and rheological properties of white flour. Any observed changes in flour quality characteristics could be related to milling differences, i.e. increases in flour extraction.

Wheat storage prior to milling had no consistent, significant effect on final quality in a standard Chorleywood Breadmaking Process (CBP). Prolonged flour storage (of up to eight months) generally resulted in a deterioration in quality as indicated by reduced CBP loaf volume. This decline in quality was associated with increased free fatty acid levels and reduced sulphydryl content of flour.

There was no evidence of varietal susceptibility to post-harvest changes, but seasonal variations had a major impact on quality for breadmaking. The magnitude of season-to-season differences generally exceeded any wheat storage effect and no solution to this natural, annual variation in protein content and protein quality could be recommended from biochemical studies.

1. INTRODUCTION

Millers require wheat varieties which will perform consistently from one season to another in order to ensure that they are able to provide their customers with a dependable product. As an indication of the importance UK millers place on varietal consistency, no cultivar which exhibits marked seasonal or site-to-site variation during assessment in National Institute of Agricultural Botany (NIAB) trials will meet the requirements of The National Association of British & Irish Millers (NABIM, 1995) Group 1 classification, i.e. varieties favoured for breadmaking. Variation in quality parameters, and hence varietal performance, is known to occur as a result of climatic and husbandry conditions during growing (Dampney *et al.*, 1996). In addition, experiences with the cultivar Pastiche showed that seasonal variability and lack of tolerance to enforced changes in UK breadmaking processes can lead to the failure of individual varieties in the marketplace (Osborne *et al.*, 1991).

Current mill intake tests only provide a means of identifying wheat samples which are unsuitable for use in a particular grist: for example due to excessive *alpha*-amylase activity, insufficient protein content or incorrect quality class. Such tests are not able to predict accurately how a particular sample of wheat will perform in breadmaking and are certainly not capable of discerning variation in end-use performance resulting from post-harvest maturation or subtle seasonal differences. It is, therefore, important to breeders and end-users alike to appreciate the extent of such quality variation, to understand the biochemical changes underlying any differences and, ultimately, to be able to identify any procedures which might alleviate the consequences of variation in milling or baking performance.

There have been many reports of “new crop phenomena” and post-harvest changes in the milling and breadmaking quality of wheat dating back to the early 1900's with many theories presented to explain observed effects. Previous storage experiments at normal temperatures (Vaidyanathan, 1987) have suggested that Falling Number values increase during storage, but it is uncertain whether such changes reflect real effects on cereal *alpha*-amylase activity or are merely a result of errors associated with sampling or differences in moisture content. Seiler and Solomons (1988) also observed an increase in Falling Number with storage time (at elevated temperatures), but this could not be related to differences in amylase activity.

For many wheat and flour users, any observed and otherwise unexplainable variation in processing performance immediately after harvest is attributed to seasonal variation or the use of freshly harvested grain which has not had the benefit of a period of maturation. Thus, the two major concerns of this project are quite closely linked. One strategy, which has traditionally been used by millers to minimise potential variation in quality is to maintain a small stock of old crop and gradually blend in increasing proportions of new crop wheat. No rules for this blending operation have been defined or documented.

Recently, there has been increased interest in the subject of post-harvest changes in wheat quality worldwide (Rao *et al.*, 1978; Posner & Deyoe, 1986; Moss & McGuirk, 1990; Gesternkorn *et al.,* 1990; Srivastava & Rao, 1991; and Shelke *et al.*, 1992 a and b) which has tried to produce quantitative evidence for perceived differences in the milling and baking performance of freshly harvested wheat. As a result of differences in approach and in the end-products examined, observed changes in processing quality and in the principal components of the wheat grain have been somewhat varied and inconsistent.

According to Posner and Deyoe (1986), post-harvest maturation makes wheat easier to mill. In studies using US Hard Red winter and spring wheat, wide variations in milling performance were found between freshly harvested and stored wheat as far as flour extraction, flour granulation and water absorption were concerned. Such changes in milling performance may be expected to affect end-use quality and small scale baking tests showed that loaf volume increased to reach a peak at about 110 days after harvest before decreasing again. Gesternkorn *et al.*, (1990) suggest that natural wheat ageing affects measured grain quality, but that this may not be reflected in baking or sensory characteristics. Other studies (Moss & McGuirk, 1990) suggested that post-harvest storage of up to 2 months had no effect on milling behaviour or final breadmaking quality, but merely had minor effects on dough strength and mixing time. Breadmaking tests included the improver potassium bromate which is no longer a permitted additive in the UK. Potassium bromate is a slow-acting, but very effective, oxidising agent which has a major role in the disulphide:sulphydryl (SS:SH) interchange reactions in bread dough (Collins, 1992) and thus may have had a major influence on the handling properties of doughs and their breadmaking performance in the Moss & McGuirk study.

Indian workers (Rao *et al.,* 1978) suggested that the reduction in loaf volume observed when samples of newly harvested wheat were baked could be attributed to low SS:SH ratios. Addition of the oxidising agent potassium bromate, which alters the SS:SH balance, had the same effect on dough rheology and breadmaking performance as wheat storage. Rao *et al.*, (1978) also observed changes in protein solubility and aggregation during post-harvest storage with implications for protein functionality in breadmaking. Differences in dough handling/stickiness with wheat age had also been observed in EC Intervention machinability test studies at FMBRA in 1981 (Anon, 1981). The pass rate in the machinability test, which uses ascorbic acid as the sole oxidising agent, improved significantly when most wheat varieties were stored for 6 months. Changes in protein solubility during storage were suggested by polyacrylamide gel studies. Thus, one hypothesis appears to be that changes in protein composition and structure are, at least partly, responsible for observed variability in dough handling and baking performance resulting from wheat storage.

Rao *et al.* (1978) also suggested that high starch gelatinisation viscosity was implicated in the poor baking performance of wheat varieties immediately after harvest. Studies on freshly milled US soft wheat for cakes and batters further implied differences in paste viscosity as a source of processing variability (Shelke *et al.*, 1992 a and b). Little is known regarding seasonal variation or possible post-harvest differences in the starch component of flour from current UK wheat varieties.

In addition, sensory and biochemical changes are known to occur in the lipid components when wheat or flour is stored for long periods of time or under unsuitable conditions (Bell *et al.*, 1979a; El Baya *et al.*, 1986). Deterioration in gluten quality, breadmaking performance and the degradation of polar lipids could be reduced by storage at 8°C or less. Measurement of wheat flour lipid composition was used to identify whether storage conditions produced any undesirable changes in the lipid components.

There has been much speculation regarding subtle seasonal differences in quality and the advantages, or otherwise, of milling new crop UK wheat immediately after harvest. This study attempts to establish the facts and determine whether simple storage has any measurable effect on wheat quality. Studies have been restricted to hard, breadmaking wheat varieties since it was essential to concentrate on one particular end-use and breadmaking quality was considered to be most susceptible to storage changes.

2. OBJECTIVES

The overall objective of this project was to investigate the causes of observed differences in the quality of home-grown wheat which occur from one season to the next. In particular, the aim was to monitor the performance of different types of breadmaking wheat over three harvest years.

The study also compared the analytical and processing properties of wheat stored under controlled conditions with the objective of identifying any quality changes which might occur with time of storage. Data emanating from this project was intended to characterise wheat types which were more or less prone to variability from climatic or storage sources. Detailed biochemical studies were carried out in an attempt to seek explanations for any observed changes in performance.

Having established the magnitude and consequences of changes which may take place as wheat ages after harvest, this project aimed to provide advice to millers on the advisability of blending old crop with new crop wheat in the immediate post-harvest period to ensure product consistency and minimise any effects of wheat maturation.

3. MATERIALS AND METHODS

3.1 Materials

Within the three years of this project, the following five varieties have been examined from the harvest indicated in brackets:

Avalon (1991, 1992 ,1993)
Mercia (1991, 1992, 1993)
Hereward (1992, 1993)
Fresco (1992)
Torfrida (1993)

The varieties were chosen to cover a wide range in protein quality, to represent different classes of breadmaking quality and to include the major breadmaking wheats in use over the time span of the project.

Previous studies, supported by HGCA (Brock, 1991; Pritchard *et al.*, 1992) permit the classification of UK breadmaking wheat varieties according to the amount and quality of their "gel protein" fraction and their performance in a high speed Chorleywood Bread Process over a range of different work input levels.
Using this classification, the varieties examined in this study can be described as follows:

Avalon is typical of a standard breadmaking variety. It has a high level of gel protein, but this lacks strength or elasticity resulting in a variety which has below average tolerance to mixing in a Chorleywood Bread Process (CBP), i.e. it produces optimum performance at a work input of around 7 watt hours per kilo (Wh/kg).

Mercia generally has slightly lower levels of gel protein than Avalon, but this protein tends to be slightly stronger and consequently better for breadmaking. Optimum performance in CBP occurs at 7 Wh/kg, but the variety has a better tolerance to mixing with satisfactory performance occurring at work levels up to 17 Wh/kg.

Hereward has a combination of high gel protein weight with a good balance of elastic and viscous properties. This produces a variety with very good tolerance to mixing in CBP and optimum performance at around 14 Wh/kg.

Fresco and Torfrida are high work input varieties, commonly classified as "extra strong". They contain high levels of gel protein which is also very strong and elastic. "Extra strong" varieties generally require additional work to fully develop the dough during mixing. Such varieties commonly produce optimum breadmaking performance in CBP at a work input level of around 18 Wh/kg.

Thus, the varieties selected cover the full range of bread wheat types in commercial use and differences in quality characteristics may be expected to influence the magnitude of any observed seasonal or storage effects.

The 1991 harvest period was without major incident. Harvesting conditions were generally favourable in the major wheat growing regions of the UK and there were no serious problems of grain shrivelling, disease or Falling Number. Samples of commercially grown Avalon and Mercia were selected on the basis of their suitability for milling and breadmaking, i.e. wheat protein contents above 11.0%, Falling Numbers above 250 seconds, absence of disease and acceptable in terms of specific weight. Two samples of Avalon [Avalon(M) and Avalon(A)] from farms in Chelmsford, Essex and Ashwell, Cambridgeshire respectively and two of Mercia [Mercia(BG) and Mercia(B)] from farms in Bowmansgreen, Hertfordshire and Bucklandbury, Cambridgeshire respectively were selected for study and sampled within three days of harvesting.

In 1992 wheat samples of the required varieties Avalon, Mercia, Fresco and Hereward were grown under contract by ADAS, Boxworth under commercial cultivation conditions aimed at producing wheat samples with above 11.0% protein. Harvesting in 1992 was generally more problematic in the UK. The harvest was split into two discrete portions, before and after the rain. May and June were characterised by warm, dry periods which led to drought conditions and rapid grain ripening. The wheat crop was generally of high protein content, but also tended to be slightly poorly filled and shrivelled. In August, a period of very wet weather delayed grain harvesting resulting in an increase in disease and a significant decrease in Falling Number in later harvested crops. Single variety wheat samples were harvested on 3rd August 1992, before the period of bad weather and were found to be acceptable in terms of Falling Number and protein content. There was some evidence of grain shrivelling, but this was not considered serious enough to warrant rejection at mill intake and was a typical feature of wheats from this part of the 1992 harvest. (Specific weights of wheat samples grown at the Boxworth site, varied from 71.0 for Avalon to 80.0 for Hereward.)

Arrangements had been made to grow the same range of wheat varieties under contract at ADAS, Boxworth in the 1992/93 season. However, grain samples proved unsuitable with regard to protein content and Falling Number. During Spring 1993 there was a period of very wet weather followed by a relatively cool period, but no prolonged spells of dry or wet weather were encountered. Temperate conditions during grain development and maturation resulted in grain with below average protein content. In addition, during the final stages of grain maturation there was a prolonged wet period which seriously hampered and delayed harvesting resulting in Falling Number problems in many wheat crops. Commercial samples of Avalon, Mercia, Hereward and Torfrida were obtained from a UK grain merchant, which despite rather late harvesting, were acceptable in terms of both protein content and Falling Number.

3.2 Methods

3.2.1 Measures of basic quality

Wheat samples were tested for protein content by Kjeldahl and for Falling Number prior to acceptance for storage trials. Visual examinations were also performed to ensure samples were clean, relatively well-filled and free from disease and insect damage. Moisture content was measured by Near Infrared Reflectance (NIR) to confirm that samples were of suitable moisture content for safe storage (Anon, 1991).

Table 1 shows the effect of seasonal variations in growing and harvesting conditions on basic wheat quality.

Moisture content was slightly high in 1993 as a result of poor harvesting conditions and samples had to be dried to ensure safe long-term storage. Protein content was acceptable for all varieties in 1991 and 1992, but only the Mercia sample in 1993 managed to meet a typical intake specification for breadmaking wheat. All varieties, except Hereward in 1993, produced acceptable wheat Falling Numbers above 250 seconds: Hereward in 1993 was marginal at 247seconds. Specific weight was below normal intake levels for Avalon(M) in 1991; Avalon, Mercia and Fresco in 1992 and for Avalon in 1993.

Table 1 Basic quality criteria of wheat samples 1991-1993

Harvest year	1991				1992				1993			
Variety	Avalon (M)	Avalon (A)	Mercia (BG)	Mercia (B)	Avalon	Mercia	Hereward	Fresco	Avalon	Mercia	Hereward	Torfrida
Moisture,%	12.8	13.7	13.9	13.9	12.4	12.7	13.8	12.8	14.4	14.7	14.9	15.7
Protein,% (N x 5.7) at 14% moisture	11.6	11.4	12.9	11.6	12.0	11.7	11.9	12.0	10.9	11.0	10.4	10.1
Falling Number,s	362	405	340	299	338	350	291	382	305	312	247	349
Specific weight, kg/hl	72.1	77.1	78.0	77.8	71.0	73.2	80.0	75.7	75.2	78.3	76.5	76.9

3.2.2 Storage conditions

Wheat samples (130 kg) were collected as soon as possible after harvest. Wheat moisture content was checked using a Sinar moisture meter to ensure that all samples were below 15% and therefore satisfactory for long-term storage. Samples were then cleaned using a Carter-Day Dockage Tester, fitted with standard screens as specified in Laboratory Bühler milling method MS 0001, to remove extraneous material (weeds, stones, husk, chaff etc.) plus severely shrivelled or undersized grains. Samples were subjected to a storage and sampling regime as shown in Figure 1.

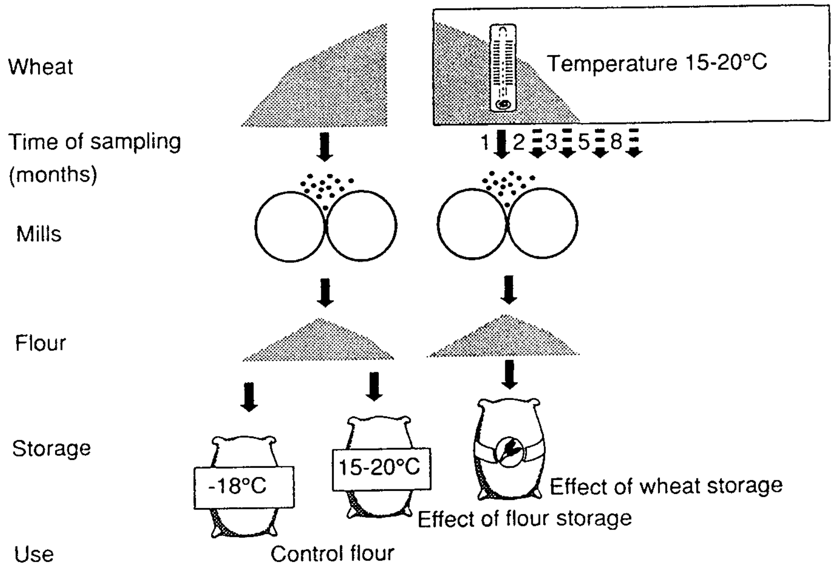


Figure 1 Wheat and flour storage conditions plus approximate post-harvest wheat sampling times used in storage studies.

Each bulk wheat sample was divided in half, the first (65kg) portion was placed in plastic boxes under controlled storage conditions of 15-20°C and relative humidity of ~50%. Sub-samples were then removed for milling and baking performance assessment at various stages after harvest (precise times of storage varied from one year to the next and are identified in tabulated test results as days after harvest). The remainder of each sample (65kg) was milled immediately after harvest to produce a white flour for analysis. This bulk white flour was sub-sampled for testing when fresh and the remainder further sub-divided for storage at -18°C and 15-20°C respectively. In all cases the flour stored at -18°C represented the stable, "control" flour. In 1991 "control" flour samples were canned under nitrogen and contained a sachet of Ageless (oxygen absorber) to protect milled samples against oxidative changes. In 1992 and 1993 canning was not practical due to difficulties scheduling this operation within 4 weeks of the initial test milling and, therefore, following exclusion of excess air, samples were sealed in double polythene bags and stored at -18°C. The remaining portion of the milled flour was stored in double, sealed polythene bags under identical conditions to the wheat i.e. 15-20°C and ~50% relative humidity in order to establish the effect of storage on flour quality.

3.2.3 Milling performance

Milling performance was assessed by a number of standard procedures which measure the effectiveness of the separation of endosperm (required for white flour production) from bran and germ (which need to be minimised to maintain flour colour and ash content), particle size and flow properties.

Since all varieties examined in this study were hard endosperm textured, wheats were conditioned to 16.0% moisture prior to Bühler milling. For large samples of wheat, the conditioning stage was executed in a Belle concrete mixer. The required amount of water was added to the wheat sample and mixing allowed to proceed for a minimum of 10 minutes. Wheat samples were conditioned for a total of 16-23 hours to permit adequate penetration of moisture into the endosperm and enable optimum separation of white endosperm and bran components.

Samples were milled on Bühler MLU 202 laboratory mills to produce white flour for subsequent analysis (Brown and Scanlon, 1992). The mills were optimised on the basis of achieving flour yields and starch damage contents as close as possible to commercial practice for a Chorleywood Bread Process flour (Osborne *et al.*, 1991). The milling procedure includes two passages through a bran finisher to permit maximum extraction of white flour. Flour extraction was measured, as a percentage, on a total products basis as:

i) straight-run flour, i.e. collection and blending of all the flour streams from the break and reduction systems of the Bühler mill, and

ii) total flour, i.e. straight-run plus additional endosperm removed from the combined bran and offal fractions during two passages through a Bühler MLU 203 impact finisher.

In order to mill the initial 65kg of four wheat samples within a short period of time, it was necessary to use two different mills. Both mills were set to achieve white flour extraction rates and starch damage levels within the accepted control limits for the milling test and checked using a "standard" wheat sample. A bulk of this "standard" wheat was maintained throughout the project and tested at each time-point to check mill performance. Each variety was milled on the same mill by the same operator at each sampling point.

It has been reported that flour granularity and sieving properties change with wheat storage, particularly during the immediate post-harvest period. In order to investigate seasonal changes in flour granularity and changes due to wheat storage before milling, detailed measurements of the particle size distribution of Bühler milled flour were performed using a Coulter Counter Model TA II (Evers, 1979). The Coulter Counter measures particle size distribution by the change in resistance caused by particles displacing isopropanol electrolyte in an orifice which has an electric current passing through it. This change in resistance produces a pulse, the size of which is directly related to the particle's volume. By measuring many thousands of particles within a sample, a picture is built up of the particle size distribution within a flour sample.

Many millers have reported problems in processing freshly harvested wheat such that the resultant flour is "fluffy" and difficult to sieve. The ease with which flour passes through the mill is important to commercial millers, but is difficult to measure on a laboratory mill and there is no standard method of assessing the magnitude of the problem in the laboratory. Flour flow problems are reported to be most severe for soft endosperm textured wheats and thus appear to be related to fracture properties during milling. Since this study only examined hard textured breadmaking wheat varieties, any changes in flour flow characteristics may be relatively minor and difficult to detect.

In this work, flour flow properties were examined using a modification of an Instron method (Neel and Hoseney, 1984). An Instron 1122 compression testing instrument was used with a standard plunger operating at 50mm/min vertical compression to measure the pressure required to cause the flour to bridge in a cylinder. The bridging threshold of flour samples was measured by compressing a 20g sample of the flour in an open-ended cylinder of fixed internal diameter (38mm). A range of forces were used to compress the sample and the minimum force , in Newtons, which caused the flour to bridge across the cylinder after removal of the force and inversion of the cylinder was reported as the bridging threshold. Measurement of the flour bridging threshold was performed on 10 individual samples of flour as soon as possible after milling. The average value is quoted.

3.2.4 Routine flour quality measurements

Flours were assessed, in terms of quality for breadmaking, using the following series of industry standard tests.

Flour colour was measured according to standard industry practice using the Kent-Jones colour grader in GCF units (Anon, 1991). This instrument indicates the level of bran contamination in a white flour by measuring the reflectance of a flour/water paste at 530nm. Since white endosperm particles reflect and bran particles absorb light, high flour colour values indicate an increase in the level of bran particles present in the flour. Bran performs no function in breadmaking and, therefore, its presence needs to be controlled to reduce variability in the performance of white breadmaking flour. In the standard laboratory milling procedure used, the aim is to obtain the maximum flour extraction from a wheat sample. No attempt was made to blend flour streams to achieve a pre-determined flour colour value as would be carried out commercially.

Ash content was also measured in this work (Anon, 1991). This provides another means of assessing the presence of bran components in white flour since in wheat over half the mineral content of the grain is present in the bran components of pericarp, testa and aleurone and the levels found are nearly three times those in the endosperm (Kent and Evers, 1994). As with flour colour grade, ash values provide a means of monitoring milling performance and variability in Bühler milled flours. In addition, wheat mineral content and hence flour mineral content is also known to differ between varieties, sites and seasons (Redman, 1980). Flour ash content was measured by total incineration of the flour sample at 900°C in platinum crucibles and subsequent weighing of the residue. The ash value obtained was converted to dry matter basis to permit between sample comparison.

The Kjeldahl procedure (Anon, 1991) was used to measure the nitrogen content of the flour and converted to protein content by use of the approved factor for wheat flour of 5.7. All protein values were converted to a standard 14% moisture basis in this work, using the moisture content determined by a standard oven technique.

The Falling Number test (Anon, 1991) was employed to estimate the cereal *alpha*-amylase activity of a flour sample by measuring the time taken for a plunger to fall a fixed distance through a heated flour/water paste and the thinning effect caused by the rapid action of cereal *alpha*-amylase on the cooked starch. The weight of flour used was adjusted according to the moisture content of the flour so that differences in dry weight tested did not influence viscosity and, hence, test results. Falling Number test results are quoted in seconds.

The Farrand method, a chemical means of measuring the total *alpha*-amylase activity of a flour, was used to provide a direct measure of enzyme activity (Anon, 1991). The rate of degradation of *beta*-limit dextrin, in the presence of a sample extract, was determined spectrophotometrically as the decrease in intensity of colour produced by dilute iodine solution under specified conditions. In commercially milled flours the test can be used to measure *alpha*-amylase of cereal and fungal origin whereas in laboratory Bühler milled flours, the measured *alpha*-amylase activity is entirely of cereal origin. This test was included to determine whether the enzyme *alpha*-amylase can actually be affected by simply storing wheat or flour for a period of time and is also used to calculate the amount of fungal *alpha*-amylase required to supplement flour samples in the standard Chorleywood Bread Process (CBP) baking test used in this work. Results are expressed in Farrand units.

The Farrand damaged starch method (Anon, 1991) measures, in an empirical way, the percentage of the starch which is damaged in flour during milling. A relationship has been established between the amount of reducing sugars produced in the presence of excess *alpha*- and *beta*-amylase and the level of damaged starch. The Farrand method measures the production of reducing sugar under specified conditions and starch damage is expressed in arbitrary Farrand units. Damaged starch granules absorb water more easily than undamaged ones affecting the ability of a flour sample to take up water during dough mixing. The miller aims to control starch damage during milling within fairly tight limits in order to comply with a specification for both starch damage and water absorption and to optimise flour quality for breadmaking. Excessive starch damage levels can lead to a flour which releases water during processing and has reduced loaf volume.

Wet gluten content (Anon, 1991) was determined using a semi-automated method, based on the Falling Number Glutomatic apparatus. A dough was mixed from wheat flour plus buffered salt solution and the starch and water-soluble proteins progressively washed out to leave behind the insoluble gluten proteins, gliadins and glutenins. The gluten ball, remaining after the washing process, was centrifuged to remove excess water and then weighed to provide wet gluten content as a percentage of flour weight. Since it has been reported that protein solubility alters with wheat age, this test was included to provide a crude measure of changes in protein solubility. In addition, the rheology of the gluten ball produced in this test was assessed using the Bohlin VOR rheometer (see Section 3.3.1).

The Brabender Farinograph was used to measure the water requirement of flour samples (Anon, 1991). By recording the torque produced during gentle mixing of flour and water the amount of water required to mix a dough of a fixed, maximum consistency was estimated. In the UK a maximum consistency of 600 Brabender units is the convention. This amount of water, the water absorption, was then used to measure a complete flour mixing curve permitting determination of the time taken to develop the dough (dough development time) and dough tolerance to prolonged gentle mixing (stability and degree of softening values). Changes in the latter values would indicate differences in dough strength arising as a result of storage conditions. The water absorption figure was also used in the standard CBP breadmaking test (see Section 3.2.5).

Working in tandem with the Brabender Farinograph, the Brabender Extensograph was used to provide a simple measure of the resistance to stretching (Resistance) and the distance the dough may be stretched before breaking (Extensibility) of a flour/salt/water dough prepared in a Brabender Farinograph under standard conditions (Anon, 1991). After moulding and resting for a fixed period (45 minutes), the dough was stretched using a hook to produce a curve showing Extensibility in centimetres and Resistance to stretching in arbitrary Brabender Extensograph Units.

The Chopin Alveograph was used according to ISO standard 5530/4 (Anon, 1983). In this test a fixed water addition level was used to mix a flour/salt/water dough under standard conditions. Dough pieces of fixed dimensions were prepared and after a resting period were inflated by air to produce a bubble. A pressure/time curve was recorded and the following measurements were made:

W: the area under the curve, which is related to the energy required to blow the bubble until it bursts, and is quoted in Joules x 10^{-4}.

P: the maximum overpressure achievable in the bubble, which is related to dough strength, and is quoted in millimetres.

L: the length of the curve, representing extensibility of the dough, and quoted in millimetres.

P/L ratio: which is obtained from the above measurements and is known as the "configuration ratio".

3.2.5 Breadmaking quality

All flours were test baked using a standard Chorleywood Bread Process (CBP) procedure one week after milling. This convention was adhered to at all times to ensure that oxidative changes in milled flour could take place, removing the complication of baking freshly milled flour, and also to provide sufficient time for the necessary quality tests to be carried out prior to baking. The recipe used in all experimental baking tests is shown in Table 2. Doughs were mixed in a Morton z-blade mixer to a total work input of 11 Wh/kg at atmospheric pressure. After final moulding, doughs were proved to a fixed height of 10cm at a temperature of 43°C. Doughs were finally baked for 25 minutes at a temperature of 244°C.

Each sample was mixed in duplicate and dough stickiness ex mixer assessed by trained bakery staff. In addition, samples of fully developed dough were taken ex mixer for evaluation of dough stickiness using the Bohlin VOR rheometer (see Section 3.3.1). Doughs were processed and baked to produce four standard 400g loaves. On the day following test baking, loaf volume was measured in millilitres using a standard seed displacement method and crumb structure assessed by experienced bakery staff on all four replicates from a single mix. A photographic record of the internal structure of the bread produced at each time-point was retained.

Table 2 Standard Chorleywood Bread Process (CBP) recipe

Ingredient	**Quantity**
Flour	1400g
Yeast	35.0g
Salt	28.0g
Fat (slip point ~ 45°C)	14.0g
Fungal *alpha*-amylase	The *alpha*-amylase activity of the flour was adjusted to 80 Farrand units by addition of a standard fungal amylase preparation.
Ascorbic acid	0.14g
Water	As determined by Brabender Farinograph, 600line (see 3.2.4)

3.3.1 Protein composition and functionality

In order to try to understand any observed changes in performance, a number of tests of intrinsic quality were carried out on flour. Some tests were also performed on glutens and full recipe bread doughs ex the Morton mixer.

The following procedures were used to measure gel protein content and quality.

Gel protein weight was determined on de-fatted flour (10g) treated with petroleum ether (boiling point [b.p.] 40-60°C, 25ml) for 1 hour, before filtering and drying. 5g of de-fatted flour was stirred with 90 ml of 1.5% sodium dodecyl sulphate for 10 minutes at 10°C and then centrifuged at 25000 rpm for 40 minutes. The weight of gel protein was then recorded and quoted as g/5g flour.

To determine gel protein breakdown rate, 50g flour and 0.9g salt was mixed with the required water level (as determined by the Farinograph 600 line method) for five minutes using a Simon Minor Pin mixer. Aliquots of dough were removed after 1, 2, 3 and 5 minutes mixing, freeze dried and ground to pass through a 250 micron sieve. Each sample was de-fatted and the gel protein weight determined as above. Gel protein breakdown rate was calculated from a semilog plot of gel protein weight versus mixing time. In addition the quality of the gel protein layer was assessed using the Bohlin VOR rheometer after a 20 minute relaxation period.

Dynamic rheological testing has been used increasingly in the study of flour components (Oliver and Pritchard,1993; Attenburrow *et al.*, 1990) and doughs (Weipert, 1990). In this study samples of gel protein, gluten and full recipe bread dough were subjected to oscillatory testing on a Bohlin VOR rheometer to provide information on their viscoelastic properties. Each sample type was examined over the frequency range 0.1-20 Hertz using the conditions shown in Table 3.

Table 3 **Operating conditions for Bohlin VOR rheometer for examination of gel protein, gluten and full recipe bread dough.**

Sample Type	Measuring System	Torque Bar, g cm	Amplitude, %
Gluten	Parallel plates	17.88	0.5
Gel Protein	Concentric cylinder	17.88	100
Bread Dough	Cone and plate	280.17	1

All the applied strains were in the middle of previously determined linear viscoelastic regions. Oscillatory testing was used to determine a series of measurements on the above test sample types.

- G' which is the elastic or storage modulus and is quoted in Pascal.
- G" which is the viscous or loss modulus, also quoted in Pascal. For all the materials studied the viscous modulus responded in the same manner as the elastic modulus and therefore only G' data have been discussed.
- G' and G" are combined in the phase angle or dynamic viscosity, $\tan^{-1} G''/G'$ and is measured in degrees. This can be used to indicate the relative dominance of the elastic and viscous properties. The phase angle is 0° for a completely elastic material and 90° for a completely viscous material.

Improvements in flour quality with storage are thought to be due to oxidative changes in wheat protein fractions resulting in protein aggregation. Size-exclusion high performance liquid chromatography (SE-HPLC) is used extensively to separate cereal proteins on a molecular size basis: the solubilised protein is carried through a column by a solvent and is fractionated into different molecular sizes according to the extent to which the proteins enter the pores of the gel matrix and are thus retarded in their flow. The technique was used to examine changes in protein aggregations within wheat flour over time and under different storage conditions and thus attempt to relate observed differences in protein functionality in breadmaking to changes in protein structure. However, technical problems with the HPLC unit which resulted in essential changes in the extraction procedure and test protocols resulted in unacceptably high variability in the data. Results have therefore only been provided which compare seasonal variations in quality as this was tested under identical conditions at the same time.

For each flour sample, sequential extractions were carried out using a buffer containing sodium dihydrogen orthophosphate (1.2% $^{w}/_{v}$) and sodium dodecyl sulphate (2.1% $^{w}/_{v}$) at pH 7.0. After centrifugation, the supernatant was decanted and frozen for later HPLC separation. The remaining pellet was re-suspended with 7.5ml of extraction buffer containing 1.5% ($^{w}/_{v}$) dithiotreitol (DTT), to reduce disulphide (S-S) bonds, and heated in a water bath at 50°C for 30 minutes with occasional stirring. This treatment separated and reduced the glutenin aggregates resulting in greater solubility and, therefore, permitted analysis by HPLC. Flour slurries were then homogenised for 15 seconds before being centrifuged (45,000 g for 40 minutes). The resulting supernatants (2nd extracts) were decanted and frozen immediately. The pellet remaining after the 2nd extraction was analysed for protein by the standard Kjeldahl method (see 3.2.4). Flour soluble protein determinations were carried out by the Lowry Folin method (Markwell *et al.*, 1978).

An LKB Bromma-twin pump system for solvent delivery/control was used in conjunction with an Ultropac TSK G4000SW gel filtration column (7.5mm x 600) fitted with an Ultropac TSK SWP guard column (7.5mm x 75). Eluted components were detected at 210nm and chromatographic traces were recorded using Interactive Microware software.

The running buffer contained 0.1% SDS and 1.2% sodium dihydrogen orthophosphate (BDH ARISTAR) in HPLC grade water (pH 7.0). It was also usual to add 0.1% sodium azide to prevent bacterial growth. HPLC water was de-gassed by vacuum pump before preparing the buffer which was then vacuum filtered through a 0.45µm cellulose acetate filter (Millipore).

Samples were thawed, then heated in a water bath (50°C/30 minutes) and then allowed to stand for 10 minutes at ambient temperature before loading on to the HPLC column.

All samples were analysed in duplicate, the second run was injected immediately after the completion of the first run using the same sample vial. The time between heating and sample loading was very tightly controlled at 10 minutes in order to minimise variability in test runs, particularly in extracts containing DTT.

The HPLC system was monitored by running a chymotrysinogen standard (1mg/ml in phosphate buffer) on a regular basis. HPLC chromatograms were analysed using the Microware computer package following manual adjustment of the baseline.

3.2.7 Available sulphydryl groups

In this project a protocol was developed to provide comparative measurements of available sulphydryl (SH) groups in milled white flour and thus detect any effect of post-harvest storage on the amount of SH oxidation. Oxidation of sulphydryl (SH) groups to disulphide S-S bonds is likely to affect the aggregation of wheat proteins, the availability of SH-groups for sulphydryl-disulphide interchange reactions and thus the physical properties of doughs produced from wheat flour (Ewart, 1988).

A method exists to measure aliphatic SH-groups, as in wheat proteins and cysteine peptides such as glutathione, by reacting them with Ellman's reagent [an aromatic disulphide 5,5'-dithiobis (2-nitrobenzoic acid)]. The displaced aromatic SH has a yellow colour, when ionised, that can be measured by absorbance at 412nm. A protocol for the use of this reagent to measure SH in a range of protein foods, including flour, has been developed (Beveridge *et al.*, 1974) but samples must first be completely solubilised in a mixture of urea and guanidinium hydrochloride. For the purposes of monitoring changes during ageing of wheat, solutions required substantial dilution to control light scattering which resulted in unacceptably low absorbance readings. Therefore, the protocol was modified to include a de-fatting stage with petroleum ether followed by acetone to remove non-polar and polar lipids.

Flour (150mg) was de-fatted using 1.5ml petroleum ether followed by two portions of acetone (1.5 ml) with centrifugation and removal of the supernatant at each stage. Samples were then treated with the Tris/glycine/EDTA (TGE) pH 8.0 buffer of Beveridge *et al.* (1974) and the protein-denaturing detergent sodium dodecyl sulphate (SDS) to give 2.5% w/v SDS in the buffer. 15µl of Ellman's reagent was added in dimethylformamide (DMF) to each replicate flour sample. Samples were shaken for 15 minutes, then centrifuged for 15 minutes before reading the absorbance at 412nm of an aliquot of the clear supernatant. This approach permitted a much higher ratio of flour to solvent, the insoluble material being removed by centrifugation to leave a supernatant with an absorbance in the region of 0.5-1.5. Samples were measured against de-fatted flour blanks (containing DMF only) and Ellman's blanks (containing TGE/SDS and Ellman's reagent only).

3.2.8 Starch properties

The Brabender Visco-Amylograph was used according to ICC Standard No 126 (Anon, 1972) to produce a starch pasting curve for samples from the 1991 harvest. In 1992 and 1993 harvest samples, the Rapid ViscoAnalyser (RVA) was employed using settings which would mimic the standard Visco-Amylograph procedure. A flour : water slurry, with a solids ratio between 0.12 (RVA) and 0.18 (Visco-Amylograph) was prepared and the viscosity measured as the temperature was increased from 30 to 95°C, cooled back and held at 50°C for a fixed period of time. A number of readings are routinely taken, the most common being:

- maximum Viscosity or Peak height, measured in Brabender units on the Visco-Amylograph and as a % on the RVA and
- temperature at which maximum viscosity occurs.

3.2.9 Lipid content and composition

Lipids are normally divided into two groups, polar and non-polar, the former being able to interact with water and form aqueous phases. Polar lipids are found in cell membranes and the major components of this group are phospholipids and galactolipids. Non-polar lipids are dominated by triglycerides and occur mainly in the embryo and endosperm. Thus, in the intact grain physical separation exists between the various lipid components which is destroyed on milling. Differences in extraction rate are also known to affect lipid composition; as extraction rate increases total lipid content increases. In addition, the situation is influenced by enzyme activity. The enzyme lipase acts on triglycerides to produce diglycerides then monoglycerides and finally free fatty acids. At each stage in the process free fatty acids are produced and therefore free fatty acid content can be used to compare the effectiveness of storage conditions.

The following measurements were made, in duplicate, on the variety Mercia only from all three harvest years. Total lipid content was determined after extraction of flour (6-7g) at ambient temperature with 50ml petroleum ether (b.p.40-60°C). The tube was centrifuged and the clear supernatant aspirated. The petrol was evaporated from a 30ml aliquot and the residue dissolved in 10ml of iso-octane for determination of fatty acid levels by a copper soap method (Murray and Moss, 1990). Values were calculated as oleic acid (% flour weight) and converted to percentage petrol extractable lipid. High performance liquid chromatography (HPLC) was used to examine lipid composition (Carr *et al.,* 1989). In particular, measurements of digalactosyldiglyceride (DGDG), monogalactosyldiglyceride (MGDG), phosphatidylethanolamine (PE) and phospatidylcholine (PC) were separated. Total glycolipid content, was expressed as a percentage of total petrol extractable lipid.

3.2.10 Specific studies on seasonal variations in quality

Total flour protein extracts were examined by SDS-polyacrylamide gel electrophoresis (SDS-PAGE) according to the basic procedure of Laemmli and Favre (1973) to look for seasonal differences in protein composition between samples of the same variety and to confirm known differences between varieties. Studies (Payne *et al.*, 1987) provided correlations between the presence of certain high molecular weight glutenin subunits (HMW-G) and breadmaking quality. Therefore, gels were scanned using a Shimadzu CS-9000 densitometer and the peak areas of specific HMW-G subunits were measured as shown in Table 4.

Table 4 Important HMW-G subunits for each wheat variety.

Variety	HMW-G subunits
Avalon	1, 2+12 and 6+ 8
Mercia	5+10 and 6+8
Hereward	3+12 and 7+9
Fresco	5+10 and 7+ 9
Torfrida	1, 5+10 and 17+18

In addition, the percentage of the total peak area represented by the relevant HMW-G bands was calculated.

Gradient SDS-PAGE was also used to examine the reduced extracts after HPLC. Fractions were obtained from the LKB Bromma Superac system and tubes were combined to give five pooled fractions for each sample in 1991 and four pooled fractions per sample in 1992 and 1993. These were then diluted two-fold with 20% trichloroacetic acid (TCA) and then left in a cool cabinet (4°C) for 48 hours to allow precipitation of protein.

The TCA-protein precipitate was centrifuged for 3 minutes and the supernatant drained. The remaining precipitate was taken up in 5µl Laemmli buffer and heated at 100°C for 3 minutes. The extracts were analysed by gradient SDS-PAGE, followed by a silver stain procedure and densitometry to measure glutenin content.

Flour pentosans are known to contribute to water binding capacity and the soluble pentosan fraction has been shown to influence dough viscosity. Total and soluble pentosans were determined using a rapid method developed by Douglas (1981). For total pentosan content, flour (4.5-5.5mg) was treated with a solution containing acetic acid, hydrochloric acid, phloroglucinol and glucose. The absorbance of the coloured product was measured at 510 and 552nm and, with reference to a standard xylose curve, the quantity of pentosan in the solution was calculated. To determine soluble pentosan content, flour samples were mixed thoroughly with water, centrifuged at 2000 x g for 10 minutes and an aliquot of the supernatant then treated according to the procedure described for total pentosan content. The insoluble pentosan fraction was calculated by difference.

4. RESULTS

For all tests, unless stated otherwise, we assume that the frozen "control" flour is stable and calculate standard deviation for test results for each variety in each season to provide an estimate of variability of the method. Least significant differences are then quoted at the 5% level. The first time-point, i.e. milling of wheat as soon as possible after harvest, is used for all comparisons involving wheat age before milling. The effect of flour storage is estimated by comparison of stored flour results with the frozen "control" flour.

4.1 Effects on milling performance

Simple mill intake tests identify basic quality differences between the same wheat variety grown in different seasons or even different locations (see section 3.2.1). Such differences will have an impact on the milling performance of individual samples, both on a laboratory and commercial scale, and thus will influence final breadmaking quality.

4.1.1 Bühler milling

Throughout this work a standard Bühler milling process was used, each variety being milled on the same mill by the same operator. In essence this means that milling conditions were controlled as closely as possible in order to measure any effect of wheat variety, seasonal variations in quality or wheat age on the quantity and quality of flour produced.

Extraction rate is expressed on the basis of recovered products in two ways: straight-run flour and total flour. Results of Bühler milling of wheat samples are shown in Appendix 1, Table 1 as
i) Extraction rate, % straight-run flour
and ii) Extraction rate, % total flour
for all wheat varieties tested from 1991, 1992 and 1993 harvests.

Since Bühler milling is the first stage in the process, it is not possible to make comparisons with frozen or stored flour. A validation exercise, involving Bühler milling of a range of wheat samples milled by the same operator on the same mill over a period of time, produced Repeatability values as shown in Table 5. These data are used to examine flour extraction rate results shown in Appendix 1, Table 1. There is a 95% probability that differences in extraction rate of more than 1.41% in straight-run flour extraction and 0.50% in total flour have not occurred by chance and thus can be related to changes in the milling performance of individual wheat samples.

The straight-run flour figure indicates the ease with which the bran can be separated from the endosperm using a simple break and reduction roll system: no attempt was made to extract the maximum white flour. For each variety and season, the extraction rate obtained after a given storage time was compared with the initial milling after harvest. For almost all varieties grown in all seasons, the amount of straight-run flour produced was lowest when the wheat sample was milled immediately after harvest. This effect was significant for 1991 harvest samples of Avalon and Mercia and for Avalon, Mercia and Torfrida grown in 1993.

Table 5 **Repeatability of extraction rate results for laboratory Bühler milling method MS0001.**

Extraction rate, %	Repeatability (2.83 x repeatability standard deviation)
Straight-run flour	1.41
Total flour (straight run + 2 finisher flours)	0.50

In 1992, average straight-run flour extraction rate values for the common varieties Avalon and Mercia were very similar to those obtained from wheat harvested in other seasons, but only small differences were observed and these rarely reached significance. The maximum improvements in straight-run yield obtained over the storage period in each year are arranged in order of magnitude in Table 6.

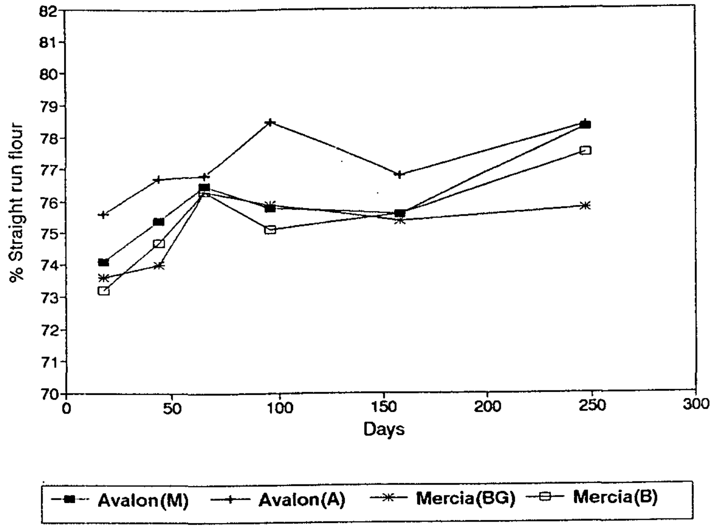
Table 6 **Maximum increase in straight-run flour yield for each variety and year of harvest.**

1991		1992		1993	
Sample	Extraction rate increase	Sample	Extraction rate increase	Sample	Extraction rate increase
Mercia (B)	4.3	Hereward	1.5	Torfrida	4.2
Avalon (M)	4.2	Avalon	1.2	Avalon	3.8
Avalon (A)	2.9	Fresco	1.1	Mercia	2.7
Mercia (BG)	2.7	Mercia	0.1	Hereward	0.4

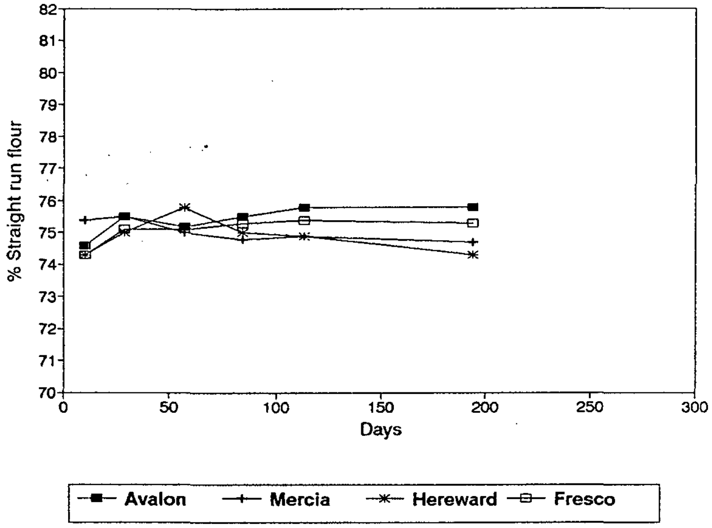
Thus, season appeared to exert an influence on this measure of milling performance with significant improvements in straight-run yield obtained for all varieties in 1991 and all except Hereward in 1993. In 1992, the overall magnitude of any flour yield differences was much smaller and only one increase in straight-run flour yield (Hereward, milled after 57 days storage) managed to reach significance.

Straight-run flour extraction rate data are also presented in Figures 2 a-c. Plots show that the main increase in straight-run extraction tended to occur within 2 months of harvest. After this time-point there was rarely any significant benefit in terms of straight-run yield. Examining

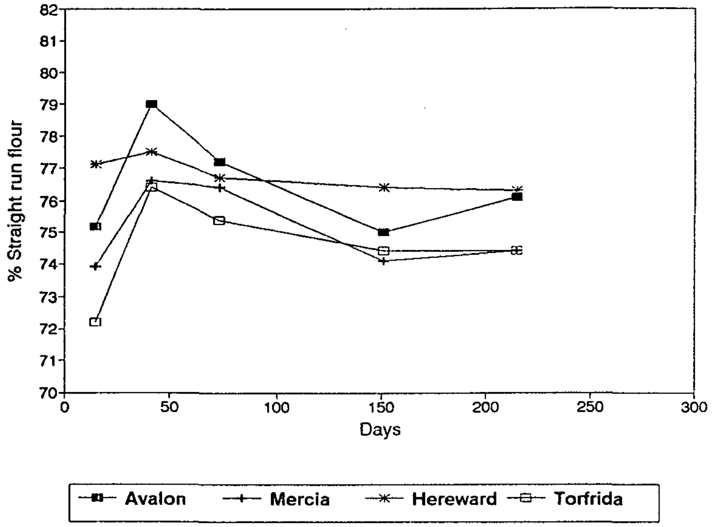
a) 1991



b) 1992



c) 1993



Figures 2 a-c **Effect of wheat storage on straight-run extraction (%) in 1991-1993 respectively.**

straight-run flour yield over the three years of interest, there was no evidence of any consistent varietal bias in results, i.e. for the varieties under examination no variety presented particular problems in milling immediately after harvest or showed particular benefits from a storage period prior to milling. On average, the variety Torfrida produced the lowest straight-run flour yield, but this variety was examined in one season only.

For the 2 years where significant improvements occurred, the time scale of yield improvements differed. In 1993 straight-run flour extraction rate increased in all varieties except Hereward when wheats were stored for up to 41 days, whereas in 1991 significant improvements continued beyond the 44 day time-point for all samples. The general cut-off point for improvement in this measure of milling performance appeared to occur at 65 days.

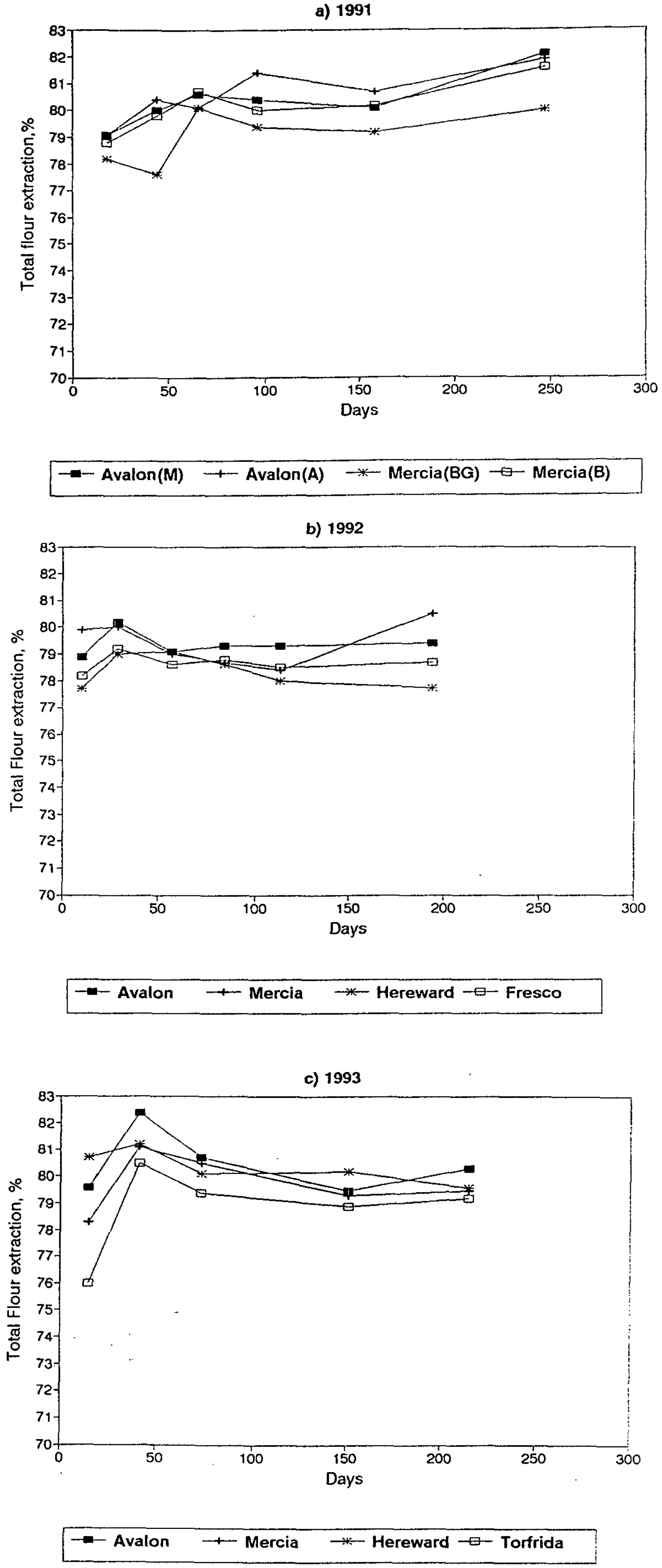
Following simple Bühler milling, the bran and fine offal fractions were passed through a bran finisher to remove additional endosperm particles and produce total flour extraction rates more typical of commercial milling practice. In the bran finisher, a vibrating action against a screen is used to detach adhering endosperm from flaked bran. Whilst straight-run flour yields may indicate differences in ease of milling samples, the total flour yield figure provides a better indication of potential effects of storage or season on commercial milling yields.

Tabulated results for total flour extraction rate are provided in Appendix 1, Table 1. These values tend to be less variable (compare Repeatability results shown in Table 5) than straight-run flour extraction rates. The total flour yield, obtained after bran finishing, is commonly used for evaluation of wheat quality and more closely corresponds to commercial practice (Anon, 1990).

The difference between straight-run and total flour extraction rate varied between 3.4% and 5.6% for the range of varieties under examination. It was not possible to test the significance of such differences, but the overall effect was generally to reduce the magnitude of any improvements in extraction rate resulting from wheat storage. This suggests that part of the variability in the milling performance of newly harvested wheat may be attributed to easier release of endosperm in Bühler milling.

Comparing total flour yields obtained immediately after harvest for each variety and season against the milling performance achieved at each time-point, significant improvements in total extraction rate resulted from a period of storage for most wheat samples examined. Again, the response was poorest in 1992 when average extraction rates for Avalon and Mercia were generally lower (Avalon some 1% lower than in 1991 or 1993 and Mercia only 0.3% lower).

The mean maximum increases in total flour yield were 1991: 1.9%, 1992: 0.95% and 1993 : 2.7%. Against a Repeatability value of 0.5%, these differences in flour extraction rate would be significant and certainly would be commercially important. Total flour extraction plots (Figures 3, a-c) show some variation in flour extraction values, but exhibit similar trends to



Figures 3 a-c Effect of wheat storage on total flour extraction (%) in 1991-1993 respectively.

those observed in straight-run flour plots (Figures 2, a-c). These observations suggest that the ease with which the straight-run component can be removed plays a role in determining the final flour yield.

There were no clear differences in milling performance between the common varieties, Avalon and Mercia. Both varieties milled well to produce similar yields of white flour. Averaging over varieties, total extraction rates obtained from milling freshly harvested wheat were between 78.7% and 78.8% in all three years of this study. Flour yields obtained from laboratory Bühler mills increased in each season when wheat samples were stored prior to milling, but in 1992 average total extraction rates for the 4 varieties did not exceed 80% at any time-point. In 1991 and 1993 average extraction rates of over 81% were possible on the laboratory Bühler mill after storage periods of 247 or 41 days respectively. The major quality difference between the 3 years in question related to grain plumpness. In particular, the 1992 samples were slightly shrivelled due to the effects of dry weather conditions. As in commercial milling systems, grain shrivelling appeared to restrict the amount of white flour which could be obtained under Bühler milling conditions. Thus, seasonal effects on milling performance of wheat samples resulted from variations in the physical characteristics of the grain.

Differences in flour extraction rate can be expected to have an effect on flour properties: chemical, physical, rheological and functional. As extraction rate increases the proportion of non-endosperm material increases and a dilution of protein quality occurs. Thus, improvements in flour yield cannot be considered to be of positive benefit if a discernible reduction in flour quality results. The miller's aim must be to maximise white flour extraction without jeopardising quality attributes.

4.1.2 Particle size

The Coulter Counter was used to produce a full particle size distribution for Bühler milled flour from all hard, bread wheats under consideration from harvests 1991-1993. In all cases, 100% of the flour was greater than 10.08 microns and 100% was below 161.3 microns. Thus, in general terms there was no major difference in particle size, but some differences in size distribution of flour particles was observed. For the purposes of this report two points in the distribution have been selected, namely 80.64 and 32 microns, to provide a snapshot of the effect of wheat age on particle size.

The percentage oversize by weight for 80.64 and 32 micron separation are presented in Appendix 1, Tables 2 and 3 respectively for each year and for each sequence of freshly milled and stored flour samples. Standard deviations were generally low with coefficients of variation for particle size measurements for frozen "control" flours ranging from 2.4% to 9.4% for the 80.64 micron separation and 0.4% to 2.9% for the 32 micron split.

In 1993 all flour samples, except Hereward, produced a significant change in the percentage of particles above 80.64 microns when wheat was milled after a period of storage. In 1991 significant increases occurred in the material over 80.64 microns following an initial storage period (typically 65 days). These changes tended to coincide with significant increases in total extraction rate. The 1992 grain samples showed the least improvement in extraction rate and changes in particle size were less consistent, being mainly negative and more variable.

Few significant differences in the percentage of flour particles above 32 microns occurred within this study, when wheat was subjected to a period of storage before milling. Effects tended to occur at the later time-points, but there was no consistency to observed changes and any differences were small, probably reflecting the low standard errors observed for this measurement. Observed differences were also unimportant technologically.

Data suggested that short-term changes during wheat storage may result in differences in milling performance which also exhibit themselves in the flour as a slight increase in the coarse particle fraction; the latter effect may be sufficient to influence flour flow characteristics.

As anticipated, flour storage had no consistent, significant effect on the percentage of particles above 80.64 or 32 microns in size.

Seasonal differences and between sample differences within the common varieties were significant for material above 80.64 microns only. Differences were often larger than any short-term storage effects, but these effects may have been influenced by the use of different Bühler mills to produce individual flour samples. The percentage of flour particles above 32 microns appeared relatively consistent and little affected by season or variety.

4.1.3 Instron Bridging Pressure

The mean of 10 vertical compression tests using the Instron 1122 provided values for bridging pressures in Newtons which are presented in Appendix 1, Table 4 for all varieties tested from the 1991-1993 harvests.

In 1991, the pressure required to force flour samples to bridge in a standard cylinder ranked varieties as follows: Avalon(M)< Mercia(B) « Mercia(BG) « Avalon(A). The two high bridging pressure samples were milled on the same mill. Despite uniform mill settings in this study, the mill used appeared to have a significant effect on flour flow characteristics and capacity to bridge under standard Instron conditions in 1991. Standard deviations of results observed for frozen "control" flour were rather high for all samples, but were particularly so for the high bridging pressure samples, and hence differences in bridging pressure with wheat age before milling failed to reach overall significance. However, for all varieties the lowest bridging pressure was indicated at the first time-point and there was a tendency for both storage of wheat prior to milling and flour storage to produce higher bridging pressures. Of particular note, the Mercia(BG) sample milled after 44 days storage showed a significant increase in pressure required to bridge the flour. This large increase was, however, not maintained for later storage periods.

Mean bridging pressures were generally low in 1992 with all varieties except Hereward producing values less than 5 Newtons for the freshly milled sample at time-point 1. Standard errors were lower than in 1991, and whilst no overall significant effect of wheat age was observed, once again there was a tendency towards increasing bridging thresholds when wheat was stored for a period before milling. Varietal differences were again observed: the test generally ranked varieties Avalon < Fresco < Mercia < Hereward and there was no obvious difference between Bühler mills.

For 1993 samples, mean bridging thresholds ranged from 4.7 to 9.7 and varieties were ranked in the following order Torfrida < Hereward < Avalon < Mercia. Mean bridging pressures did not vary significantly when wheat was stored for 151 days. At the final time-point large increases in the pressure required to bridge samples of Avalon and Mercia flour appeared to occur. However, parallel increases in bridging pressure were observed in the frozen, "control" flour at this time-point suggesting that effects in freshly milled flour were not real.

Comparing the varieties Avalon and Mercia, which were grown over all three years, it appears that seasonal and milling differences interact to exert effects on this bridging pressure. Mean values for Avalon ranged from 1.98 to 28.8 and for Mercia from 5.1 to 12.1 Newtons. In both cases the lowest values were produced in samples from the 1992 harvest suggesting that some feature of the 1992 crop resulted in flour which bridged easily in the standard Instron cylinder. The highest values were observed in samples from the 1991 harvest when a particular Bühler mill was used which produced flour with a low tendency to bridge. Thus, it is possible that some commercial milling systems may be more sensitive to bridging problems. In addition, there did not appear to be any relationship between flour particle size and the inclination for flours to bridge at low pressures.

4.2 Effects on flour quality characteristics

4.2.1 Flour ash content

Flour ash content provides an indication of non-endosperm components in a white flour sample because pure starchy endosperm contains relatively little mineral matter. As flour extraction rate increases more bran, aleurone and germ may become included in the flour and an increase in flour ash content results.

Flour ash content results are presented in Appendix 1, Table 5 for each year and for each sequence of freshly milled, stored and frozen "control" samples. Flour ash content should not be affected by storage conditions as it is fixed by the milling process and therefore the standard error exhibited in test results for frozen "control" flours provides an estimate of variability of the method. Figures 4 a-c illustrate the trends in ash values with age of wheat sample before milling for 1991 to 1993 sample sets.

In 1991 the lowest average ash content was obtained in flours produced from freshly harvested wheat. Significant increases in flour ash content resulted when wheat samples were subjected to a period of storage before milling. Maximum flour ash contents were obtained at different time-points for different samples and there was no consistent varietal effect. Significant increases in ash content could generally be related to significant increases in total flour extraction rate, i.e. increased extraction rate resulted in an increase in the level of non-endosperm material in 1991 flour samples.

1992 samples showed greater variability in ash content data for frozen "control" flour samples. For the common varieties, Avalon and Mercia, average ash values were higher than the equivalent 1991 controls. The presence of higher levels of non-endosperm material in 1992 flour samples may be as a direct result of grain shrivelling which may have caused differences in water partitioning during conditioning or greater difficulty in separating endosperm from bran. Differences in ash content after defined periods of wheat storage were generally small and non-significant. Since changes in flour extraction were smaller in samples from this season, this finding was not unexpected.

Ash content reached a maximum in all flour samples milled after 41 days storage in 1993. This coincided with maximum flour extraction rate in all varieties.

For a particular sample of wheat a direct relationship is known to exist between flour extraction rate and flour ash content. Comparing ash content plots [Figures 4 (a to c)] with equivalent total flour extraction results [Figures 3 (a to c)], it is obvious that the relationship holds within this study and that flour ash content values support real differences in milling yield and flour properties as a result of ageing wheat before milling. When growing conditions result in significant effects on basic wheat quality attributes, in this case the packing density or specific weight of the grain, this may be expected to affect ash content of the milled flour. Small changes in specific weight have been shown to have little effect on flour extraction (Hook, 1984). Differences in specific weight of 6.1 and 4.8 kg/hl were observed between extreme samples of Avalon and Mercia grown in 1992 and 1991. Differences of this magnitude have been shown to affect the quantity (see 4.1.1) and may be expected to affect flour quality attributes, particularly breadmaking potential.

No consistent varietal effect on wheat ash content was observed in this study. Ash content is known to vary with year, growing location and variety (Redman, 1980). However, samples were obtained from different locations making comparison of varietal data questionable.

4.2.2 Flour colour grade

Strong varietal differences in flour colour are known to exist, reflecting differences in endosperm colour. For example, the variety Avalon tends to produce a much creamier coloured flour than Mercia and this is normally indicated by an increase in flour colour values. However, within a sample, flour colour grade provides an indication of bran contamination and may be expected to vary with any changes which might influence the ease of separation of endosperm and bran and hence lead to differences in flour extraction rate.

Results of flour colour measurements are presented in Appendix 1, Table 6 for each variety and year examined. Storage at -18°C should stabilise the flour with respect to colour grade and examination of colour values for frozen "control" flours showed that for most samples tested standard deviations were relatively low and generally within the quoted standard deviations for Reproducibility for the standard test of 0.24 colour grade units.

Comparing freshly milled flour data with the "control" flour, there was a tendency towards increased flour colour in all varieties in 1991. In comparison with the first milling of each sample, significant increases in flour colour occurred as follows:

> for Avalon(M) when wheat was stored for 65, 96 and 247 days before milling;
> Avalon(A) at 96 and 247 time points only;
> Mercia(BG) after 247 days storage
> and Mercia(B) at 65, 158 and 247 days.

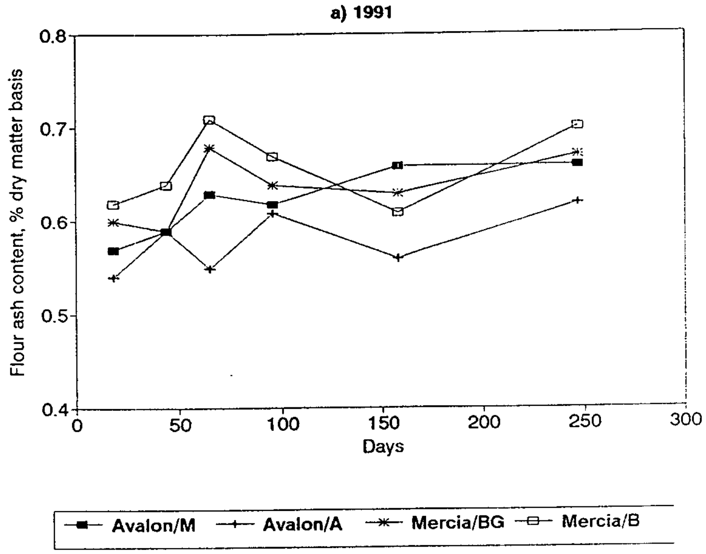
As for ash content, significant increases in colour could generally be associated with increases in total flour extraction rate rather than straight-run extraction values. This suggests that the bran finishing process resulted in greater amounts of non-endosperm material in the flour.

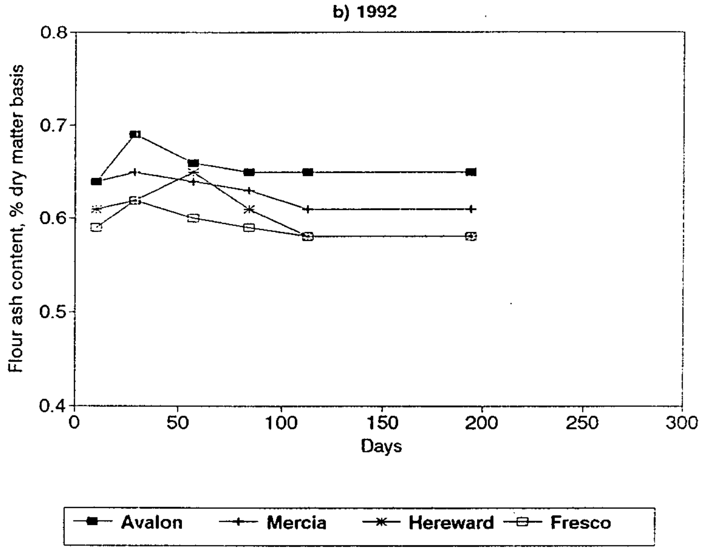
In samples from the 1992 harvest, significant increases in flour colour occurred after 29 days storage in all varieties except Mercia. However, this effect was only maintained in the Hereward sample beyond this time-point. Increases in flour colour were again associated with an increase in total flour extraction.

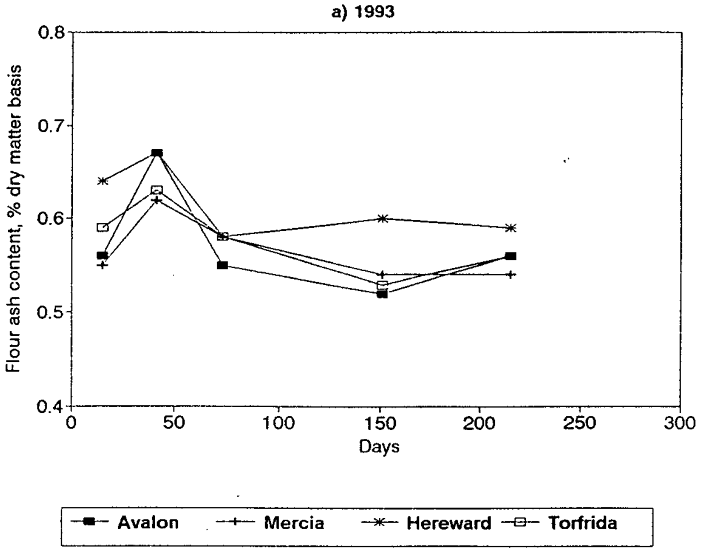
Large varietal differences existed between samples tested in 1993 with Hereward and Torfrida producing rather dark flours with average colour grades of over 3.0 whereas the varieties Avalon and Mercia produced more normal flour colour values averaging 1.4 and 0.4 colour grade units respectively in the frozen "control" samples. For Hereward and Torfrida, a period of storage prior to milling had virtually no effect on flour colour and any changes observed were negative. This is in contrast to previous observations and may be related to the particular examples of the varieties selected in 1993. In Avalon and Mercia significant increases in flour colour occurred when wheat was stored for 41 days before milling, but this effect was not sustained over later sampling points.

There was no significant effect on flour colour of storage at temperatures between -18 and +20°C. Storage at ambient temperature is said to result in darkening of the flour. In this study, storage under controlled, ambient conditions of 15 to 20°C for periods of up 247 days was found to have no effect on flour colour grade measurements; the values obtained being within the expected Repeatability of the test.

No consistent seasonal trends in flour colour were indicated, but large differences in flour colour were observed between the individual Avalon samples examined from the same harvest; Avalon(M) produced an average flour colour grade figure of 1.62 while Avalon(A) produced superior flour colour values averaging -1.04 colour grade units. Values for individual Mercia samples were more similar producing average flour colour readings of 0.71 and 0.84 for the two sites examined in 1991.







Figures 4 a-c **Effect of wheat storage on flour ash content (%, dry matter basis) in 1991-1993 respectively.**

Expected varietal differences in flour colour were generally confirmed. Within each season, Mercia samples normally produced significantly lower colour grade values than Avalon. The exception to this was Avalon(A) which produced exceptionally low flour colour values. There was no explanation for this observation as the sample was typical of Avalon with respect to basic quality attributes and flour extraction rate.

4.2.3 Protein content

Results of Kjeldahl flour protein determinations are presented (on a 14% moisture basis) in Appendix 1, Table 7 for each variety and year studied. Increases in flour yield can result in an increased proportion of aleurone tissue in the milled flour product which has high protein content but a deleterious effect on breadmaking quality.

Significant differences in flour protein content of 0.4% were produced at the 44 day time-point for both Avalon samples in 1991. This shift in protein content coincided with significant increases in flour extraction rate. Although a protein increase was indicated for the Mercia(BG) sample, this failed to reach significance due to above average variability in protein values for the "control" samples of this variety.

Small and generally insignificant changes in flour protein content were observed when wheat was milled after a period of storage in 1992.

Significant shifts in protein content were observed in 1993 samples of Avalon and Mercia flour only. For both varieties, positive effects (Avalon at 41 days and Mercia at 41 and 73 days) corresponded to significant increases in extraction rate of over 2.0%. However, for the Avalon sample reductions in protein content were also noted when wheat was stored for 151 days or longer. This drop in protein content could not be explained in terms of loss of extraction rate.

Mean protein contents for freshly milled flour of each variety tested in each season are shown in Table 7.

Wheat protein content of the test samples varied as a result of differences in growing conditions for the three seasons in question and, hence, considerable differences existed between the levels of protein in the final milled flour. The magnitude of these differences was much greater than that observed for wheat storage and may be expected to have a significant effect on the final breadmaking quality of each sample. Varietal differences in protein content were also exhibited, with Mercia tending to produce higher protein content than Avalon. However, this effect is purely due to choice of sample as, with the exception of 1992 samples, varieties were grown at different sites.

Table 7 **Mean protein content, expressed as % N x 5.7 on 14% moisture basis, for freshly milled flour produced from samples in 1991 to 1993.**

Variety	Year		
	1991	1992	1993
Avalon (M) Avalon (A)	10.75 10.48	10.98	9.88
Mercia (BG) Mercia (B)	11.58 10.65	11.40	10.24
Hereward		10.95	9.34
Fresco		11.13	
Torfrida			9.12

4.2.4 Falling Number

Falling Number determinations provide an indirect measure of cereal *alpha*-amylase based on its effect on paste viscosity. Results of Falling Number determinations are presented in Appendix 1, Table 8 for each variety tested in each year together with means, standard deviations and $LSD_{5\%}$ for the frozen "control" samples.

No overall, significant effect of wheat or flour storage on Falling Number was indicated in this study. Large differences existed between the varieties under test.

4.2.5 Alpha-amylase

Direct measurements of cereal *alpha*-amylase were performed using the standard Farrand procedure and results are presented in Appendix 1, Table 9 for each year and for each storage regime together with means, standard deviations and $LSD_{5\%}$ for frozen "control" samples.

In both 1991 and 1992 *alpha*-amylase levels were very low, as would be expected from wheat samples with Falling Numbers above 330 seconds. Farrand *alpha*-amylase levels ranged from 0 to 2 units and given this low level of activity there was no effect of storage regime or variety on this parameter.

Flour samples from the 1993 harvest were slightly more active in terms of amylase activity. Avalon and Hereward, produced average *alpha*-amylase levels of 5.6 and 17.6 Farrand units respectively, relating to Falling Numbers of 252 and 180 seconds. For these more active samples, *alpha*-amylase levels were very consistent in the frozen "control" flour and well within the collaboratively measured Reproducibility of the method. Examination of the freshly milled Avalon and Hereward flour, suggested there may be some small changes in *alpha*-amylase activity when wheat was stored for a period before milling. Results only reached significance for the more active Hereward sample when it had been stored for a period of 41 days before milling and the effect was not sustained over prolonged storage. There was no evidence that this isolated effect could be attributed to a change in milling performance. The *alpha*-amylase activity of Mercia and Torfrida samples studied in 1993 was low and as in other seasons totally unaffected by storage. In conclusion, controlled storage of wheat prior to milling did not appear to affect *alpha*-amylase enzyme levels and confirmed the lack of significance of storage on Falling Number results.

Similarly, storing flour at between 15 and 20°C had no effect on cereal *alpha*-amylase activity.

4.2.6 Starch damage

Farrand starch damage results are presented in Appendix 1, Table 10 for each variety and storage condition under consideration. Within the "control" frozen samples, starch damage values were relatively consistent with standard deviations of 0.5 to 2.22, all of which lie within the quoted Reproducibility standard deviation value of 2.41.

In most samples studied in 1991 and 1992, a significant increase in starch damage values occurred when wheat was stored under controlled conditions before milling. However, there was no consistency to the data, i.e. a significant increase in the 1991 Mercia(B) occurred at the 65 day time-point, but later millings produced starch damage levels which were not significantly different to the initially milled sample. For 1993 samples, there was some evidence of decreasing starch damage with wheat storage time, but again trends were not consistent over all varieties.

Since damaged starch is created during milling there should be no significant effect of flour storage on starch damage levels. Results confirmed that this was the case.

Comparing across different harvest years, seasonal and site differences between common varieties account for considerable differences in starch damage levels. For example in the variety Avalon samples could be ranked in terms of starch damage as follows:

> 1993 > 1991 Avalon (M) > 1992 > 1991 Avalon (A) with average values ranging from 37 to 23 Farrand units respectively.

Normally one would expect protein content to be a strong contributing factor to starch damage levels. However, observed differences in starch damage appeared to be related to grain hardness, wheat conditioning prior to milling or variability in milling performance under standard Bühler milling conditions rather than protein content in this study. For example, 1993 samples tended to produce above average starch damage levels and below average grain protein content.

4.3 Effects on dough rheology

Under this heading, routine tests used by the milling industry to measure dough rheology in empirical terms only will be considered.

4.3.1 Brabender Farinograph

The amount of water, corrected to 14% moisture content, required to mix a dough to a consistency of 600 Brabender Units for each variety and storage regime is presented in Appendix 1, Table 11.

Analysis of the frozen "control" data shows that this measurement was relatively consistent exhibiting standard errors which were generally less than 0.7%. This compared favourably with the quoted Reproducibility standard deviation of 0.55% for this test and suggested that the storage conditions used were effective with respect to water absorption.

Within this 3 year study, storing wheat for a period of time before milling produced both significant increases and decreases in flour water absorption. In some varieties and seasons the lowest water absorption values were to be found in the samples milled immediately after harvest and in others the highest. Changes seem to be unconnected with storage time prior to milling. Storage of milled flour also appeared to have no effect on water absorption capacity. Comparing the common varieties over the three seasons in question, there was no obvious seasonal difference in results. Differences between the two samples of Avalon and Mercia tested in 1991 were as large as any seasonal variation in water absorption. The 1992 Fresco sample produced significantly lower water absorption figures than other breadmaking varieties examined in this study. Thus, between sample differences in water absorption appeared to outweigh any effects of storage regime.

No consistent, significant effects of wheat or flour storage on other Farinograph characteristics were observed in this work.

4.3.2 Brabender Extensograph

Results obtained for each sample and storage practice are presented in Appendix 1, Table 12 for Resistance (Brabender units or BU) and in Table 13 for Extensibility (cm).

Analysis of frozen "control" data shows that considerable variation in Resistance values exists when the same sample was tested at different times by the same operator. The standard error values varied from 2.5 to 60.2 BU with coefficients of variation generally in excess of 10%. These were within the values for Reproducibility standard deviation and coefficient of variation for Resistance quoted in the standard method of 49.0 and 13.5% respectively. The high values produced indicate the inherent lack of precision in the technique.

Over the three years of this study, wheat storage before milling had no consistent, significant effect on dough Resistance. However, significant changes in Resistance did occur in particular varieties and years. In 1991, when Resistance values and standard errors were low, significant increases in dough Resistance were observed for Avalon(M) stored for 44 and 158 days and for Mercia(BG) when wheat was stored for 96 and 158 days before milling. In the Avalon(A) sample, a small, but significant reduction in Resistance occurred when wheat was stored for 96 days before milling. This inconsistency and the fact that samples milled after further storage produced flour with similar Resistance values to flours tested initially suggested that there was no consistent effect of storage time on dough Resistance. In confirmation of this, no significant effects of wheat storage on dough Resistance were detected in 1992 or 1993 samples.

Reproducibility standard deviations and coefficients of variation values for Extensibility are quoted at 0.82cm and 5.5% respectively. Many of the standard deviations of results for frozen "control" samples were above this level, indicating the considerable variability observed in dough Extensibility measurements in this study. In particular, samples of Avalon in 1991 and Mercia plus Fresco in 1992 exhibited high standard deviations. Against this background variability, no overall effect of wheat age before milling was observed on dough Extensibility as measured by Extensograph. In the 1991 Mercia(B) sample, a significant reduction in dough Extensibility occurred when wheat was stored for a period of 44 days before milling, but this change was not maintained over succeeding milling dates. No significant changes in Extensibility values were observed for any variety in later harvest years.

There was a suggestion in 1991 that flour storage at 15 to 20°C tended to reduce dough Extensibility and increase Resistance in the variety Mercia, but this observation was not supported by data for Avalon in the same year or any variety studied in other seasons.

Seasonal differences between varieties far outweighed any differences resulting from the storage regime. Comparing the common varieties Avalon and Mercia over the 3 harvest years, the 1993 samples exhibited much higher Resistance and lower Extensibility values than samples from the 1991 or 1992 harvests. In fact the 1991 and 1992 figures were more typical of these two standard varieties. Avalon is generally represented as a rather weak, extensible breadmaking variety and Mercia as an average strength UK bread wheat being more Resistant and slightly less Extensible. For both varieties, the 1993 flours produced shorter and tougher doughs with Avalon being more seriously affected than Mercia. Both characteristics would be likely to have a negative impact on breadmaking quality.

4.3.3 Chopin Alveograph

Results for the Alveograph parameters W and P/L for each variety and storage practice are presented in Appendix 1, Tables 14 and 15 respectively. Average standard errors for frozen "control" flours were 11.8 for W and 0.199 for P/L. These figures compare with quoted standard deviations for Reproducibility of 17.3 and 0.092 respectively. Thus, P/L values recorded in this work for "control" frozen samples exhibited more variability than expected from the standard method. Since there was no trend in the results towards an increase or decrease in P/L values, this data suggested that Alveograph values are more variable than reported in the ICC standard rather than indicating poor stabilisation of the "control" samples.

Comparing W values for flour freshly milled at different time-points with the initially milled sample, there was no consistent, significant effect of wheat age before milling on Alveograph W. In 1991, significant increases in W were recorded in Avalon samples at particular time-points, i.e. 158 days for Avalon(M) and 65, 158 and 247 days for Avalon(A). In 1992, significant decreases in Alveograph W were produced in all varieties at one or more milling time-points. In both years, standard deviations observed in some "control" samples were significantly lower than quoted values and this resulted in apparent significant differences which would not be technologically important. In 1993, when "control" flour standard deviations were more normal, only two isolated, significant increases in Alveograph W were observed namely Torfrida after 73 days storage and Hereward after 151 days storage.

For Alveograph P/L values, wheat age before milling produced a number of isolated significant increases and decreases in results. However, in almost all cases further storage resulted in a return to P/L values which were equivalent to those obtained for the initially milled sample. The one exception to this was the variety Avalon in 1993 where the P/L values were significantly higher than would normally be expected for this variety and showed both significant increases and decreases with time of milling. Such inconsistency could not be related to storage time before milling and appeared to reflect variability in results of an operator sensitive test.

To examine the effect of flour storage on Alveograph W, results were compared with the mean value obtained for the relevant "control" flour. For most varieties tested there appeared to be a trend towards increasing Alveograph W with time of flour storage, the effect reaching significance in a number of cases. However, there was no consistency to such effects and they tended to be associated with samples where low standard deviations were recorded. Similarly, there was no overall significant effect of flour storage on P/L. In a few isolated instances a significant increase in P/L occurred at a particular storage point, but these effects were not confirmed by continued storage.

As for other rheological measurements, seasonal differences between the common varieties suggested that Alveograph parameters could be used to rank protein quality obtained in different harvests as follows: 1993 > 1991 > 1992. Both Alveograph W and P/L follow this pattern. However, this does not reflect differences in breadmaking quality observed in this work (see Section 4.4) and illustrates the rather weak correlation which exists between Alveograph characters and final breadmaking quality.

Strong varietal differences in Alveograph W are known to exist and results generally reflect the gel protein and work input classification given previously in Section 3.1. Comparing W values i.e. protein strength of varieties the following general ranking could be produced:

"extra strong" varieties (Torfrida and Fresco) > Hereward >Mercia and Avalon.

An exception to this was observed for Hereward in 1993 which produced lower Alveograph W values than Mercia or Avalon, but was considered atypical.

For P/L, starch damage also exerts a strong influence on results and therefore it is not surprising that year-to-year variation was greater than any varietal effect. Thus, seasonal effects on Alveograph parameters were frequently greater than any differences observed as a result of storage practice.

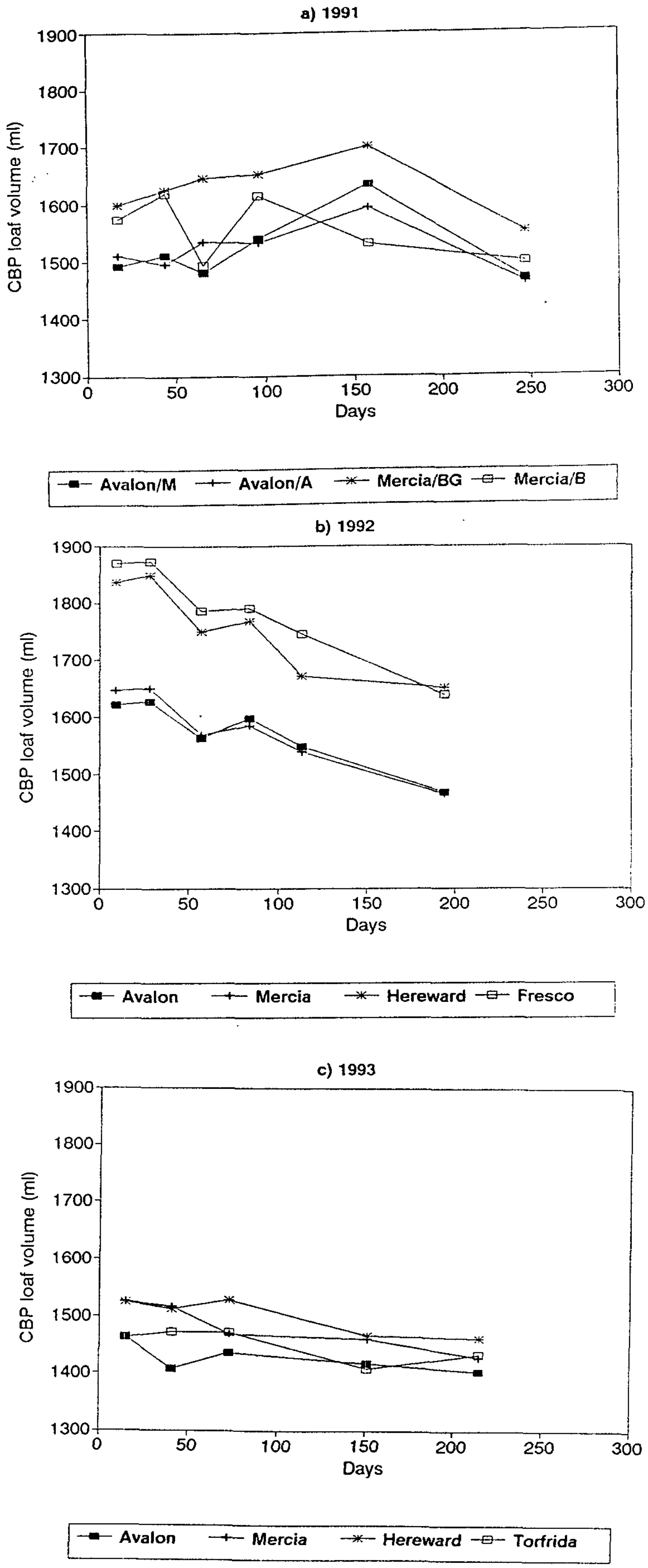
4.4 Effects on breadmaking quality

All freshly milled samples were baked one week after completion of milling using a standard (400g loaf) Chorleywood Bread Process baking procedure. This protocol was adhered to in order to remove the complication of oxidative changes which are known to occur in flour in the first few days after milling (Fisher *et al.*, 1937).

Test baking results are presented as loaf volume (ml) in Appendix 1, Table 16 for each sequence of freshly milled, stored and frozen "control" flour samples.

Flour storage conditions have been shown to affect breadmaking performance. A study of the effects of prolonged storage of flour at ambient and 25°C showed significant effects on dough rheology and CBP breadmaking performance (Bell *et al.*, 1979a) It is, therefore, important to distinguish between any effects caused by storage of wheat at 15-20°C and those which would occur if the flour samples were stored under the same conditions. As for other tests, we assume that the frozen "control" flour is stable and use the variability in loaf volume test results found for each variety in each season to provide standard error values and hence an estimate of variability of the method. Standard errors tended to increase as mean loaf volume in a variety or season increased. Given the magnitude of loaf volume variation, few significant differences occurred as a result of storing wheat samples for a period before milling. Storage in cans after nitrogen treatment, in the presence of an oxygen scavenger and at -18°C has been shown to prevent oxidative changes in wheat flour and has been successfully used to store flour over a 66 month period (Bell *et al.*, 1979a). At least part of the fluctuation in volume may be attributed to unavoidable differences in baking conditions such as differences in yeast activity or processing differences.

When samples of Mercia and Avalon were baked immediately after harvest in 1991, average loaf volumes of 1588 and 1502ml respectively were produced. Such loaf volumes would be considered to be satisfactory for the respective varieties. Standard errors for CBP loaf volume varied between 24 and 41 ml for the four samples tested. In all samples in this year, regardless of variety, there was a tendency for loaf volume to increase when wheat samples were allowed to age before milling. Figure 5a shows changes in loaf volume associated with wheat storage time for Avalon and Mercia in 1991. However, the apparent optimisation of breadmaking quality which occurred after 5 months in all samples except Mercia(B) was not maintained with further storage.



Figures 5 a-c **Effect of wheat storage on CBP loaf volume (ml) in 1991-1993 respectively.**

Loaf volumes achieved at the end of the wheat storage period in 1991 were all below that obtained for fresh wheat milled immediately after harvest. In addition, the effect of wheat storage only reached significance in one of the four samples, Avalon(M). No milling parameter or basic flour quality character could be identified to account for this observed temporary improvement in breadmaking performance.

In 1992, excellent loaf volumes were produced for all varieties when wheat was milled immediately after harvest and no significant improvement occurred as a result of storing wheat before milling. On the contrary, breadmaking quality tended to decline with wheat storage time with significant reductions in loaf volume apparent in Mercia and Fresco by the end of the wheat storage period (see Figure 5b). A noticeable decline in loaf volume occurred in frozen "control" samples over this time period suggesting, either that storage at -18°C was insufficient to inhibit deteriorative changes in the flour, or that systematic differences in baking conditions occurred which affected all breadmaking test results . Since standard errors for loaf volume were generally greater in 1992 than in either of the other years investigated, the latter appeared to be the case.

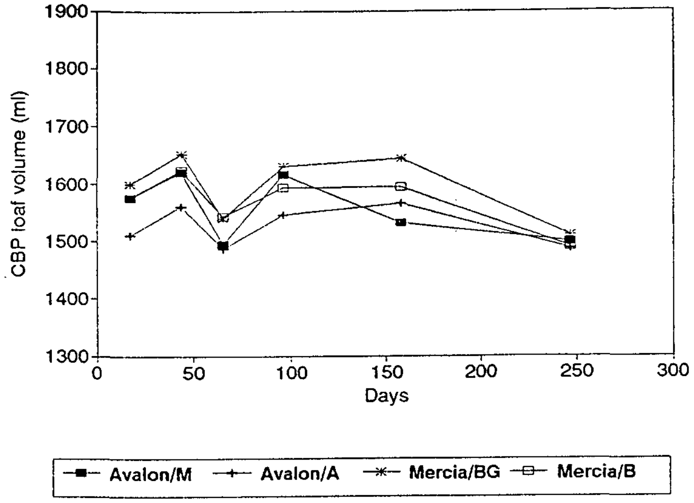
For all varieties loaf volume was inferior in 1993; this coincided with low flour protein content. As can be seen in Figure 5c, all varieties showed a tendency towards reduced loaf volume with wheat storage time in 1993. This effect only reached significance for the Mercia sample which had the lowest $LSD_{5\%}$ of all samples tested in this study.

Flour storage, under conditions of 15-20°C for a prolonged period, tended to reduce loaf volume in all varieties and seasons (Figures 6a-c). This reduction in loaf volume was significant for all varieties in 1992, when average breadmaking performance of the samples was good. However, it should be noted that variability in test results was relatively high in 1992 and the pattern of changes produced for stored flour almost exactly mimics that observed for freshly milled flour suggesting that day-to-day differences in breadmaking may have a greater influence on results than any storage regime (compare Figures 5b and 6b).

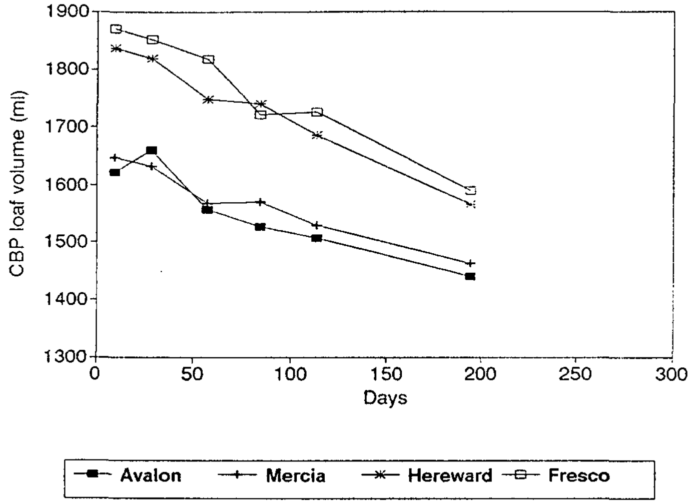
Substantial variability in loaf volume results was observed between the three seasons in question. Differences in average loaf volume between the common varieties, Avalon and Mercia, grown in 1991, 1992 and 1993 can be partially explained by differences in average protein content for the samples concerned (see Table 8) but protein quality must also play a role. For example, similar loaf volume values were obtained in 1991 for Avalon(A) and Avalon(M) samples which had flour protein contents of 10.48 and 10.75% respectively, suggesting that protein quality was superior in the Avalon(A) sample.

There was no evidence of varietal differences in response to storage conditions. Trends shown for stronger varieties, like Fresco and Torfrida, reflected those observed for the weaker varieties Mercia and Avalon. Comparing the breadmaking performance of the four varieties grown in 1992 at Boxworth (Figure 6b), it is obvious that varieties fall into two distinct groups. Changes in loaf volume were of similar magnitude for both quality groups (i.e. Hereward and Fresco consistently produced CBP loaf volumes around 200ml higher than Avalon and Mercia regardless of the time-point during wheat storage.

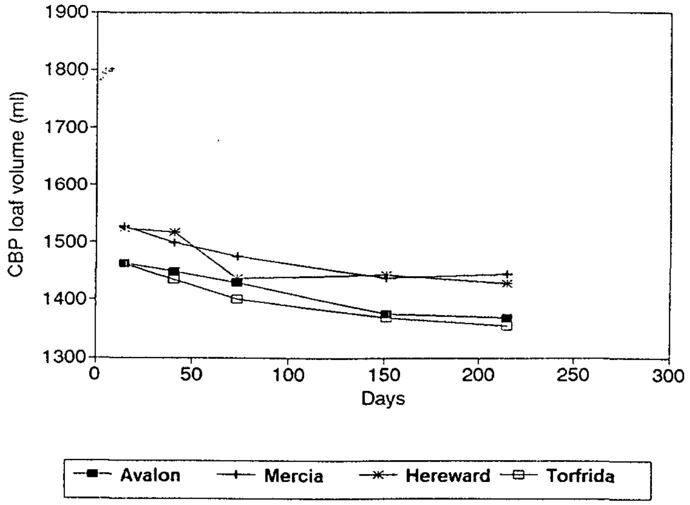
a) 1991
Stored flour



b) 1992
Stored flour



c) 1993
Stored flour



Figures 6 a-c Effect of flour storage on CBP loaf volume (ml) in 1991-1993 respectively.

Table 8 **Mean loaf volume (ml) for freshly milled flour produced from samples in 1991 to 1993. [The relevant mean flour protein content (% N x 5.7 on 14% moisture basis) is presented in brackets].**

Variety	Year		
	1991	**1992**	**1993**
Avalon (M) **Avalon (A)**	1521 (10.75) 1522 (10.48)	1570 (10.98)	1426 (9.88)
Mercia (BG) **Mercia (B)**	1630 (11.58) 1556 (10.65)	1575 (11.40)	1484 (10.24)
Hereward		1754 (10.95)	1498 (9.34)
Fresco		1783 (11.13)	
Torfrida			1450 (9.12)

4.5 Effects on protein functionality

4.5.1 Flour: gel-protein weight

Gel protein weight data are presented in Appendix 1, Table 17 for all varieties and time-points over the 3 years of this study.

No significant correlations were observed between gel protein weight and increasing storage time in any season or variety, i.e. no general relationship appeared to exist between this parameter and storage time. A few isolated significant effects on gel protein content were observed during storage, but trends differed between seasons and varieties and there seemed to be little consistency to the data. Observations from each season and variety follow.

In 1991 trial samples, standard errors of measurement were relatively high for Avalon samples compared with Mercia. Using least significant differences to compare results obtained for freshly milled and "control" frozen flour samples, significant reductions in gel protein weight occurred in Avalon(M) when wheat was milled after a storage period of 44 and 158 days whilst significant increases in this parameter were observed for Mercia(BG) between 44 and 96 days storage. These isolated effects were observed against a background of rather variable results for frozen "control" flour samples and were not related to any changes in protein content or other flour quality parameters arising from differences in milling performance.

In general, gel protein weights were higher in 1992 than in the 1991 season samples. Comparing the common varieties over the three years in question, gel protein weight increased by over 1.1g/5g in Avalon in 1992 when compared with the 1991 samples whereas flour protein content only increased by around 0.5%. This suggests that an increased proportion of HMW glutenin type proteins were laid down in wheat samples during the 1992 growing season. Gel protein weight data divided the varieties into two distinct groups: the first group Avalon and Mercia had gel protein levels of between 10 to 11g/5g whilst Hereward and Fresco produced average gel protein weights in excess of 12.9g/5g flour sample.

It was impossible to elicit a coherent picture from wheat storage data in 1992. In the superior varieties, Hereward and Fresco a period of storage tended to result in an increase in gel protein weight. Significant differences occurred after a storage period of 29 days in Hereward and for the 84 and 113 day time-points only in Fresco. For the variety Avalon, results were rather erratic, but overall no significant differences were observed between the gel protein content of flour from the initial milling and flour produced from stored wheat. The Mercia sample showed a significant drop in gel protein content when wheat was stored for 57 days, but this reduction was not maintained in samples stored for longer periods.

In general, gel protein weights were lower in 1993 than in either 1991 or 1992 as a direct consequence of reduced protein content in flour samples from this season. In addition, gel protein weight data exhibited considerable variability as indicated by high LSD values in Appendix 1, Table 17. Against this background no significant differences in this parameter were identified.

There was no evidence that storage of milled flour at temperatures between 15 and 20°C had any effect on this quality parameter. This suggests that isolated effects observed in freshly milled flour samples may have occurred as a result of some slight change in the chemical composition or physical properties of the flour produced at different milling times.

Thus, the major differences in gel protein weight appeared to occur as a result of seasonal differences in wheat quality. The effect of season appeared to be much more consistent and of greater magnitude than any changes resulting from wheat age or flour storage conditions.

4.5.2 Flour: gel protein breakdown rate

Gel protein breakdown rates are presented for all varieties and all storage conditions in Appendix 1, Table 18 together with means, standard errors and least significant differences ($LSD_{5\%}$) for frozen "control" flours.

Gel protein breakdown rate provides a measure of protein-protein interactions within a dough sample. High values for gel protein breakdown rate, of above 1, indicate a rather weak variety where protein-protein bonds break down during continued mixing. Low breakdown rate values, of less than 0.3, indicate strong wheat varieties which would be difficult to fully develop in a standard CBP system where the work input was fixed at 11Wh/kg.

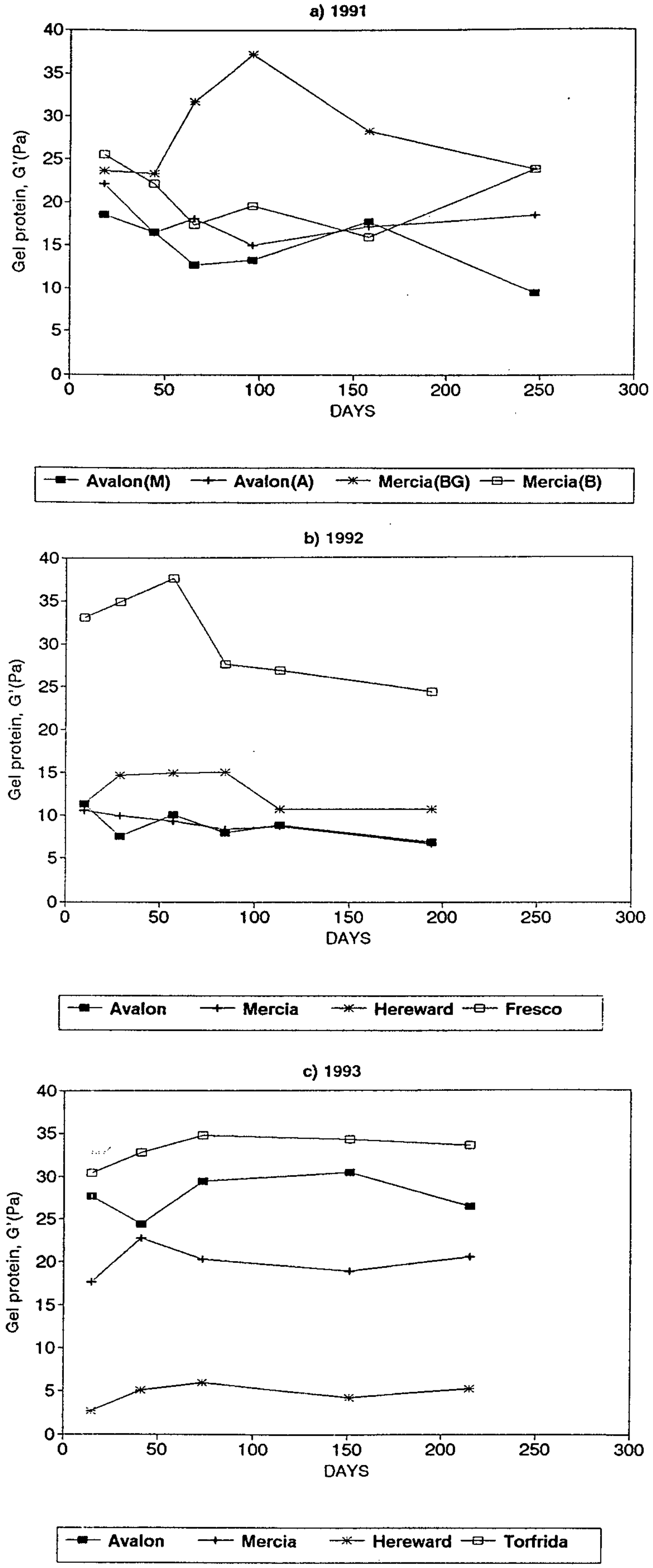
In only two comparisons was a significant correlation found to exist between gel protein breakdown rate and time of storage after harvest. These were 1991 harvest samples Mercia(B) with a correlation coefficient of 0.96 and Mercia(BG) where a value of 0.81 was observed between this quality measure and age of wheat before milling. In all other cases, there was no significant effect of increasing storage time on gel protein breakdown rate.

Comparing this quality parameter over different seasons and varieties a number of significant changes were observed when wheat samples were stored for fixed periods of time.

In 1991, all varieties exhibited significant reductions in gel protein breakdown rate over the storage period examined. Average breakdown rates during mixing of 0.8 for Avalon and 0.59 for Mercia samples in 1991 were typical of these varieties. The lower value for Mercia reflected the slightly better HMW glutenin subunit composition in this variety. For Avalon samples, a reduction in breakdown rate occurred after storage for 44 days and no further significant change was observed following continued storage of wheat at 15-20°C. The position was rather different for Mercia where prolonged periods of storage appeared to be necessary to generate a significant effect on breakdown rate. In the stronger sample, Mercia(BG), a storage period of 95 days was required before a significant reduction in breakdown rate was detected. The equivalent value for the Mercia(B) sample was 247 days storage. The general decreasing trend in this measurement with time of storage in 1991 is shown in Figure 7a.

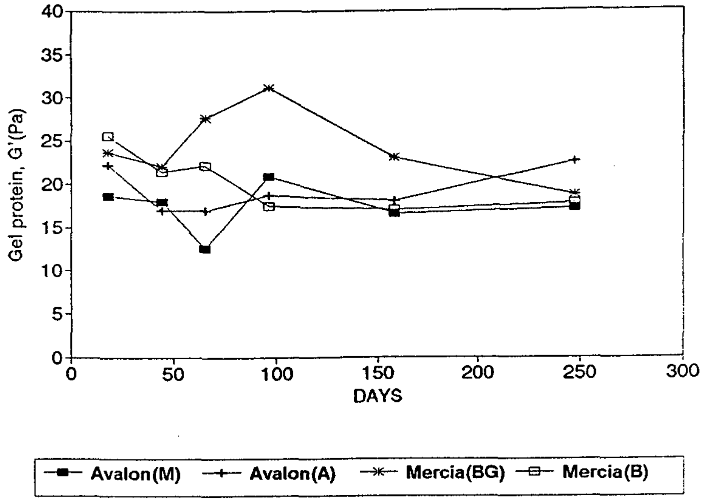
The effect of wheat age on gel protein breakdown rate was generally not significant in 1992. The three varieties Avalon, Mercia and Hereward produced average breakdown rates of 0.69 to 0.93. The "extra strong" variety Fresco produced an average breakdown rate of 0.31 suggesting this sample was borderline in terms of suitability for a standard CBP baking system. With the exception of Fresco, standard errors of gel protein breakdown rate were rather high and thus differences failed to reach significance. In addition, there was also no evidence of any consistent trends in this quality parameter. A single significant reduction in breakdown rate was observed for Fresco after 57 days wheat storage in 1992, suggesting an increase in protein-protein interactions. Samples taken at later sampling dates reversed this effect. It has been calculated that varieties with gel breakdown rates of less than 0.3 may present mixing problems under standard CBP conditions of 11Wh/kg (Pritchard *et al.*, 1992) and therefore any significant reduction in this parameter in a variety like Fresco could have detectable consequences in terms of breadmaking quality.

In 1993, samples of Avalon and Hereward appeared slightly unusual in their gel protein characteristics. Avalon had a very low gel protein breakdown rate (average 0.23) whilst the value for Hereward was higher than average value 0.86. The latter may be partly explained by the inferior quality of the 1993 Hereward sample, but no satisfactory explanation exists for strong protein characteristics observed in Avalon. The Mercia sample had a smaller amount of better quality protein in 1993 compared with other years, a further indication that when protein content drops there may be some compensation in protein quality. Torfrida, with an average breakdown rate of 0.18, was typical of an "extra strong" variety. This variety has been examined in some detail (Pritchard & Bhandari, 1992) and been shown to be variable in

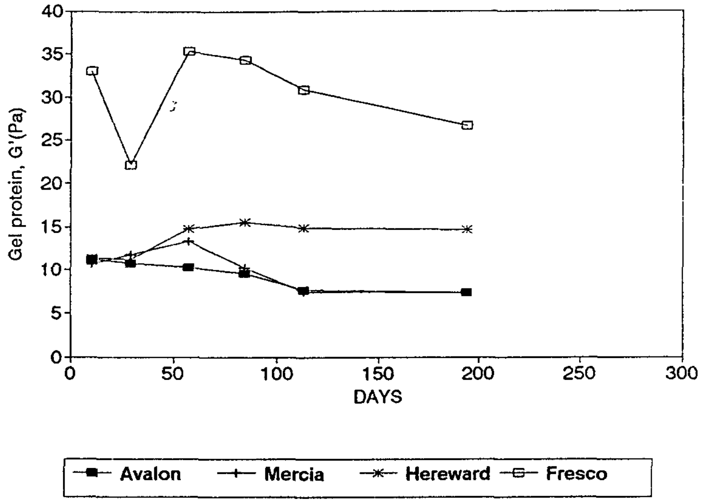


Figures 7 a-c **Effect of wheat storage on gel protein breakdown rate in 1991-1993 respectively.**

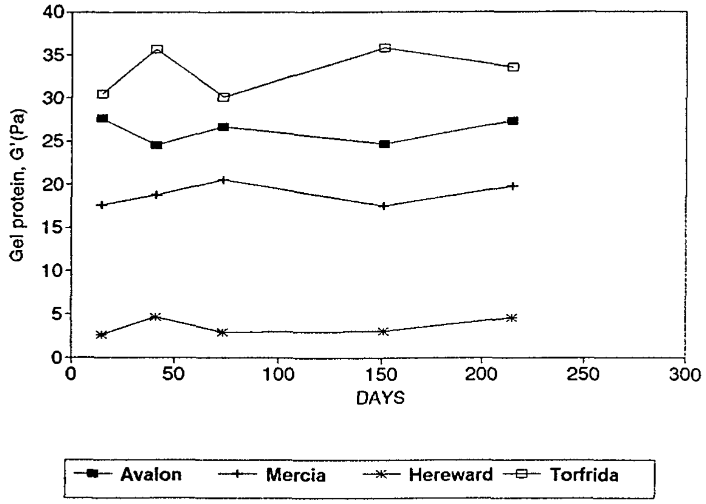
a) 1991
Stored flour



b) 1992
Stored flour



c) 1993
Stored flour



Figures 8 a-c **Effect of flour storage on gel protein breakdown rate in 1991-1993 respectively.**

terms of "extra strong" characteristics. There was a tendency for decreasing gel breakdown rate for Mercia and Torfrida, but against the background variability observed for this parameter in 1993 samples no significant effects were found for any variety.

There was some evidence that storage of milled flour at temperatures between 15 and 20°C had a significant effect on this quality parameter. The pattern of change in stored flour generally reflected that for wheat storage, but changes were more pronounced. Significant reductions in breakdown rate were observed for Mercia in 1991. Effects of storage time on wheat and flour for all three seasons are shown in Figures 7 a-c and 8 a-c respectively suggesting that changes in protein-protein interactions can occur in both maturing wheat and flour.

As for gel protein weight, significant seasonal variations in breakdown rate were observed. Between season differences (Appendix 1, Table 18) were frequently of greater magnitude than changes produced by storage conditions and would be expected to significantly affect breadmaking quality. Comparing the common wheat varieties, Avalon and Mercia, over the three years of this study both have higher breakdown rates in 1992 than in 1991, suggesting that protein quality was inferior in 1992 when protein content was significantly higher.

4.5.3 Flour: Elastic or storage modulus, G'

Elastic modulus of gel protein results, measured using the Bohlin VOR rheometer under standard conditions are shown for all varieties and all storage conditions in Appendix 1, Table 19 together with means, standard errors and least significant differences ($LSD_{5\%}$) for frozen "control" flour.

Elastic modulus (G') provides another measure of protein quality. This measure is now used routinely in quality assessment of wheat varieties in Recommended List and therefore considerable background data exist for some of the varieties under consideration in this study. Low values for G', below 20 Pa, indicate a weak variety which may breakdown during the standard CBP mixing process and produce bread of inferior volume and crumb structure. High G' values, above 40 Pa, indicate "extra strong" wheat varieties which may require additional mixing in a high speed breadmaking system such as the standard CBP procedure used in this work. Again, under-performance in terms of loaf volume and crumb score could result if such samples were assessed using a CBP baking procedure with a fixed work input of 11Wh/kg.

In only one comparison was a significant correlation found to exist between gel protein G' and time of storage after harvest. For Mercia from the 1992 harvest, a correlation coefficient of 0.97 was obtained between this quality measure and age of wheat before milling. In all other comparisons, there was no significant effect of increasing storage time on elastic modulus. In addition, only very few significant changes in G' occur when wheat is stored for a period of time before milling and there was no consistency to results.

In 1991, Mercia and Avalon samples produced typical average G' values of 17.0 Pa and 22.6 Pa respectively; the slightly better values for Mercia reflected the presence of high molecular weight subunits 5+10 in Mercia. For Avalon, there appeared to be a tendency towards lower G' values, i.e. a deterioration in quality with wheat age, but this only reached significance after storage periods of 96 days for the Avalon(A) sample and 247 days for the Avalon(M) sample. Mercia samples proved less consistent with no significant effect on Mercia(BG) sample and a significant increase after 96 days storage in Mercia(B) which was not sustained with continued storage of the bulk wheat.

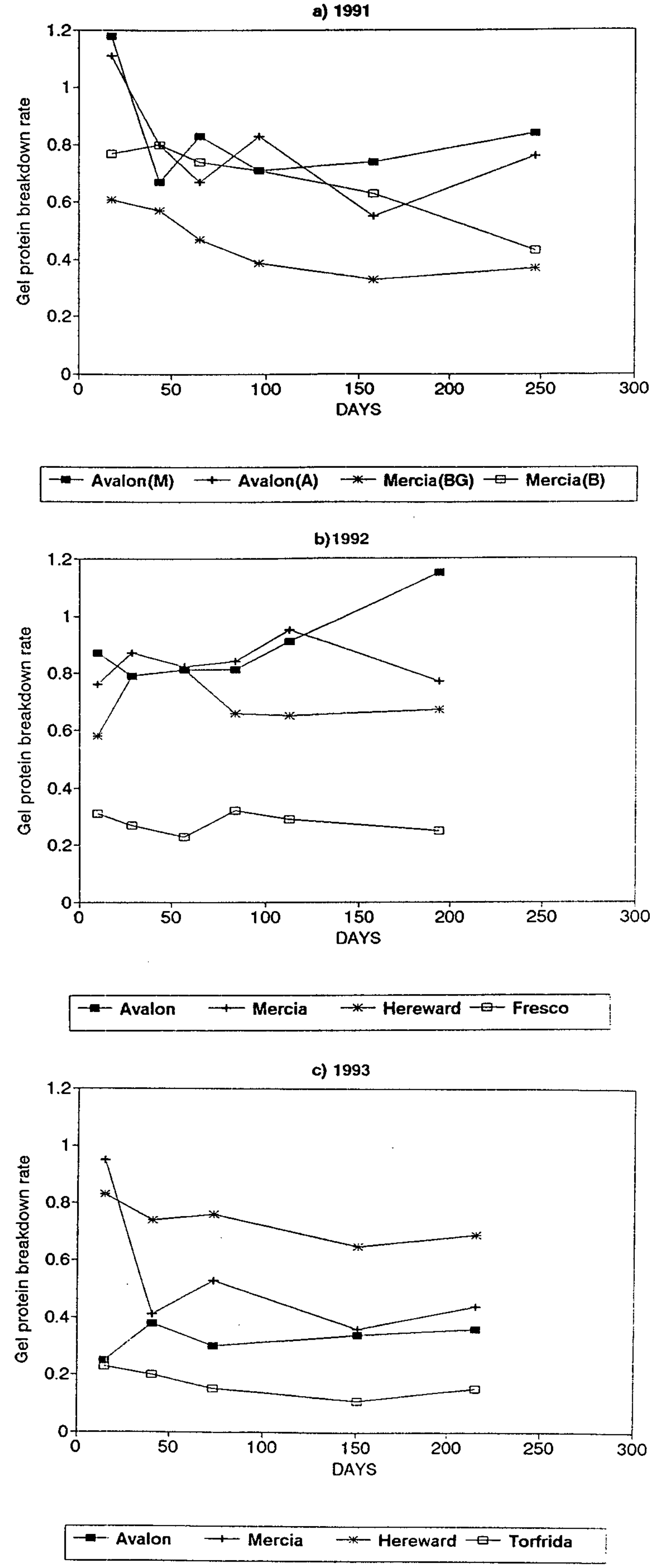
Elastic modulus and gel breakdown rate are opposing measures of protein strength and an inverse relationship would be expected between these two quality parameters. Changes in G' for Avalon samples were contrary to those expected from changes in gel breakdown rate and hence did not support any relationship between these two quality measures. It was only in the Mercia(BG) sample that observed increases in G' were mirrored by decreases in breakdown rate.

For all varieties in 1992, flour protein content was above average at around 11%. Gel protein weights were correspondingly high, significantly above those for 1991 varieties. However, this increase did not appear to have been translated into quality as evidenced by low G' values. Standard errors were high compared with the magnitude of G' and gel protein elastic modulus was not significantly affected by wheat age for the varieties Mercia, Hereward or Fresco. A significant deterioration in protein strength (G') occurred in the variety Avalon and this appeared to be maintained after 84 days storage. (A trend towards decreasing quality was implied in breakdown rate data for this sample, but the effect failed to reach significance).

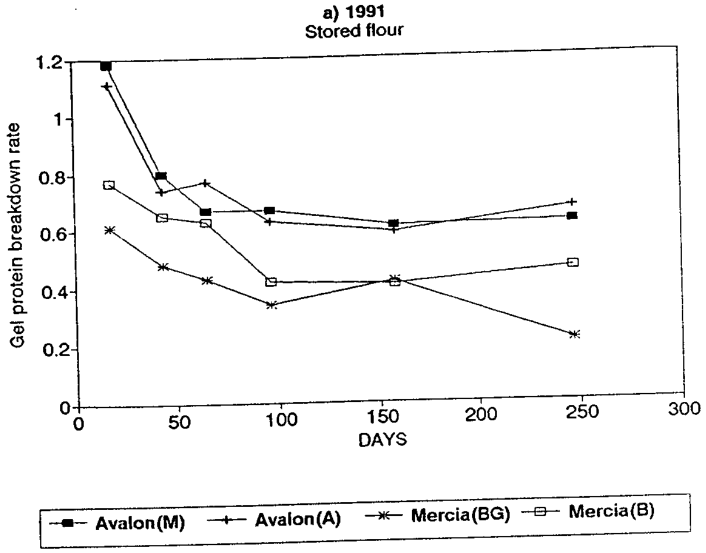
As for breakdown rate, samples of Avalon and Hereward examined in 1993 were atypical in terms of elastic modulus. Of the remaining varieties Mercia and Torfrida, significant increases in G' were observed after storage for 41 days for Mercia and 73 days for Torfrida. These effects supported trends observed in breakdown rate.

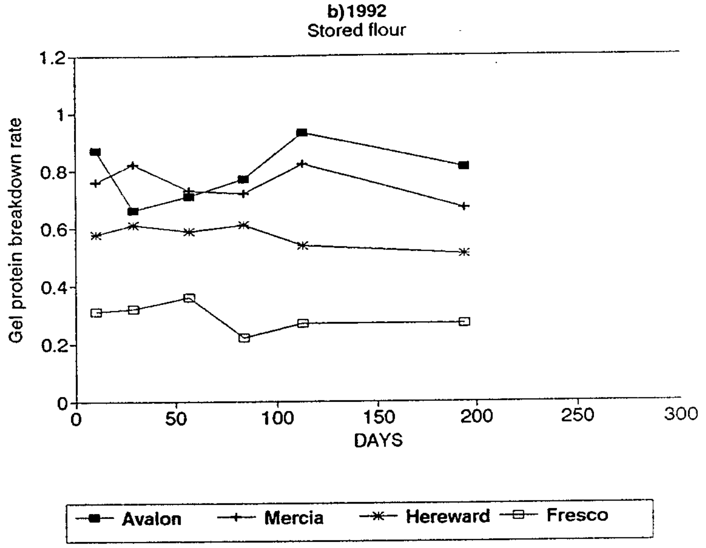
There was little evidence that storage of milled flour at 15-20°C had any significant effect on elastic modulus (G'). Effects of storage time on wheat and flour for all three seasons are shown in Figures 9 a-c and 10 a-c respectively. Comparison of Figures 7a-c and 9 a-c suggests that differences in milling performance had more effect on gel protein elastic modulus than on gel breakdown rate. The observed increases in flour extraction when wheat was stored for a period of time before milling would result in an increased proportion of non-endosperm components in the final flour and as a consequence protein functionality would be expected to decrease.

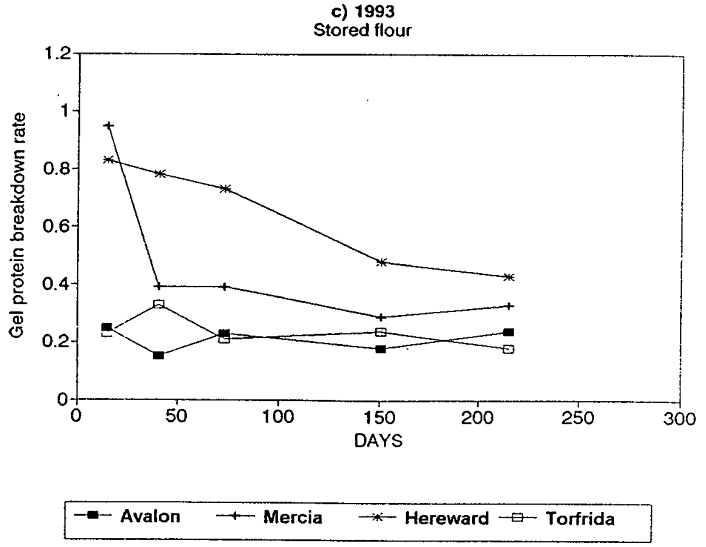
In common with other quality measurements, significant seasonal variations in elastic modulus occurred over the three years of this study (see Appendix 1, Table 19). Between season differences were significant in all varieties where comparisons could be made and were generally larger than any change produced by storage conditions. Differences of the magnitude observed in Mercia and Avalon over the three years of this study would be expected to have a significant effect on basic breadmaking quality.



Figures 9 a-c **Effect of wheat storage on gel protein elastic modulus (G', Pascal) in 1991-1993 respectively.**







Figures 10 a-c **Effect of flour storage on gel protein elastic modulus (G' , Pascal) in 1991-1993 respectively.**

If we disregard the atypical sample of Hereward where protein quality has been affected by growing conditions, data seemed to suggest an inverse relationship between protein content and protein quality, i.e. either gel protein breakdown rate or elastic modulus. Thus, it is possible that the wheat plant has some mechanism for increasing protein quality to compensate for lack of protein content. Alternatively, when the climatic conditions in a particular season (such as 1992) are conducive to the production of high protein content this may lead to a dilution of the functional HMW glutenin proteins.

The viscous modulus, G" responded in a similar manner to G' in this study and therefore results have not been shown.

4.5.4 Flour: Phase angle

Gel protein phase angle ($\tan^{-1}$ G"/G') was less than 45° for all flour samples and showed no significant effect of storage regime. Values of around 33°+/-8 were achieved for all samples. These are typical of breadmaking wheat varieties and indicate the dominance of the elastic properties of dough in overall rheological behaviour. Thus, a reasonable balance of elastic and viscous properties was found in all samples i.e. within the range generally considered to be desirable for satisfactory breadmaking performance. Where comparisons could be made over three years, phase angle was highest in 1993 and lowest in the 1992 samples.

4.5.5 Gluten content

Wet gluten was isolated from white flour using the Falling Number Glutomatic gluten washer. Wet gluten is directly related to flour protein content, but protein aggregations which affect solubility may be expected to influence final values.

Results are presented in Appendix 1, Table 20 for all varieties and time-points studied over the three years of this work. Means, standard deviations and $LSD_{5\%}$ are presented for the frozen "control" flour. Considerable variability in test results was observed in this study, e.g. standard deviations within a single variety flour were as low as 0.25 for Mercia(B) in 1991 and as high as 1.42 for Fresco in 1992. The quoted standard deviation of Reproducibility for wet gluten content is 1.5 and thus data produced for "control" flours were within the normal range of variability.

No overall significant effect of wheat storage before milling on wet gluten content was observed in this study. Comparing all results for freshly milled wheat back to the initial milling, only three significant reductions in wet gluten content occurred. These were Avalon(M), the 1992 Hereward sample and the 1993 Torfrida sample. In all cases a reduction in insoluble gluten protein, shown as lower wet gluten content, occurred after long periods of storage i.e. 158, 194 and 215 days respectively. In two of the three cases, further storage of these wheat samples resulted in wet gluten contents which were not significantly different to the value obtained in samples tested immediately after harvest. This suggested that observed differences were not real and wheat storage had no significant effect on wet gluten content.

No significant effect of flour storage on wet gluten content was observed for any variety or season.

As expected, this quality characteristic was affected by annual differences in protein content. For the common varieties, Avalon and Mercia, wet gluten contents were lowest in 1993 when protein content was below average. Similarly in 1991 the Mercia(B) sample, which had nearly 1% lower protein content than the Mercia(BG) sample , had a significantly lower wet gluten content.

The ratio between wet gluten content and protein content should be relatively stable and for normal flour samples should be greater than or equal to 2.7. This relationship was observed for most varieties and seasons in this study. The major exceptions to this occurred for the strong varieties (Fresco in 1992 and Torfrida in 1993) where rather low wet gluten recoveries were observed and mean ratios of wet gluten to protein content of 2.57 and 2.51 were obtained respectively. These ratios were below the average for standard wheat varieties. Fresco and Torfrida are known to produce strong, tough gluten and this may have affected the performance of the standard gluten washing test. The high standard errors for wet gluten content found in the Fresco sample tend to support this theory. Such samples may benefit a modification to the protocol, i.e. mixing with increased buffered salt solution in order to produce a slacker dough from which the starch and soluble proteins could be removed more easily. The 1993 Avalon sample also produced a low mean wet gluten to protein content ratio of 2.56. This sample was also more Resistant in the Brabender Extensograph and Chopin Alveograph test than any other sample of Avalon examined in this study and rather atypical of this weak breadmaking variety.

4.5.6 Gluten: elastic modulus

Samples of prepared gluten were allowed to rest for a period of 20 minutes before measurement of elastic modulus using a Bohlin VOR rheometer. Results of elastic modulus (G') obtained for gluten samples are presented for all varieties and storage conditions in Appendix 1, Table 21 together with means, standard deviations and $LSD_{5\%}$ values for frozen "control" flour samples. Typical values range between 3.72 and 25.55 x 10^2 Pascal for the varieties under consideration.

A general decline in G' values was recorded over the storage period for most varieties under all storage conditions. Since reductions in elastic modulus were also observed in the frozen "control" flour, this suggests that this measurement was susceptible to small differences in the preparation of the wet gluten. Observed variability was high with coefficients of variation ranging from 16 to 32.5%. Against this background there were few consistent, significant differences in gluten G' associated with age of wheat before milling. In 1991, no significant effects were observed in any variety. All varieties in 1992 and only Mercia after 215 days storage in 1993 showed significant reductions in gluten G' due to wheat storage. However, in all cases where significant effects were observed, the frozen sample tested at the same time-point produced a similar or lower G' value suggesting effects were not real.

Varietal and seasonal differences appeared to be significant. Table 21 in Appendix 1 shows the mean gluten G' value for the frozen "control" flour for each variety tested in each year harvest. Examining seasonal effects, i.e. comparing common varieties grown in different years, the average G' values can be used to rank samples as follows:

1993 higher than 1992 similar to 1991.

This suggests that the samples examined from the 1993 harvest produced an increase in the number of protein-protein interactions, i.e. stronger glutens. The 1993 samples were characterised by low protein content and below average CBP loaf volume and therefore it appears that increases in gluten strength are of little value unless supported by improvements in protein content. Whilst Fresco and Torfrida, would normally be classified as "extra strong" on the basis of their gel protein strength neither achieve gel protein G' values of above 40 (x 10^3 Pascal) in this study (see Appendix 1, Table 19). No relationship between gluten G' and CBP loaf volume has been established and hence no guidelines for optimum performance have been validated. The highest gluten G' values were generally obtained for the variety Fresco in 1992 and for Torfrida in 1993, but the differences between these and the other breadmaking varieties were not significant (Avalon in 1993 and Hereward in 1992 produced similar gluten G' values to these nominally "extra strong" varieties). High gluten G' values support gel protein G' results observed in this study. Further work would need to be carried out and variability in test results reduced if this method of measuring protein strength was to have any value as a predictor of protein quality and breadmaking performance.

4.5.7 Dough ex CBP mixer: dough stickiness

Full recipe CBP doughs were removed from the mixing bowl and tested within 1 minute of the completion of mixing on a Bohlin VOR rheometer. Dough stickiness was considered to be of particular interest as this is perceived to be a problem facing the baking industry at harvest changeover, particularly when new crop wheat is introduced rapidly.

Initially, it had been suggested that the maximum strain reached by a dough when subjected to an oscillation test on the Bohlin rheometer could be related to dough stickiness. However, studies carried out in 1991 showed this measure to be remarkably consistent at between 2.18 and 2.35 for all bread doughs, to be unaffected by wheat variety or storage conditions and to bear little relation to subjective dough handling assessments made by the baking team.

Using a cone and plate measuring system with an applied strain of 0.0018, standard Bohlin measurements of G', G'' and phase angle were also taken. Of these measurements, the phase angle has been correlated with dough stickiness (Lindahl and Eliasson, 1992)

Phase angle data for full recipe dough samples are presented in Appendix 1, Table 22 for all varieties and storage conditions together with means, standard deviations and $LSD_{5\%}$ for frozen "control" flours.

For all varieties, seasons and storage conditions the phase angle was less than 45° indicating that dough elasticity dominates over dough viscosity. Phase angle values ranged from 14.35 to 32.9 over the varieties and seasons examined and variability within the frozen "control" samples was relatively high which resulted in few significant effects. In addition, trends in phase angle tended to occur in frozen "control" samples as well as stored wheat or flour samples tested at a particular time-point. This suggests that any observed effects were not real and that baking conditions on a particular day may have influenced results more than any seasonal or storage differences.

When phase angle results were compared with subjective assessments carried out by bakery staff, there was some evidence of a relationship; doughs classified as "very sticky" tended to have phase angles of greater than 26° whilst doughs considered to be "normal" tended to have phase angles of less than 24°. Given the variability in test results observed and the fact that most dough samples produce values within the region 24-27°, it appears likely that this test would not be sensitive enough to distinguish between slight differences in dough stickiness. There was no evidence to support the view that significant changes in dough handling properties occurred when wheat was permitted a period of storage before milling.

4.6 Available sulphydryl groups

Data relating to total available sulphydryl (SH) groups in flour samples are presented in Appendix 1, Table 23 for all varieties and storage regimes examined over the three year period together with means, standard deviations and $LSD_{5\%}$ values for frozen "control" flours.

Wheat storage is thought to influence the level of available SH groups as oxidation produces disulphide bonds which may affect the aggregation of gluten proteins. Reductions in the level of available SH groups can thus be used to indicate the amount of SH oxidation occurring in flours after milling.

The total available sulphydryl (SH) groups varied between 0.48 and 0.85µmole/g flour in this study. Values quoted in the literature (Grosch, 1986) are between 0.56 and 1.92µmole/g flour covering a range of flour types and measured by different techniques, i.e. amperometric or polarographic titrations of SH with silver or organo-mercurial compounds. Values obtained in this study for UK grown wheat milled to produce white flour on a laboratory Bühler mill tended to lie towards the bottom of the quoted range. All samples were tested in triplicate at each time-point. Mean values are quoted, but considerable variability was observed within replicates results produced for a single sample. Standard deviations ranged from 0.015 to 0.062.

The SH content of frozen "control" samples fluctuated by around 5% (similar to that quoted above) about mean values (µmole/g flour) of 0.7 for Avalon(M), 0.65 for Avalon(A), 0.74 for Mercia(BG) and 0.77 for Mercia (B) in 1991. Flour SH content would not be expected to change in an oxygen free environment and therefore this variability can be attributed errors in the test method. In 1991, available SH groups tended to increase with storage in all varieties suggesting a gradual change in the redox state towards reduction with storage time (see

Figure 11a). In particular, significant increases in SH content were observed in flour milled from the Avalon(M) sample after storage for 65 days. An isolated significant increase was also shown for flour milled after storage for 96 days for the Avalon(A) sample. The presence of additional SH groups in flour milled after a period of storage would provide increased availability for interchange with disulphide bonds in dough and could result in a weakened gluten structure with consequently reduced breadmaking performance.

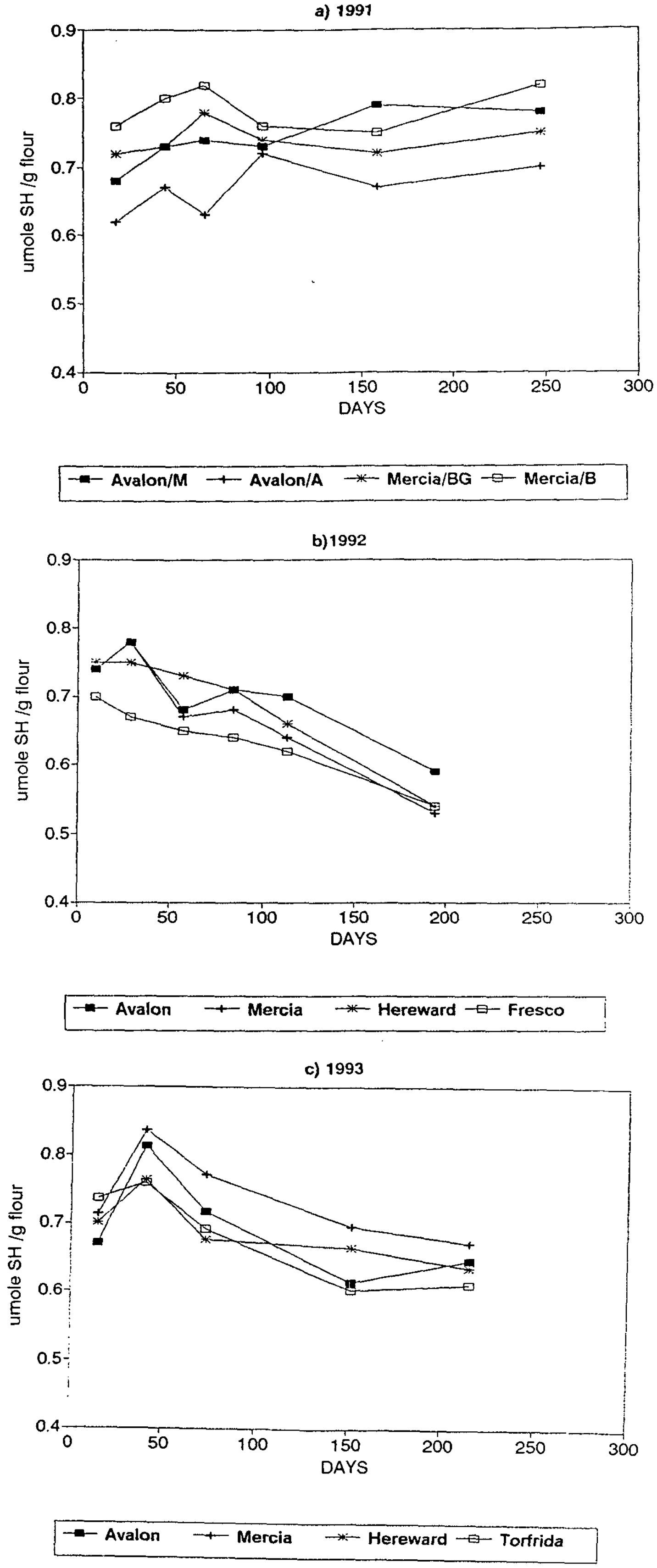
Significant correlations between available SH groups and time of wheat storage before milling appeared to exist for all samples examined in 1992. However, downward trends in SH content were observed under all storage regimes, i.e. even "control" flour stored at -18°C showed some evidence of reduced SH levels with time. In this case, flour was merely frozen and not gas packed in nitrogen, as had been the case in 1991. Originally it was thought that this treatment was not rigorous enough to fully stabilise the bulk flour in terms of available SH groups. However, a comparison of variability in SH measurements obtained for frozen "control" flour in 1993 with 1991 gas packed material shows that standard errors were very similar in flours from these two seasons and very different to 1992 values. Given this discrepancy and the obvious agreement between results obtained at each time-point, it seems likely that 1992 SH results have been affected in a systematic way by some variation in methodology. SH measurements were performed to a strict time schedule, i.e. within 2-3 days of milling or removal of stored samples from -18°C cold storage. However, it is possible that even small time differences could have a significant effect on this measurement.

Given the observed variability in measured SH content in frozen "control" flour in 1992, standard errors and hence calculated least significant differences were high. Despite high $LSD_{5\%}$ values, storage of grain prior to milling appeared to produce reductions in measured SH groups in all varieties in 1992 (Figure 11b). However, this observation is in contrast to results obtained in 1991 and due to the concerns expressed above, should be treated with some caution.

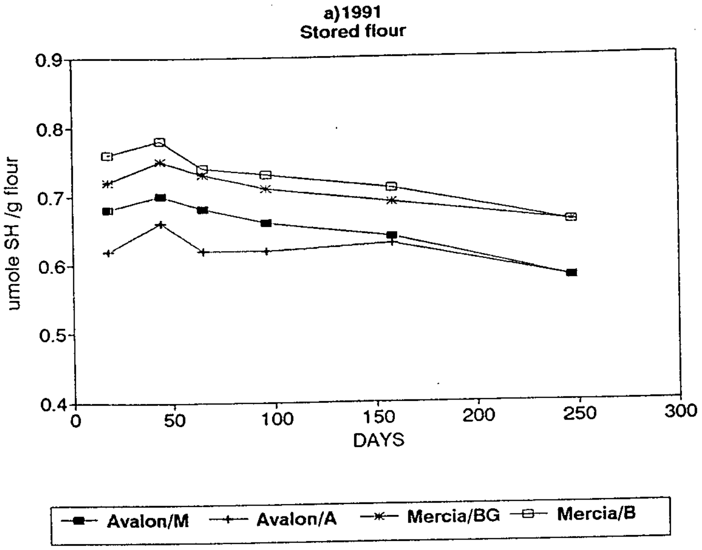
In 1993 no clear trend was observed in terms of SH content and wheat age before milling. Higher SH values were obtained for all varieties when the samples were subjected to a short storage period of 41 days, but this increase was also reflected in frozen "control" samples and continued storage resulted in a reversion to the original levels in Avalon and Mercia. Only the variety Torfrida exhibited significantly lower SH values with prolonged storage of wheat before milling (Figure 11c).

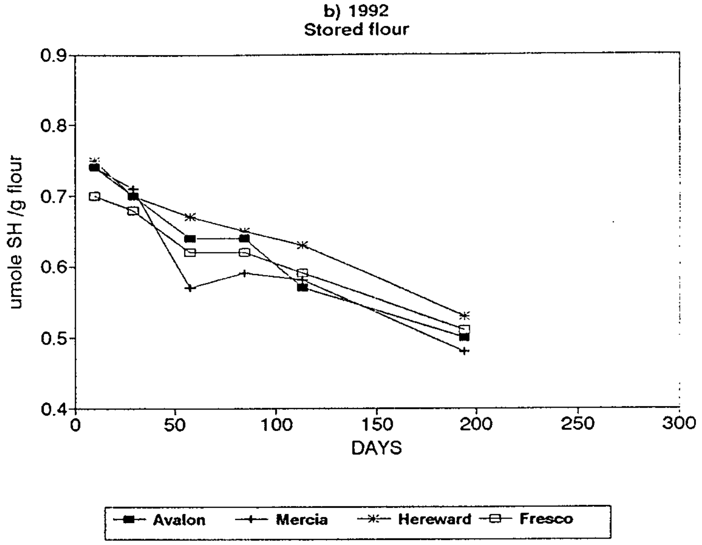
Considerable variability was observed in this measurement and it appears likely that the method suffers from a lack of sensitivity making it difficult to detect small differences in SH content which might be technologically significant.

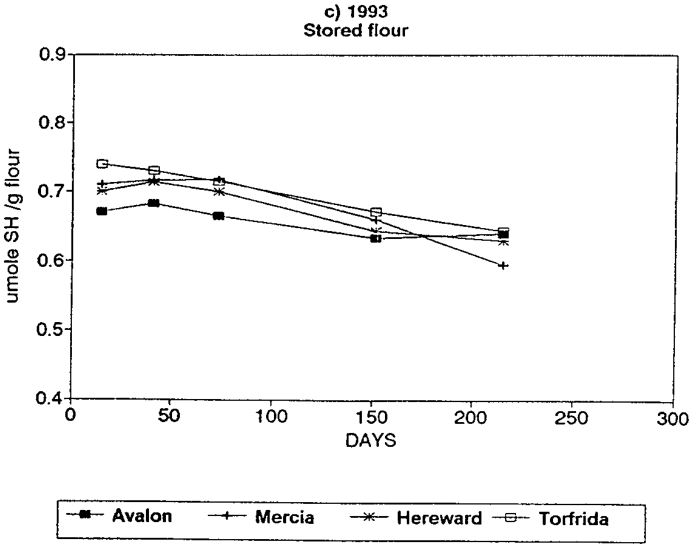
Given the apparent variability of the test method, one consistent trend was noted. Storage of bulk milled flour under controlled temperature conditions resulted in a gradual reduction in measured SH content in all three years (Figures 12 a to c). The effect was significant in all 3



Figures 11 a-c **Effect of wheat storage on available SH-groups (µmoles/g) in 1991-1993 respectively.**







Figures 12 a-c **Effect of flour storage on available SH-groups (µmoles/g) in 1991-1993 respectively.**

years and for all varieties except Avalon in 1993 at the end of each storage trial. This reduction in available SH groups suggested gradual oxidation of sulphydryl to disulphide bonds. Such changes in the SH:SS balance in a flour sample would be expected to increase protein aggregation which should result in improvements in breadmaking performance.

Examination of varietal data over the three seasons in question showed that there were no obvious varietal or seasonal differences in the available SH content of newly harvested wheat. Despite observed differences in protein content and protein quality, the SH content at the beginning of each storage trial was relatively consistent at 0.62 to 0.76μmole/g flour for all varieties examined.

4.7 Starch pasting properties

The Rapid Visco-Analyser (RVA) provides a rapid means of monitoring starch cooking properties and can be programmed to produce a curve similar to that obtained with the slower and more traditional Brabender Visco-Amylograph which was used at the start of this project. During these tests the temperature is raised to 95°C and wheat starch is gelatinised with a consequent rise in viscosity. A number of measurements can be taken from the pasting curves produced, but it is the viscosity or peak height which is most important. This is measured in arbitrary Brabender units for the Visco-Amylograph and as % viscosity for the RVA (the numbers obtained using the RVA are approximately 6-8 times lower than the Brabender instrument).

Results for the Brabender Visco-Amylograph (1991) and RVA (1992 and 1993) for each variety and storage practice are presented in Appendix 1, Table 24. Average coefficients of variation for frozen "control" flour were 14.5 % for the Brabender Visco-Amylograph and 3 to 4% for the RVA. The Brabender figures compare favourably with the quoted coefficient of variation for Reproducibility of 22.3% for the ICC standard method suggesting satisfactory stabilisation of the "control" frozen samples. No comparable data is available for the RVA.

In all seasons a period of storage prior to milling resulted in significant decreases in peak viscosity as measured by the Brabender Visco-Amylograph or RVA. For all samples except the 1993 Hereward sample and Avalon (M) significant reductions in viscosity occurred after a relatively short period of storage (41 days in 1993, 29 days in 1992 and between 44 and 65 days in 1991). Despite the consistent downward trend in all varieties and seasons during the early stages of storage, peak height results generally returned to values close to the original level by the end of the storage period.

Flour storage under controlled conditions of 15-20°C significantly increased peak viscosity in every variety and season. However, these effects only reached significance when flour was stored for a period in excess of 3 months.

Seasonal variations in peak viscosity appeared to be of greater magnitude than differences resulting from storage regime. Comparing RVA values, peak viscosity was significantly higher in 1992 than in 1993. No consistent varietal trends were observed and data from 1991

, where the Brabender instrument was used, suggested that considerable differences existed between examples of the same variety grown in the same year. For example, Avalon(A) produced peak viscosity figures more than double those obtained for the Avalon(M) sample.

4.8 Lipid analysis

Work was limited to the examination of a single variety in each season as the analyses are very labour intensive. Petrol extractable lipids and, in particular, petrol extractable polar lipids are known to be beneficial in terms of breadmaking performance. These components of the lipid fraction were monitored over the storage period. In addition, during flour storage most lipids are gradually broken down through lipolytic activity to give fatty acids. Unsaturated fatty acids in sufficient quantities have been shown to be associated with reductions in loaf volume under prolonged storage conditions.

4.8.1 Total petrol extractable lipid

Results of percentage total extractable lipid for the variety Mercia in each season and under each storage regime are presented in Appendix 1, Table 25. Standard errors were relatively constant at 0.055 to 0.065% for frozen "control" flours and reflect the variability in results obtained using this test method.

Comparing freshly milled wheat flour at each storage point with frozen "control" flour results indicated that a period of storage prior to milling had no significant effect on the amount of extractable lipid to be found in the final flour. Similarly, storage of flour under controlled ambient conditions had no effect on the amount of lipid extracted from Mercia flour samples in any season.

Mean values for the frozen "control" Mercia flour for the three years in question were 0.902% in 1991, 0.936% in 1992 and 0.937% in 1993 respectively indicating that seasonal differences had no obvious effect on total lipid content in this variety, i.e. all results were within the standard errors of the measurement.

4.8.2 Glycolipid content of free lipids

Polar lipids influence breadmaking performance, but their effect depends on both the concentration and type of lipid present. Results of total glycolipid content in free lipid, expressed as a percentage, for the variety Mercia are presented in Appendix 1, Table 25. Standard errors were relatively high at 1.47 to 2.14 representing coefficients of variation of between 12 and 19.5%. Imprecision in this measurement was particularly evident in 1991 where flours tested after a period of 44 or 65 days storage had substantially lower glycolipid levels regardless of storage regime.

Comparing freshly milled flour with the frozen "control" at each storage point showed no consistent significant effect of storing wheat prior to milling on glycolipid content. Sizeable reductions observed in 1991 samples after an initial storage period of 44 or 65 days, just failed to reach significance. This trend was evident in all samples at these time-points and was not sustained when milling was further delayed in this season. These facts suggest that changes were due to a systematic error in the methodology. Changes in glycolipid content of flour milled from stored Mercia wheat in both 1992 and 1993 were generally small and non-significant.

Similarly storage of flour under controlled ambient conditions in 1991 appeared to produce a significant reduction in glycolipid content, but again this effect was not maintained in flour samples stored under the same conditions for longer periods and can be linked to errors in the assay at the 44 and 65 day storage point. In all other seasons the glycolipid content of Mercia flour was unaffected by storage under controlled conditions.

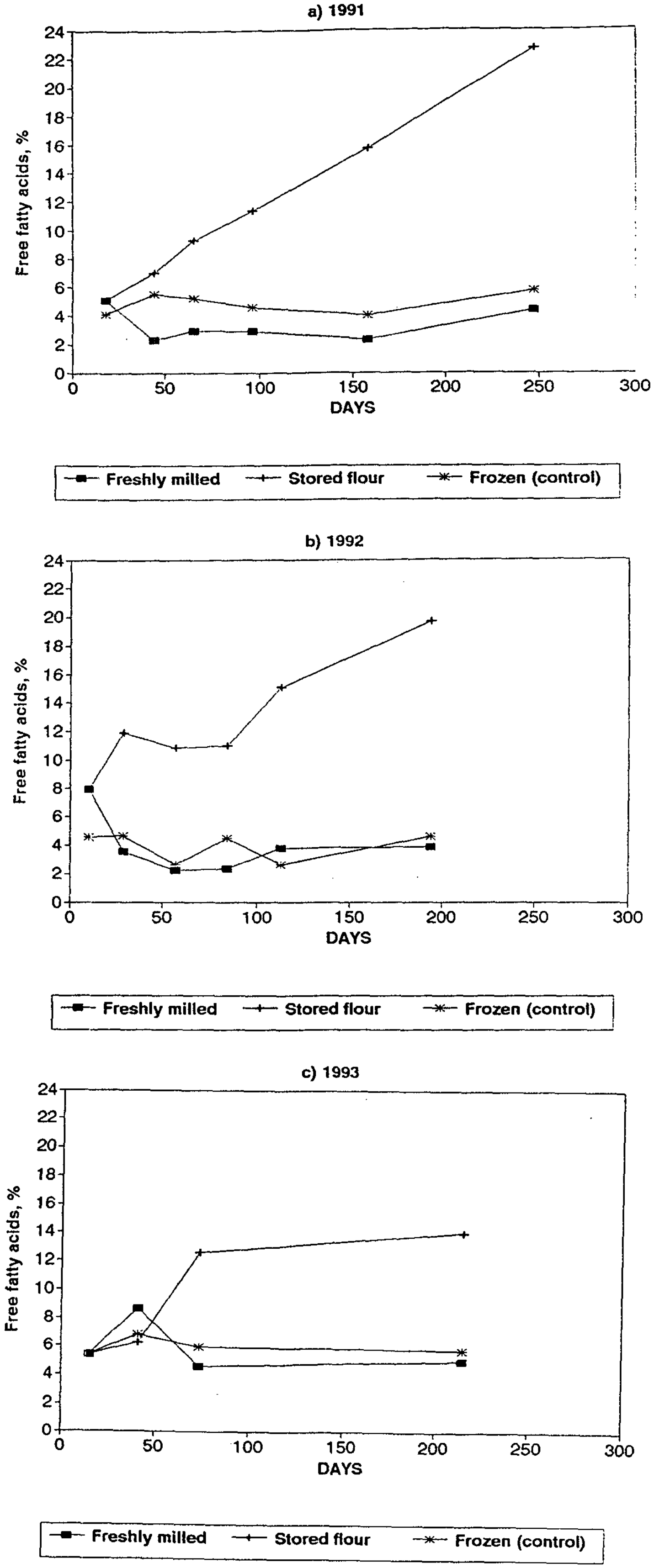
Mean values for the glycolipid content of free lipid in frozen "control" Mercia flour were 10.97 in 1991, 13.12 in 1992 and 12.08 in 1993. These values imply that glycolipid content differs from one season to another, but examination of the data in Appendix 1, Table 25 shows that the 1991 mean value was strongly influenced by the generally low values observed at the 44 and 65 day time-points and when these low values were removed , a mean of 12.3% was produced suggesting that this parameter was not significantly affected by seasonal differences in quality.

The analysis of free lipid and non-starch lipid extracts (1993 samples only) by HPLC failed to indicate significant differences in glycolipid components. Measurement of the most important glycolipids as digalactosyldiglyceride, monogalactosyldiglyceride, phosphatidylethanolamine and phosphatidylcholine showed no obvious difference in these components in 1993 flour samples. This suggests that the differences in milling performance observed in 1993 were insufficient to significantly influence glycolipid composition. Substantial changes in the glycolipid component of wheat flour lipids are required to significantly affect breadmaking quality. Therefore, it is unlikely that the content and composition of wheat flour glycolipids contributed to the small changes in bread quality observed for the variety Mercia over the time scale of this study in 1993.

4.8.3 Free fatty acid content

Free fatty acid contents, expressed as a percentage of total free lipid, for Mercia flour from each harvest year and storage regime are presented in Appendix 1, Table 25. Standard errors were relatively high at 0.61 to 0.96% corresponding to coefficients of variation of 10 to 23%. There was no evidence that gas packing under nitrogen followed by freezing was more effective in stabilising flour in relation to free fatty acids than simple storage at -18°C. In fact variability in 1991 data, where inert gas packaging was used, was greater than that observed in frozen stored samples in 1993.

In 1991 and 1992, flour free fatty acid levels were significantly higher in the initially milled sample and storage of the wheat prior to milling resulted in significant reductions in free fatty acid levels. This observation was not confirmed in 1993 when a slight (non-significant increase) in fatty acid content was detected when wheat was subjected to an initial period of



Figures 13 a-c **Effect of storage on free fatty acid levels (%) in freshly milled and stored flour in 1991-1993 respectively.**

storage. Prolonged storage of wheat before milling did not affect free fatty acid levels in this season suggesting that any effect was short-term i.e. likely to occur during the first month after harvest.

Flour storage under controlled ambient conditions resulted in significant increases in free fatty acid levels in all three seasons (see Figures 13 a-c). Flour storage for prolonged periods resulted in an increase in free fatty acid levels of approximately 15% in 1991, 8% in 1992 and nearly 5% in 1993. Reductions in CBP loaf volume were also observed when flour was stored for prolonged periods of time (see Figures 6 a-c), but the most significant effect was observed in 1992 when the increase in free fatty acid content was intermediate and wheat storage produced a similar decrease in loaf volume over the same time period (See Figure 5b). Therefore, due to variability in loaf volume data it was not possible to determine the significance of increasing free fatty acid levels on breadmaking quality when flour was stored under ambient conditions for periods of around 6-8 months. The position is further complicated in that the rate at which free fatty acid levels increase in flour during storage also depends upon the lipase activity of the flour. Lipase activity was not monitored in this work as the aim was to identify whether changes in important components of the lipid fraction play a role in quality differences in breadmaking i.e. to identify the effect rather than the cause in this instance.

Mean free fatty acid levels in frozen "control" Mercia flour were 4.87% in 1991, 4.06% in 1992 and 5.95% in 1993 respectively. Whilst data seemed to suggest that seasonal differences may affect free fatty acid levels, the limitations of the data made it impossible to confirm this suggestion.

4.9 Specific studies on seasonal variations in quality

4.9.1 SDS gel electrophoresis of total proteins

Samples of the initial milling for each variety and season combination were stored at -18°C for comparison by SDS polyacrylamide gel electrophoresis at the end of this study. Total protein extracts were prepared and fractionated on gradient SDS gels where separation occurs on the basis of molecular weight. A standard cocktail of molecular weight (MW) reference proteins consisting of the following : Cattle pancreas Trypsin inhibitor (MW=6.2k), Cytochrome C (MW=12.3k), Myoglobin (MW=17.2k), Soy bean Trypsin inhibitor (MW=21.5k) Carbonic anhydrase (MW=29.5k), Lactate dehydrogenase (MW=35.5k) Ovalbumin (MW=45k), Bovine serum albumin (MW=67k), Transferrin (MW=78k), Phosphorylase-b (MW=97.4k), β-Galactosidase (MW=116k) and Myosin (MW=200k) were separated on the same gel. With reference to the molecular weight markers, the HMW glutenin sub-unit bands associated with quality were identified and densitometry used to compare the peak areas of these technologically important proteins.

Electrophoretic separation of the total protein extracts from all samples are shown in Figure 14. The large protein species, which migrate slowest through the gel are found at the top of the gel. The largest of these, the HMW-G subunits have been shown to account for 60% of the variation in breadmaking quality in UK wheats (Payne *et al.*, 1987) and to be the principal components of gel protein (Pritchard and Brock, 1994).

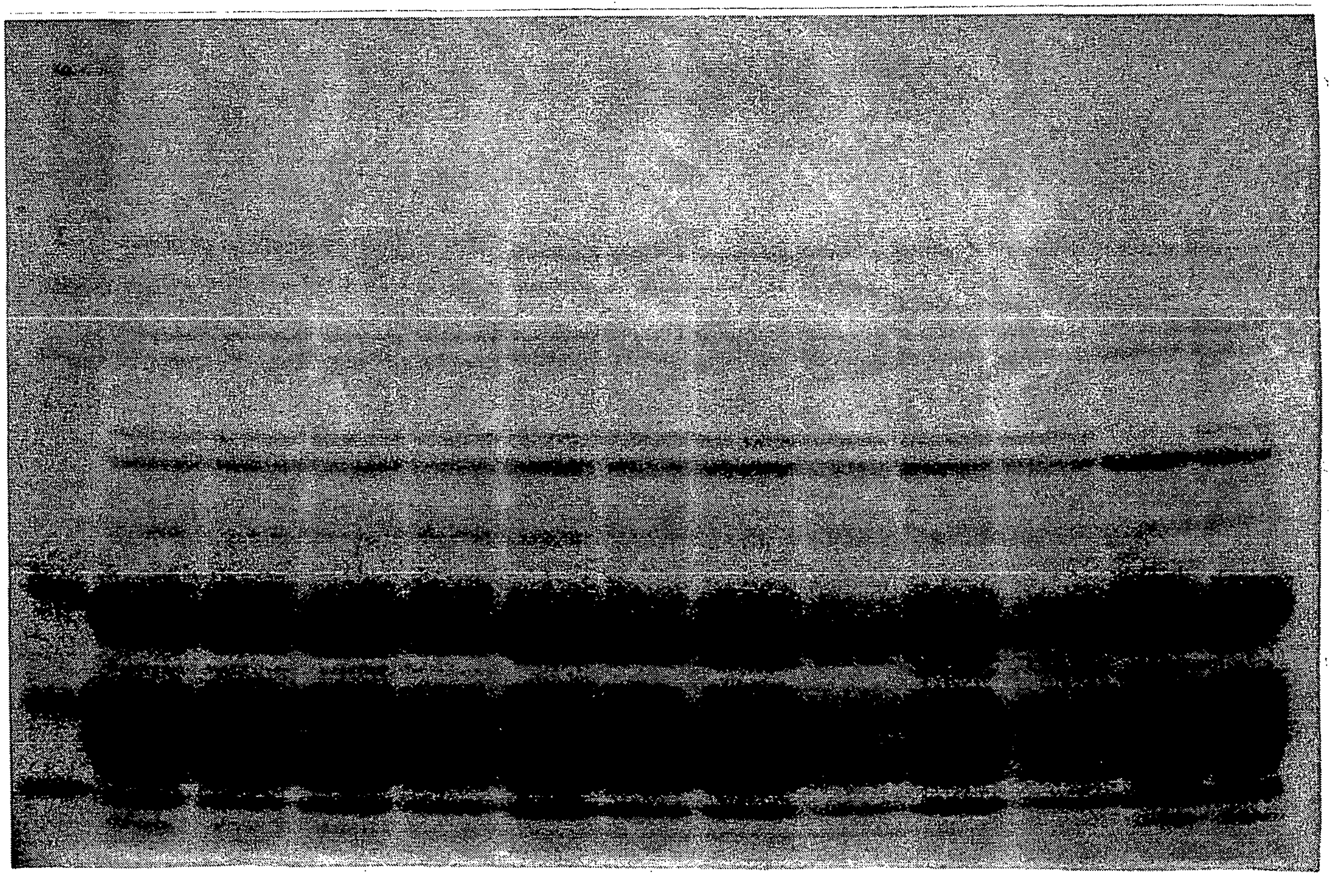
Comparing Avalon across the three years of testing (Tracks 2-5 of Figure 14) there were no obvious differences in total protein composition i.e. no differences in the basic electrophoretic pattern despite observed seasonal differences in breadmaking performance. Densitometric scans of tracks 2-5 Figure 14 confirmed that there were no major differences in the electrophoretic band pattern or intensity of bands of the Avalon samples under consideration.

For Avalon, the bands 1, 2+12 and 6+8 have been correlated with breadmaking quality and the peak area for these specific HMW-G subunits are shown in Table 9 together with the ratio of these quality proteins. The HMW-G fraction as a percentage of the total protein in the reduced extracts were also calculated in an attempt to identify relationships with the initial CBP loaf volume obtained for each flour sample.

Table 9 Protein composition studies for frozen "control" Avalon flour ex 1991 to 1993 harvests.

Sample	**Peak area of HMW-G subunits 1 and 2+12**	**Peak area of HMW-G subunits 6+8**	**Ratio of subunits (1 and 2+12) : (6+8)**	**Percentage HMW-G subunits of total peak area**	**CBP Loaf Volume, ml**
1991 Avalon(M)	4954	3564	1.39	4.81	1492
1991 Avalon (A)	4834	3630	1.33	4.94	1511
1992 Avalon	4294	3142	1.37	4.22	1622
1993 Avalon	5054	3848	1.31	5.03	1464

Within this rather limited data, no clear relationship was observed between protein composition and breadmaking quality within the variety Avalon. For example, both high and low CBP loaf volume was associated with high HMW-G score, i.e. for 1992 Avalon and 1991 Avalon(M) high HMW ratios were associated with significantly different CBP loaf volumes. Similarly, despite a reasonably large range in values for the percentage of HMW-G subunits to total protein in the extract, this measure of protein quality fails to rank samples correctly in terms of loaf volume. In fact, the best breadmaking sample of Avalon was produced when the levels of important HMW-G subunits in the total protein extracts were lowest (Avalon 92 where % HMW-G = 4.22). In contrast, it is to be expected that high levels of the important HMW-G subunits would be associated with good breadmaking performance. This suggests that the level of HMW glutenin subunits are not the only factors controlling final breadmaking quality.



From l to r tracks are as follows: **1**-Molecular weight standards, **2**-1991 Avalon(M,), **3**-1991 Avalon(A), **4**-1992 Avalon, **5**-1993 Avalon, **6**-1991 Mercia(BG), **7**-1991 Mercia(B), **8**-1992 Mercia, **9**-1993 Mercia, **10**-1992 Hereward, **11**-1993 Hereward , **12**-1992 Fresco and **13**-1993 Torfrida.

Figure 14 Electrophoretic separation of total protein extracts by gradient SDS-PAGE.

Examining the variety Mercia over the three years of testing (Tracks 6-9 of Figure 14), it is obvious that no major differences in protein composition occur as a result of seasonal differences in the variety, i.e. the electrophoretic band patterns are the same, the only differences exist in band intensity. Scanning Mercia tracks by densitometry suggested that the levels of lower molecular weight material was reduced in the 1993 harvest sample and highest in the 1991 Mercia(BG) sample. Levels of high molecular weight glutenin subunits appeared to be similar for all samples of Mercia.

For the variety Mercia, the high molecular weight glutenin bands 5+10 and 6+8 are important in terms of breadmaking performance. The peak areas of these functional protein subunits alone and in relation to the total protein content of the prepared extracts are presented in Table 10 together with the initial CBP loaf volume results.

Table 10 Protein composition studies for frozen "control" Mercia flour ex 1991 to 1993 harvests.

Sample	**Peak area of HMW-G subunits 5+10**	**Peak area of HMW-G subunits 6+8**	**Ratio of subunits (5+10) : (6+8)**	**Percentage HMW-G subunits of total peak area**	**CBP Loaf Volume, ml**
1991 Mercia (BG)	5060	3244	1.56	4.56	1600
1991 Mercia (B)	5062	3238	1.56	4.63	1575
1992 Mercia	4792	3018	1.59	4.39	1647
1993 Mercia	3998	2702	1.48	4.11	1526

Seasonal differences in CBP loaf volume over the three years were smaller for Mercia than observed for Avalon (maximum difference in loaf volume was 121ml for Mercia compared with 158ml for Avalon). For the variety Mercia HMW-G ratio appeared to bear some relation to final breadmaking performance in a CBP process : in general terms decreasing loaf volume was accompanied by decreasing HMW-G ratio.

The observed range in percentage HMW-G in relation to total protein in the extract was smaller for the variety Mercia. As for Avalon, there appeared to be no relationship between loaf volume and the percentage of technologically important HMW glutenins with the highest loaf volume produced by the 1992 Mercia sample which had the second lowest percentage HMW glutenins and the lowest CBP volume achieved by the 1993 Mercia sample which had the lowest level. Once again, high loaf volume appeared to be related to relatively low percentages of the important HMW glutenin subunits.

The remaining three varieties: Hereward (Tracks 10 and 11), Fresco (Track 12) and Torfrida (Track 13) present very different electrophoretic band patterns as seen in Figure 14. The peak areas of the important functional protein subunits alone and in relation to the total protein content of the prepared extracts are presented in Table 11 for the varieties Hereward, Fresco and Torfrida together with the initial CBP loaf volume results.

For Hereward, which was examined in two years, the lower subunit ratio and lower percentage of the important HMW glutenins appeared to result in better breadmaking performance. The contribution of HMW glutenins to total protein in Hereward was the lowest of all varieties studied suggesting that the combination of subunits 3+12 and 7+9 is more effective in terms of CBP breadmaking. No comparisons are possible for Fresco and Torfrida. However both varieties had relatively high levels of HMW glutenin protein related to good breadmaking performance in Fresco in 1992 and mediocre for Torfrida in 1993.

Table 11 **Protein composition studies for frozen "control" samples of Hereward, Fresco and Torfrida flour ex 1992 and 1993 harvests. (The important HMW-G subunits for each are shown in brackets)**

Sample	Peak area of HMW-G subunits Group 1	Peak area HMW-Group 2	Ratio of subunits Group 1:Group 2	Percentage HMW-G subunits of total peak area	CBP Loaf Volume, ml
92 Hereward	(3+12) 3252	(7+9) 2988	1.08	3.51	1837
93 Hereward	(3+12) 3450	(7+9) 3016	1.14	3.80	1524
92 Fresco	(5+10) 5726	(7+9) 3394	1.69	5.17	1870
93 Torfrida	(1 and 5+10) 4708	(17+18) 2672	1.76	4.82	1463

In conclusion, these results show that the major differences in percentage HMW-G occur between varieties, i.e. are genotypic and relatively small differences occur within a single variety grown in different seasons. Results also suggest that the percentage of significant HMW glutenin protein in a sample is not an adequate indicator of final breadmaking performance in a standard CBP system.

4.9.2 Size-exclusion High Performance Liquid Chromatography (SE-HPLC) of protein extracts

Size-exclusion HLPC separation was limited to examples of the varieties Avalon and Hereward. Results obtained for first and second extracts of freshly milled flour for varieties Avalon in 1991-1993 and Hereward in 1992 and 1993 are presented in Table 12.

Table 12. Comparison of protein extracts (1 and 2) by Size Exclusion - High Performance Liquid Chromatography (SE-HPLC) for selected varieties.

Variety/year	**Total area x 10^4**	
	1st extract	**2nd extract**
1991 Avalon (M)	33.9	11.3
1992 Avalon	31.4	14.8
1993 Avalon	28.9	25.4
1992 Hereward	33.7	15.7
1993 Hereward	31.4	17.2

For Avalon, there was some evidence of differences in amount of protein in first and second extracts within the three samples examined. Glutenin protein too large in molecular size to be solubilised in the first extract would be reduced in size by treatment with dithiothreitol and result in an increase in the amount of second extract and therefore and an inverse relationship between amount of first and second extract was indicated for Avalon samples. However, the amount of first or second extract present could not be related in any way to breadmaking performance. An increase in second extract levels would be expected to indicate an increase in aggregated glutenin protein and thus associated with improved breadmaking performance. In contrast, the optimum CBP loaf volume for Avalon was obtained for the 1992 sample (see Table 9): a sample which had intermediate values for both first and second extracts. The 1993 Avalon sample was somewhat atypical in terms of protein functionality, as measured by gel protein breakdown rate, and this is confirmed by the SE-HPLC data where the amount of aggregated glutenin protein appears to be abnormally high. On this occasion a high level of second extract was certainly not associated with increased loaf volume or overall quality.

Comparing the Hereward samples, the 1992 flour contained higher levels of first extract than the inferior quality flour milled in 1993. Again the drop in first extract for 1993 flour was accompanied by an increase in second extract levels, but this could not be related to an improvement in breadmaking quality (the average CBP loaf volume for Hereward was 1837ml in 1992 and 1524ml in 1993).

Overall, limited SE-HPLC data appeared to indicate that varietal influences were greater than differences in protein aggregation. When the atypical Avalon 1993 sample was excluded, observed differences in first or second extracts were relatively small and neither individual values nor ratios of 1st/2nd extract could not be related to improvements in breadmaking quality.

4.9.3 Pentosan content

Endosperm cell walls in wheat are composed mainly of pentosans and thus differences in milling performance are likely to influence the amount of total pentosan in freshly milled flour. Pentosans have important water binding properties and soluble pentosans, in particular, are known to exert a positive effect on water absorption capacity. Therefore, differences in pentosan content and composition may be expected to affect Farinograph characteristics, dough handling properties and perhaps contribute to observed seasonal variations in quality. Total and soluble pentosan levels together with the percentage soluble contribution to total pentosan content are presented in Table 13 for frozen "control" flours from each season and variety examined. (Insoluble pentosans are normally determined by difference and have not been quoted).

Total pentosan contents tended to be at the lower end of the range previously observed for UK wheat flour (Stevens *et al.*, 1989) whereas soluble pentosan levels were typical of those observed in 1989.

Comparing the common varieties, Avalon and Mercia, over the three seasons in question; 1993 flour samples appear to have higher total pentosan contents than 1991 which in turn were generally higher than 1992 samples. This suggests that year-to-year differences in total pentosan content may occur and that an inverse relationship exists between protein content and total pentosan levels. Given the limitations of the data, it was difficult to identify particular trends with respect to variety except, that within a season, Hereward tended to have a low total pentosan content. The contribution of soluble pentosans in each flour sample appeared to be independent of total pentosan content, i.e. the highest levels of soluble pentosan were found in 1991 samples which were only average in terms of total pentosan content. As a result the contribution of the soluble pentosan fraction differed from one season to another, being lowest in 1993 and constituting a higher proportion of the total pentosan content in 1991.

Table 13 Comparison of total and soluble pentosan contents of control white flour produced from wheats ex 1991 to 1993 harvests.

Sample	Total pentosan, % flour weight	Soluble pentosan, % flour weight	Soluble pentosan, % of total pentosan content
1991 Avalon(M)	1.61	0.61	37.8
Avalon(A)	1.51	0.47	31.1
Mercia(BG)	1.49	0.55	36.9
Mercia(B)	1.58	0.46	29.1
1992 Avalon	1.42	0.53	37.3
Mercia	1.50	0.35	23.3
Hereward	1.40	0.42	30.0
Fresco	1.27	0.33	26.0
1993 Avalon	1.74	0.44	25.3
Mercia	1.67	0.45	26.9
Hereward	1.58	0.44	27.8
Torfrida	1.84	0.50	27.1

5. DISCUSSION

Ageing or maturation of wheat relates to the changes which may occur during storage and result in either optimisation of quality, provide the desired consistency for particular end-uses or cause significant deterioration in quality characteristics. Under normal conditions, wheat is used by the miller within 12 months of harvest and it is therefore important to ensure that normal storage practice does not significantly affect the quality of his prime raw material. In addition, the miller needs to identify any beneficial changes in quality and seek potential ways to artificially induce them. Thus, the comparison of freshly milled wheat and frozen "control" flour is of prime interest. The flour processor, in this case bread baker, needs to have a raw material of consistent quality. Harvest changeover has traditionally been a problem time when differences in quality have apparently been perceived by processors: these may occur as a result of differences in the underlying quality of the miller's raw material leading to variation in flour quality and may be associated with subtle biochemical changes in one or more of the resulting major flour components. A better understanding of the differences which can occur as a result of seasonal or short-term changes and their effects on milling and breadmaking processes may help scientists to advise processors how to minimise effects of harvest changeover. Few studies have been directly related to the detection and understanding of quality changes in the immediate post-harvest period. This may be partly due to technical and practical problems associated with obtaining freshly harvested grain and processing large quantities rapidly on a pilot scale.

A small, but significant, proportion of post-harvest losses in wheat grain are purported to be due to changes during storage through respiration, loss of viability or biochemical deterioration which result in changes in nutritive and end-use quality (Pomeranz, 1992). Deterioration in cereal lipids may be oxidative or hydrolytic, the former resulting in typical rancid flavours and odours and the latter producing free fatty acids. In whole wheat grains , the lipid components are preserved from oxygen in the air and the presence of natural antioxidants prevents oxidative rancidity from becoming a problem. When grain is stored under adverse conditions, i.e. high moisture and temperature where mould growth and general quality deterioration is likely to take place then lipolytic activity results in breakdown of lipids to form free fatty acids and glycerol. For this reason, changes in lipid extractability and composition are often used as indicators of serious grain deterioration due to poor storage conditions. In this study mature, clean wheat in good physical condition was stored at moisture contents of 14% or less and temperatures of -18°C or between 15 and 20°C for a maximum of one year. Given the good condition of grain (low moisture content and low levels of broken or damaged grain) and controlled storage conditions it is unlikely that respiration would have a major effect post-harvest. Biodeterioration may be expected to be slow and hydrolytic breakdown of lipids is unlikely. This study indicated that storage of bulk wheat for over 8 months, prior to milling, did not produce a detectable decrease in lipid extractability or increase in free fatty acid levels thus confirming the efficacy of the controlled storage conditions used.

Gas packing under nitrogen had been adopted in a study of prolonged storage of flour (Bell *et al.*, 1979a) and proved to be an effective means of stabilising flour over the six year span of that investigation. In the first year of the current study, samples were gas packed under nitrogen in tins and a proprietary oxygen scavenger added before storage at -18°C. In later years the constraints of timing resulted in gas packaging being impractical and "control" flours were sealed in double polythene from which excess air had been excluded before storage at -18°C. Inert gas storage offers no protection against hydrolytic rancidity (Galliard, 1989). It does confer some protection against oxidative rancidity, but in flour hydrolytic changes must precede oxidative ones. Thus, storage at -18°C should be an effective means of stabilising flour quality in terms of flour lipids and other quality parameters. Certainly, there was no evidence that storage under inert gas was essential for flour stability over the more limited time-span of this study.

Milling yields tended to be lowest when wheat was milled immediately after harvest and a period of maturation prior to milling appeared to result in an increase in straight-run flour, i.e. easier release of endosperm in 7 out of 8 samples tested in either 1991 or 1993. In addition the magnitude of the extraction effect differed from one year to another, i.e. in 1992 no significant improvement in milling yield was observed for straight-run or total extraction flour. There was some evidence that the flour produced had a higher ash content and was slightly coarser. These observations support a change in milling performance and, in particular, the increase in particle size reported by Posner and Deyoe (1986). Differences in total flour extraction observed in this study were not as significant as those reported by Posner and Deyoe (1986) who found a 2-5% increase in total extraction under small-scale milling conditions. Their studies also suggested that improvements related to flour ageing were more pronounced where wheat moisture content was relatively high. There was no evidence to support this premise in this study as significant increases in flour extraction occurred for wheat at both ends of the moisture spectrum. Studies by Shelke *et al.* (1992a), who used a controlled milling system to produce low extraction rate (~70%) and flour with similar granularity to commercial cake flour, suggested there was no effect of wheat age on extraction rate or on chemical composition of flour. The use of controlled, low extraction rate in the Shelke study is likely to have influenced results. Typical UK extraction rates would be closer to 80%, i.e. similar to those observed in the current study. The increases in straight-run flour of between 2.7 and 4.3% observed when wheat was subjected to a short storage period prior to milling would be commercially relevant to the UK milling industry and would support the theory that wheat mills differently when it is fresh. A patent (Hoseney *et al.*, 1993) claims to have overcome the need for a period of storage before milling by hydrating wheat with 4-5% additional water, then drying back to the original moisture content before milling. This process is intended to improve the millability of freshly harvested wheat, increasing the capacity of freshly milled flour to rapidly hydrate and thus produce a flour which is optimised for baking. This claim is untested for UK wheat, but may offer the miller a means of alleviating the perceived problems of milling soft wheats immediately after harvest.

Differences in physical grain properties were observed in the three seasons examined which may be expected to impact on milling performance. In particular, three of the four wheat samples examined from the 1992 harvest had low specific weights i.e. Avalon at 71.0kg/hl, Mercia at 73.2kg/hl and Fresco at 75.7kg/hl. Despite the generally poor relationship between specific weight and flour yield reported by Hook (1984) and confirmed in this work by the lack of effect of low specific weight on flour extraction in 1992, grain shrivelling can be expected to influence milling performance and may affect water uptake, moisture partitioning within the grain during conditioning and fracture properties during Bühler milling. For the two seasons where milling performance improved with storage, the major change occurred within 44 days and further storage rarely produced significant improvements in flour yield. Due to the lack of response in flour extraction in 1992, it is not possible to provide firm guidelines with regard to storage of wheat in order to optimise flour yield, but the tradition of blending "old crop" wheat for the first 6 to 8 weeks after harvest would appear to be sufficient to counteract any loss in milling performance encountered at harvest changeover.

Flour bridging is a problem which can arise when flour is discharged from bins. Equally, a flour which has a propensity to bridge may cause problems during the dressing or sieving stages of milling. Certainly, the miller perceives that freshly harvested grain is softer to mill and presents greater problems in sieving due to apparent "fluffiness". The Instron bridging pressure test was used in an attempt to measure changes in flour flow properties. There was a suggestion that the capacity of flour to bridge was at a maximum, i.e. bridging pressures were lowest in freshly milled new crop wheat and subtle changes in particle size distribution towards coarser flour following a period of storage also tended to support this view. However, the errors associated with the Instron test made it impossible to reach a firm conclusion on whether flour bridging was a significant issue in milling freshly harvested bread wheat and hence whether storage for a defined period of time could reduce the problem. The inclusion of a soft variety in the study may have clarified the position, but such cultivars are not favoured in the UK for breadmaking and therefore are not readily available commercially.

Improvements in the breadmaking quality of flour following an initial period of storage have been documented (Fisher *et al.,* 1937; and Zeleny, 1954). The addition of artificial ageing agents, blending of old and new flour, aeration during transportation or a period of storage in silos resulted in observable improvements in breadmaking performance. The flour maturation process encompasses a number of reactions which can be summarised as follows:

In flour, the rate at which fat is hydolysed depends upon factors which affect enzymatic activity i.e. storage temperature, moisture content and availability of substrate which is in turn affected by extraction rate (Berger, 1994). During milling, non polar lipids in particular, are distributed throughout the milled flour making them more accessible to oxygen and enzyme activity. Lipase action results in the breakdown of triglycerides to fatty acids and glycerol. In the presence of oxygen, the enzyme lipoxygenase can then further transform free fatty acids and, to a limited extent, monoglycerides to produce peroxy radicals which may lead to the formation of disulphide bonds. Ultimately, such changes in the redox state in dough may result in improvements in gluten development and breadmaking properties. Increases in dough strength have been observed in French breadmaking systems (Berger, 1994) which have been associated with rapid oxidative changes in flour, but there is a suggestion that any gain in quality would be small and may be difficult to detect unless the original freshly milled flour is slightly sub-optimal in quality terms. Oxidative changes occur relatively quickly, typically in 3-7 days. Under commercial UK conditions, major processors receive flour by tanker. Tankers are normally loaded by blowline or fluidisation of the flour with air. Both filling methods would result in increased exposure of flour to oxygen and thus accelerate the oxidation process. Thus, it is likely that such changes would occur commercially within 2 to 3 days. Within this study it was totally impractical to mill, evaluate quality and test bake within 3 days. In addition, no bulk transfer of flour was carried out. For this reason a standardised protocol was adopted where baking was performed 7 days after the completion of milling and a strict testing timetable was adhered to for all quality measurements carried out. Therefore, no attempt was made to evaluate the rapid maturation changes which occur during the early stages of storage and it is assumed that freshly milled flour at each time point would be optimised in terms of breadmaking potential and any difference in performance should be related to changes occurring in the stored grain or differences in its milling performance. During prolonged storage of flour under ambient conditions continued lipid oxidation leads to the formation of increasing levels of free, unsaturated fatty acids with deleterious effects on flour quality characteristics and breadmaking performance (Bell *et al.*, 1979a).

Observed milling differences may be expected to influence traditional measures of flour quality. As far as empirical measurements of dough rheology, namely Brabender Farinograph, Extensograph or Alveograph changes in measured characteristics appeared to be unconnected with wheat age before milling or even flour storage conditions. Other flour quality measures, such as ash content and colour grade, were affected by changes in total flour extraction rate which resulted from wheat storage prior to milling. Both ash and flour colour measurements are affected by the amount of non-endosperm material in Bühler milled white flour and increases thus reflect increased effectiveness of the bran finishing process rather than a direct effect of storage prior to milling on these two parameters. Reported effects on Falling Number and *alpha*-amylase have been somewhat varied, increases in *alpha*-amylase activity were observed (Zeleny, 1954) during the early stages of storage whereas other workers (Seiler and Solomons, 1988) reported an increase in Falling Number which was not associated with a decrease in *alpha*-amylase activity when wheat was stored for short periods of time at elevated temperatures of 21°C or above. Over the relatively wide range of Falling Number and *alpha*-amylase values encountered in this study, there was no evidence of any effect of storage on these quality characteristics. The flour pasting characteristics were measured by the Rapid Visco-Analyser or Brabender Visco-Amylograph in this work and significant decreases in peak viscosity were observed after a short period of wheat storage for most varieties and seasons studied. However, this initial decrease in viscosity was not sustained when wheat was subjected to prolonged storage. Changes in paste viscosity appeared to coincide with the slight increases observed in flour particle size which occurred when wheat was milled after a short storage period. The overall conclusion from pasting studies carried out in the current investigation is that controlled storage of wheat at 15 to 20°C over a period of up to 8 months has no consistent effect on paste viscosity. This is in contrast to the work of Shelke *et al.* (1992b) who related increases in cake batter viscosity at both ambient and increased temperature with wheat age before milling. The Shelke study also detected a rise in the temperature at which the first rapid increase in paste viscosity occurs during a standard Amylograph heating cycle when wheat was allowed to age for up to

4 months before milling. This effect was not observed in this examination of the effects of storage on the characteristics of UK wheat. However, significant increases in peak viscosity were found in this work when white flour was stored at 15-20°C for periods in excess of 3 months. This confirms the findings of Shelke *et al.* (1992b) and Srivastava and Rao (1991), both of whom used flours with much higher peak viscosities than have been used in our experiments. Srivastava and Rao (1991) observed particularly significant increases in peak viscosity when flour was stored at 27 and 37°C, but found no changes in amylolytic enzymes. Under the severe temperature storage conditions used in the Srivastava and Rao (1991) study, selected to relate to the warm storage conditions observed in India, significant deteriorations in flour quality occurred within 2 months i.e. earlier than in our work,. Similar increases in peak viscosity were recorded by Loney and Meredith (1974) for storage of wheat flour and starch under less severe conditions which these workers associated with decreases in enzyme activity. Thus, flour storage at temperatures of 15°C or above and for periods greater than 3 months may be expected to increase paste viscosity. This information may be more relevant to end-users requiring to produce a batter during their process, e.g. cake and wafer manufacture but may also contribute to the deterioration in breadmaking performance observed for stored flour.

Any changes in protein, lipid and carbohydrate composition may be expected to impinge on breadmaking quality and there is some evidence that the breadmaking quality of both newly harvested wheat and freshly milled wheat flour tends to improve during an initial storage period (Pomeranz, 1971). However, studies suggest that a point is reached beyond which further storage no longer improves baking performance and, ultimately, extended storage of flour leads to a steady deterioration in quality. In this investigation breadmaking tests were always carried out 1 week after milling in order to eliminate the effect of oxidative improvement of flour influencing baking results. Thus any observed changes in breadmaking quality should be related to biochemical changes occurring in the entire stored wheat grain or resulting from differences in the quality of the milled product.

Warwick *et al.* (1979) suggested that oxidative changes may have dual effects. In early storage, oxidative processes may actually result in improvements in baking quality whilst continued storage results in the production of free radicals which may affect protein structure and produce a deterioration in breadmaking quality. Experiments over a two year period (Jones and Gersdorff, 1941) using storage conditions of -1 and 24°C suggested that there was a decrease in protein solubility and digestibility with prolonged storage. Reductions in salt- and alcohol-soluble proteins were indicated although there was virtually no change in total protein content or free ammonia nitrogen. Later studies Seibel and Weipert (1973) working with German wheat and Rao *et al.* (1978) observed a decrease in soluble protein after a short period of storage. However, the differences in protein solubility observed by Seibel and Weipert (1973) failed to produce any consistent effect on breadmaking quality. Whilst protein solubility per se was not measured in this investigation, protein studies included attempts to measure protein aggregation using size-exclusion HPLC and available sulphydryl groups. However, the biochemical techniques employed appeared to lack the required sensitivity and produced considerable variability in data which made it impossible to detect small, though possibly technologically significant, differences in protein composition.

Differences in flour extraction were found to exist between newly harvested and stored wheat. Any change in the distribution of lipid between white flour and the discarded bran components should result in a detectable change in the total extractable lipid fraction. Against a background of variable total lipid content data, there was no evidence of any significant effect when wheat was stored prior to milling in this study . Warwick *et al.* (1979) showed rapid increases in free fatty acids occurred during the first 2 months of storage at around 12°C, but no significant change in baking quality resulted. Total lipid content decreased and the observed increase in free fatty acids could be accounted for by decreases in triglyceride levels. Morrison (1963) showed a steady increase in free fatty acid levels in wheat flour stored at moisture contents of 13-14%. Only significant changes in the percentage of free fatty acids were observed when flour was stored at 15-20°C within the time-frame of our experiments. During flour storage, most lipids are gradually broken down through lipolytic activity to give fatty acids. Unsaturated fatty acids in sufficient quantities reduce loaf volume and decrease lipid extractability by petrol. Lipolysis of the beneficial flour glycolipids was also confirmed in long-term storage studies (Bell *et al.*, 1979b) to occur after a period of 6 months at ambient temperature. The removal of the beneficial effect of glycolipids would be expected to strengthen any effect of unsaturated fatty acids. Wheat storage conditions used in this study had little effect on free fatty acid content, glycolipid composition or total extractable lipid levels of Mercia flour. The data produced from the various lipid analyses was rather variable, making it difficult to detect anything other than major changes in lipid composition.

Bell *et al.* (1979b) studied the effects of long-term storage on three flour types (strong, medium and weak) on breadmaking quality using three baking systems: long fermentation, Chorleywood Bread process (CBP) and activated dough development (ADD). CBP was found to be the most sensitive to deteriorative changes and the time taken for stored flours of different breadmaking quality to first show a significant loss in loaf volume was relatively consistent at between 27 to 30 months for flours varying in protein content from 10.3 to 13.5%. Polar lipids, extractable from flour with petrol are widely held to be those which influence breadmaking behaviour, particularly the petrol-extractable glycolipids. Since fat addition does not improve dough expansion when petrol-extracted flour is used, these lipids must also be important with respect to the fat requirement of a flour and hence fat response in a standard CBP breadmaking system. However, other factors are clearly involved because correlations between loaf volume and petrol extractable glycolipids obtained by Chung *et al.* (1982) for US wheat and Bekes *et al.* (1986) for Canadian wheat were not confirmed for UK (Bell *et al.*, 1987), French (Berger, 1983) or New Zealand wheat (Larsen *et al.*, 1989). US and Canadian wheats have been bred from limited genetic stock compared with the more varied ancestry found in wheats from the other countries. A good relationship was found between baking quality and petrol soluble lipid in wheats bred to differ only at the 5D chromosome (Morrison *et al.,* 1989). This difference also affects the hardness of the wheat sample, but does not influence gluten properties. The lower petrol soluble lipid content of US and Canadian wheats and the higher bread volume obtained for North American compared with UK data may also be factors which improve the correlation. Comparative figures suggest that only small variations in the amounts and composition of flour lipids exist between varieties which suggests that it must be their associations with particular dough constituents which determine the extent of dough expansion and hence loaf volume potential. Total glycolipid content of petrol extracted flour was determined in each season and over the chosen storage period for the variety Mercia only, but no significant effect of wheat or flour storage regime was observed within this study.

Suggestions of changes in disulphide/sulphydryl ratios have been made (Rohlich and Thomas, 1967; Rao *et al.*, 1978). Rheological changes have been related to SH:SS interchanges and the ratio correlated with loaf quality. Rao *et al.*, also suggested that in newly harvested wheat SS:SH ratios were low, but increased with storage. In the present study total available SH-groups were measured, but no consistent trend in SH levels were observed for wheat storage. Decreases in SH-content would be associated with an increase in disulphide bonds in dough with consequent strengthening of gluten structure and potential for improved breadmaking performance. Variability in the data contributed to our failure to detect differences which may be technologically significant, but there appeared to be little evidence of a relationship between improvements in breadmaking performance and SH-levels in this study.

Wheat storage prior to milling appeared to have no consistent effect on performance in a standard CBP process. Wheat storage resulted in loaf volume increases in 1991 which, though sizeable, were not sustained over prolonged storage periods of over 8 months. In other seasons the tendency was towards reductions in breadmaking quality when wheat was stored for periods in excess of 4 months, but test data showed considerable variability suggesting that the effect of baking day may be more significant than potential effects of wheat storage. Performance in a standard breadmaking process, such as the CBP, depends on the complex interactions between proteins, lipids and carbohydrates. As indicated, reported changes in the major flour components resulting from storage trials tend to be antagonistic in nature and thus may be partly responsible for inconsistency in the data and lack of significance in terms of effects on breadmaking. In this work wheat storage was found to produce small and generally insignificant effects on the properties of all 3 major flour components and the combined effect of these changes appears to be insufficient to affect CBP bread quality consistently or significantly. This suggests that a) the CBP process is relatively tolerant to subtle changes in flour quality or b) uncontrollable differences in the standard breadmaking process used in this study can result in loaf volume and quality differences which may mask any small differences resulting from wheat storage. Certainly the work of Bell *et al.* (1979a) suggested that high speed mixing and the addition of ascorbic acid, as used in the standard Chorleywood Bread Process, may conceal small effects resulting from short-term storage of wheat or flour. In contrast when Bell *et al.* (1979b) studied the effect of long-term flour storage on performance in three breadmaking processes, the CBP method was found to be most sensitive to flour quality deterioration associated primarily with the lipid component. In the context of previous studies, this investigation would be considered to involve short-term storage of wheat and flour where a significant increase in free fatty acid levels was observed in stored flour only. Certainly, the variability in CBP baking data was of some concern and standard deviations observed in this study were often above those expected in this standard procedure. However, the fact that slight differences in baking conditions appeared to significantly affect performance in the CBP suggests that slight modification of the baking short-term storage of wheat. Harvest changeover has often been considered to present dough stickiness problems in commercial bread production systems; the suggestion being that dough produced from freshly harvested wheat tends to relax more quickly, presents handling problems in the bakery and displays signs of fragility resulting in damage in the final loaf. In order to combat these problems, bakers have traditionally added less water to the dough and hence suffered yield losses The dough rheology test employed to measure dough stickiness lacked the required sensitivity to detect small differences in dough stickiness. Manual assessments by bakery staff suggested that dough stickiness did tend to decline with age of sample before milling, but due to the subjective nature of this assessment it was not possible to form any firm conclusions on this issue. However, at no stage during our experimentation did dough stickiness present extreme problems within the bakery such that noticeable damage to the baked product occurred and in all cases doughs could be processed normally under pilot scale baking conditions. It is possible, that in a pilot scale bakery, staff take greater care of dough during the mixing, dividing and proving stages of baking or that the laboratory process is more tolerant than a commercial production plant. Alternatively, the perceived effect on dough processing performance may be partly attributable to seasonal differences in wheat quality where changes in composition, e.g. protein and pentosan content may result in dough handling differences. It is possible that small, stepwise changes in quality occur during the season as the miller has to search more extensively to source suitable wheat varieties for breadmaking flour. These small differences may be accommodated within the tolerance of commercial high speed mixing systems and it is only at harvest changeover when flour quality differences may be of a different order of magnitude that processing and product quality differences become detectable.

In this study breadmaking varieties, which covered the full range of protein strength, were selected in an attempt to identify whether particular varietal types were more or less susceptible to short-term or seasonal variations in end-use quality. Major quality differences existed between the varietal types examined, but wheat variety was not found to influence the magnitude of any observed storage effects on CBP loaf volume, i.e. the stronger varieties (Hereward and Fresco/Torfrida) examined in 1991 and 1992 showed similar response patterns to the weaker varieties (Avalon and Mercia).

The magnitude of seasonal differences in quality significantly outweighed those resulting from wheat storage conditions for most parameters. An exception to this rule were improvements in flour yield which occurred when wheat was stored for a short period prior to milling. Protein quality and protein content exert a major influence on final breadmaking performance. In this work an inverse relationship was noted between protein content and protein strength (as measured by rheology of the gel protein fraction). Within a single variety, when grain protein content was low, protein quality appeared to increase as a compensating measure. Initially, this finding was somewhat surprising, but has since been confirmed in data from Recommended List trials. In low protein years, protein elasticity or strength (gel protein G') tends to increase. For some varieties examined in Recommended List trials, this combination has resulted in "extra strong" protein with consequent reduction of breadmaking performance in CBP and Spiral mix breadmaking systems. One explanation may be that continued laying down of protein reserves in high protein harvest years favours the accumulation of gliadin or low molecular weight glutenin proteins rather than the technologically important high molecular weight glutenin proteins which are measured in the gel protein test. Electrophoretic separation of total protein extracts of flour from a single variety grown in different seasons suggested no difference in basic protein composition; scans of electrophoretic patterns could virtually be superimposed. Slight differences in degree of protein aggregation appeared to exist, but there was no consistent pattern to the data and no obvious correlation with breadmaking quality for either high molecular weight glutenin measurements from gel scans or peak areas from SE-HPLC traces. In fact, wheat genotype appeared to exert the major influence on the amount of important high-molecular weight glutenin (HMW-G) protein and seasonal variation in this parameter could not be associated with an effect on basic breadmaking quality. Total pentosan content differed from season to season and appeared to be inversely related to flour protein content. Seasonal differences in the contribution of soluble pentosans were also observed, but again these could not be related to either improvements or deterioration in breadmaking quality. Pentosan levels are known to contribute to differences in water absorption capacity, as measured by the Farinograph (Stevens *et al.,*1989). Seasonal differences in water absorbing capacity of common varieties were observed , but differences in protein content and starch damage in the milled flour produced in different harvest years obscured any obvious relationship. Pentosans may also be expected to affect dough handling properties, but the dough stickiness test used appeared to lack sensitivity and did not support the view that large differences in dough characteristics were produced ex CBP mixer.

When flour, rather than wheat, was stored at 15-20°C, significant reductions in CBP loaf volume occurred in 9 of the 12 samples examined over the 3 year period. A typical shelf life for white flour under standard storage conditions would be 6 months and the data provided in this study would tend to support this. During prolonged storage of flour significant increases in free fatty acid levels occurred which may be expected to reduce breadmaking quality, but this effect appeared to be counteracted by changes in protein functionality. Decreases in available sulphydryl groups suggested gradual oxidation of sulphydryl to disulphide bonds and an increase in protein aggregation. This tended to support observations of decreased gel protein breakdown rate. Such effects on protein structure would be expected to improve breadmaking performance. Although there was a general decline in loaf volume over the storage period in each year, significant reductions did not normally occur until the ultimate time-point of the experiment (usually 7-8 months) suggesting that the effect of increased free fatty acid levels only began to dominate during the latter stages of storage. Work of Bell *et al.* (1979a and b) showed significant reductions in CBP loaf volume occurred when medium and strong wheat flour was stored at ambient temperature for over 30 months; for weak flour nearly 4 years storage was required before a significant reduction in loaf volume occurred.

6. ACKNOWLEDGEMENTS

The author gratefully acknowledges financial support of the Home-Grown Cereals Authority. The contribution of the following colleagues at the Chorleywood site of CCFRA is also acknowledged: Brenda Bell, Graham Brown, Dr Philip Greenwell, Ged Oliver, Dr Peter Pritchard and Sarita Whitton.

7. REFERENCES

Abdelrahan, A. and Spies, R., 1986. In "Fundamentals of Dough Rheology" Faridi, H. and Faubion, J.M. (eds) Am. Assoc. Cereal Chem. St Paul MN.

Attenburrow, G., Barnes, D.J., Davies, A.P. and Ingman, S.J., 1990 Rheological properties of wheat gluten. J. Cereal Sci., 12, 1-14.

Anon, 1972. ICC Standard No. 126. Method for using the Brabender Amylograph. International Association for Cereal Science and Technology.

Anon, 1981. Annual Report on projects for the year ending 31st March 1981, Volume 1, 6-9. Reported by the Flour Milling & Baking Research Association to the Ministry of Agriculture, Fisheries & Food, September 1981.

Anon, 1983. ISO No. 5530/4. Wheat flour - Physical characteristics of doughs - Part 4: determination of rheological properties using an Alveograph. International Standards Organisation, Switzerland.

Anon, 1990 Protocol for testing wheats in Recommended and National List trials. FMBRA, Chorleywood.

Anon, 1991. In "Flour Testing Panel Methods" published by FMBRA, Chorleywood.

Bekes, F., Zawistowska, U., Zillman, R.R. and Bushuk, W., 1986. Relationship between Lipid content and composition and loaf volume of twenty-six common spring wheats. Cereal Chem., 63, 327-333.

Bell, B.M., Chamberlain, N., Collins, T.H., Daniels, D.G.H. and Fisher, N., 1979a. The composition, rheological properties and breadmaking behaviour of stored flours. J. Sci. Food Agric., 30, 1111-1122.

Bell, B.M, Daniels, D.G.H. and Fisher, N., 1979b. The effects of pure saturated and unsaturated fatty acids on breadmaking and on lipid binding, using Chorleywood Bread Process doughs containing a "model fat". J. Sci. Food Agric., 30, 1123-1130.

Bell, B.M, Daniels, D.G.H., Fearn, T. and Stewart, B.A., 1987. Lipid compositions, baking qualities and other characteristics of wheat varieties grown in the UK. J. Cereal Sci., 5, 277-286.

Berger, M., 1983. Soft Wheat Lipids : 2 - Composition of free and bound lipids in flour from eight varieties of soft winter wheat. Sci. Aliments., 3, 181-217.

Berger, M., 1994. Flour Aging. In " Primary Cereal Processing" Godon, B. and Willm, C. Eds., VCH Publishers Inc., New York

Beveridge, T., Toma, S.J. and Nakai, S., 1974. Determination of SH- and SS-groups in some food proteins using Ellmans reagent. J. Fd. Sci., 39, 49-51.

Brock, C.J., 1991. Making best use of wheat varieties. Chorleywood Digest No.112, 47-50.

Brown, G.L. and Scanlon, M., 1992 NAMAS accreditation for experimental milling at FMBRA. Chorleywood Digest No.117, 50-54.

Carr, N.O., Daniels, N.W.R., and Frazier, P.J., 1989. Lipid complex formation in wheat flour doughs in "Wheat End-Use Properties" Proceedings of ICC Meeting, University of Helsinki, 151.

Chamberlain, N., Collins, T.H. and Fisher, N., 1980 Methods for the production of acceptable bread from storage-deteriorated flours. J. Food Technol., 15, 515-521.

Chung, O.K., Pomeranz, Y. and Finney, K.F., 1982. Relation of polar lipid content to mixing requirement and loaf volume potential of hard red winter wheat flour. Cereal Chem., 59, 14-20.

Collins, T.H. ,1992 The Chorleywood Bread Process in 1992. Chorleywood Digest No 140, 128-132.

Dampney, P,M., Salmon, S.E., Pritchard, P.E. and Greenwell, P.G., 1996. Management of breadmaking wheat : effects of extra nitrogen on yield, grain and flour quality. Project Report No 109, Home-Grown Cereals Authority, London.

Douglas, S.G., 1981. Rapid method for the determination of pentosans in wheat flour. Food Chem., 7, 139-145.

El Baya, A.W., Fretzdorff, B. and Munzing, K., 1986. The behaviour of lipids during the controlled atmosphere storage of wheat. Getreide Mehl Brot, 40, 71-78.

Evers, A.D., 1979. Coulter counter particle size measurement. FMBRA Bulletin, 1979, No 1, 13-14.

Ewart, J.A.D., 1988. Studies on disulphide bonds in glutenin. Cereal Chem., 65, 95-100.

Fisher, E.A., Halton, P. and Carter, R.H., 1937. Studies on the storage of wheaten flour. I The influence of storage on the chemical composition and baking quality of flour. Cereal Chem., 14, 135-161.

Galliard, T., 1989. Rancidity in cereal products in "Rancidity in Foods" Eds. Allen, J.C. and Hamilton, R. J., Elsevier Applied Science.

Gesternkorn, P., Weipert, D., El Baya, A.W., Munzing, K., Meyer, D., and Zwingelberg, H., 1990. Changes in grain quality during storage. Getreide Mehl Brot, 44, 104 & 106-111.

Grosch , W., 1986. Redox systems in dough in " Chemistry and Physics of Baking" Eds. Blanshard, J.M.V., Frazier, P.J. and Galliard, T., Royal Society of Chemistry, London.

Hook, S.C.W., 1984. Specific weight: is it a meaningful measurement of wheat quality? FMBRA Bulletin, 91-98.

Hoseney, R.C., Faubion, J.M., and Shelke, K., 1993. US Patent No 5, 194, 276.

Jones , D.B. and Gersdorff, C.E.F., 1941. The effect of storage on the protein of wheat, white flour, and whole wheat flour. Cereal Chem., 18, 417-434

Kent, N.L. and Evers, A.D., 1994. In "Technology of Cereals" 4th Edition, Pergamon Press, Oxford.

Laemmli, U. and Favre, M., 1973 Maturation of the head of bacteriophage T4. J Mol. Biol., 80, 575-599.

Larsen, N.G., Humphrey-Taylor, V.J. and Baruch, D.W., 1989. Glycolipid content as a breadmaking quality determinant in flour from New Zealand wheat blends. J. Cereal Sci., 9, 147-157.

Lindahl, L. and Eliasson, A.-C., 1992. A comparison of some rheological properties of durum and wheat flour doughs. Cereal Chem., 69, 30-34.

Loney, D.P. and Meredith, P., 1974 Note on amylograph viscosities of wheat flours and their starches during storage. Cereal Chem., 37, 489-499.

Markwell, M.A.K., Haas, S.M., Bieber, L.L and Tolbert, N.E., 1978. A modification of the Lowry procedure to simplify protein determination in membrane and lipoprotein samples. Analytical Biochemistry, 87, 206-210.

Morrison, W.R., 1963. The free fatty acid content of some wheat flours. J. Sci. Food & Agriculture, 14, 870-873.

Morrison, W.R., Law, C.N., Wylie, L.J., Coventry, A.M. and Seekings, J., 1989. The effect of group 5 chromosomes on the free polar lipids and breadmaking quality of wheat. J. Cereal Sci., 9, 41-51.

Moss, R. and McGuirk, M., 1990. Freshly harvested wheat - influence on milling and baking quality. Proceedings of the Fortieth Australian Cereal Chemistry conference, Royal Australian Chemical Institute, 102-106.

Murray, L.F. and Moss, R., 1990 Estimation of fat acidity in milled wheat products. Part 1. Colorimetric determination. J. Cereal Sci.,11, 171-177.

NABIM, 1995. NABIM Wheat Guide. National Association of British & Irish Millers, 21 Arlington street, London SW1A 1RN.

Neel, D.V., and Hoseney, R.C., 1984. Factors affecting flowability of hard and soft wheat flours. Cereal Chem., 61, 262-266.

Oliver, G. and Pritchard, P.E., 1993. Rheology of the gel protein fraction of wheat flour. In 'Food Colloids and Polymers: Stability and Mechanical Properties'. Dickinson, E. and Walstra, P. Eds., Royal Society of Chemistry, Cambridge UK, 225-259.

Osborne, B.G., Stewart, B.A., Salmon, S.E., Pritchard, P.E. and Brown, G.L., 1991. The breadmaking quality of Pastiche. Project Report No 31, Home-Grown Cereals Authority, London.

Payne, P.I., Nightingale, M.A., Krattinger, A.F., and Holt, L.M., 1987. The relationship between HMW glutenin subunit composition and the bread-making quality of British-grown wheat varieties. J. Sci. Food Agric., 40, 51-65.

Pomeranz, Y., 1971. A review of some recent studies on biochemical and functional changes in mold-damaged wheat and wheat flour. Cereal Sci.Today, 16, 119-122 and 131.

Pomeranz, Y., 1992. In "Storage of Cereal Grains and Their Products: Biochemical, Functional , and Nutritive Changes During Storage. " Sauer, D.B, Ed., Minnesota, USA, 55-141.

Posner, E.S. and Deyoe, C.W., 1986. Changes in milling properties of newly harvested hard wheat during storage. Cereal Chem., 63, 451-456.

Pritchard, P.E., and Bhandari, D.G., 1992. The glutenin fraction of wheat proteins: biochemical studies of its importance in the bread baking process. MAFF Commission Project Report No F9/89/3.

Pritchard, P.E., and Brock, C.J., 1994. The glutenin fraction of wheat protein: the importance of genetic background on its quantity and quality. J. Sci. Food Agric., 65, 401-406.

Pritchard, P.E., Collins, T.H., Little, K. and Sang, B.E., 1992. The characteristics and processing requirements of wheat for breadmaking. Project Report No.60, Home-Grown Cereals Authority, London.

Rao, S., Vakil, U.K. and Sreenivasan, A., 1978. Comparative studies on physicochemical and baking properties of newly harvested and stored Indian varieties of wheat. J. Sci. Fd. Agric., 29, 155-164.

Redman, D.G., 1980. Recent research on ash content. FMBRA Bulletin, No. 6, 276-284.

Salmon, S.E. and Burbridge, K.M., 1985. Wheat variety identification by polyacrylamide gel electrophoresis. FMBRA Bulletin, No 2, 78-88.

Seiler, D.A.L. and Solomons, L.E., 1988. Reducing microbial counts in home-grown wheat by storage at elevated temperatures. Project Report No 15, Home-Grown Cereals Authority, London.

Shelke, K., Hoseney, R.C., Faubion, J.M. and Curran, S.P., 1992a. Age-related changes in the cake baking quality of flour milled from freshly harvested soft wheat. Cereal Chem., 69, 141-144.

Shelke, K., Hoseney, R.C., Faubion, J.M. and Curran, S.P., 1992b. Age-related changes in the properties of batters made from flour milled from freshly harvested soft wheat. Cereal Chem., 69, 145-147.

Srivastava, A.K. and Rao, P.H., 1991. Changes in the pasting, rheological and baking qualities of flour during short-term storage. J. Food. Sci. Technol., 28, No 3, 153-156.

Stevens, D.J., Hook, S.C.W. and Waterfield, M.P.N., 1989. The contribution of pentosans to flour water absorption. FMBRA Bulletin, No 5, 159-163.

Vaidyanathan, L.V., 1987. Precision and reliability of measuring Hagberg Falling Number of wheat including variability associated with crop husbandry and grain handling. Aspects of Applied Biology, 15, 495-513.

Warwick, M.G., Farrington, W.H.H. and Shearer, G.J. (1979). Changes in total fatty acids and individual lipid classes on prolonged storage of wheat flour. J. Sci. Food Agric., 30, 1131-1138.

Weipert, D., 1990. The benefits of basic rheometry in studying dough rheology. Cereal Chem., 67, 311-317.

Zeleny, L., 1954. Chemical, physical, and nutritive changes during storage. Pages 46-76 in "Storage of Cereal Grains and their Products" Anderson, J.A. and Alcock, A.W. Eds., Minnesota, USA.

APPENDIX 1

Table 1: Effect of wheat storage on straight run and total flour extraction rate (%).

Straight run extraction					Total extraction			
1993								
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	75.2	73.9	77.1	72.2	79.6	78.3	80.7	76.0
41	79.0	76.6	77.5	76.4	82.4	81.1	81.2	80.5
73	77.2	76.4	76.7	75.4	80.7	80.5	80.1	79.4
151	75.0	74.1	76.4	74.4	79.5	79.3	80.2	78.9
215	76.1	74.4	76.3	74.4	80.3	79.5	79.6	79.2
Mean	76.50	75.08	76.80	74.56	80.50	79.74	80.36	78.80
1992								
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	74.6	75.4	74.3	74.3	78.9	79.9	77.7	78.2
29	75.5	75.5	75.0	75.1	80.2	80.0	79.0	79.2
57	75.2	75.0	75.8	75.1	79.1	79.0	79.1	78.6
84	75.5	74.8	75.0	75.3	79.3	78.7	78.6	78.8
113	75.8	74.9	74.9	75.4	79.3	78.4	78.0	78.5
194	75.8	74.7	74.3	75.3	79.4	80.5	77.7	78.7
Mean	75.40	75.05	74.88	75.08	79.37	79.42	78.35	78.67
1991								
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	74.1	75.6	73.6	73.2	79.1	79.1	78.2	78.8
44	75.4	76.7	74.0	74.7	80.0	80.4	77.6	79.8
65	76.5	76.8	76.3	76.3	80.6	80.1	80.1	80.7
96	75.8	78.5	75.9	75.1	80.4	81.4	79.4	80.0
158	75.6	76.8	75.4	75.6	80.1	80.7	79.2	80.2
247	78.3	78.4	75.8	77.5	82.1	81.9	80.0	81.6
Mean	75.95	77.13	75.17	75.40	80.38	80.60	79.08	80.18

Table 2: Effect of storage on mean Instron bridging pressure (Newton) for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	5.0	5.8	6.0	3.6	4.9	3.7		6.4	6.2	6.8	6.4	4.6
41	3.0	6.8	8.3	7.0	6.6	5.8	7.8	4.6	7.1	7.6	7.1	3.4
73	8.1	6.0	11.0	6.1	6.4	9.0	9.8	4.6	6.2	8.5	5.1	5.1
151	6.6	7.6	9.0	8.0	5.6	7.0	7.2	5.6	6.8	7.4	5.4	6.4
215	18.4	15.6	11.2	8.1	12.8	16.0	10.8	6.0	12.0	18.0	10.8	4.2
Mean									7.660	9.660	6.960	4.740
Stan									2.198	4.206	2.048	0.999
LSD(5%)									5.648	10.808	5.263	2.568
1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	2.0	4.6	7.5	2.7	2.0	4.6	7.5	2.7	2.0	4.6	7.5	2.7
29	3.2	4.0	5.8	3.1	3.7	3.1	8.4	3.1	2.6	4.8	8.6	3.7
57	3.9	6.2	7.9	4.0	3.5	4.2	6.9	5.4	2.5	5.7	8.8	2.2
84	2.8	6.3	9.5	4.6	3.0	7.1	9.1	6.4	1.6	5.4	9.8	2.7
113	2.7	5.5	10.8	4.1	3.0	6.4	8.0	4.3	1.6	6.2	7.6	2.8
194	2.8	5.9	8.5	4.8	3.8	6.6	8.6	4.7	1.6	3.9	7.7	3.4
Mean									1.983	5.100	8.333	2.917
Standard deviation									0.426	0.757	0.824	0.495
LSD(5%)									1.043	1.855	2.019	1.212
1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	3.5	23.0	7.1	4.1	3.3	22.0	7.0	4.0	3.1	21.0	6.9	3.8
44	7.7	29.0	43.0	6.4	7.8	35.0	39.0	18.0	3.7	53.0	17.0	7.7
65	3.8	25.0	21.0	4.7	4.2	24.0	17.0	3.9	6.7	38.0	19.0	8.3
96	4.8	26.0	20.0	9.8	3.7	22.0	14.0	7.7	3.0	17.0	12.0	5.4
158	4.0	19.0	23.0	3.5	8.1	25.0	25.0	5.3	8.5	23.0	6.2	8.5
247	4.8	24.0	23.0	5.7	5.4	26.0	23.0	7.8	5.0	21.0	12.0	7.0
Mean									5.000	28.833	12.183	6.783
Standard deviation									2.018	12.681	4.716	1.681
LSD(5%)									4.945	31.068	11.554	4.118

Table 3: Effect of storage on particle size (% greater than 80.64 microns) for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	37	40	46	37					39	46	48	41
41	43	49	49	42	36	45	47	39	42	48	50	44
73	41	42	44	40	40	47	48	41	42	49	47	43
151	43	48	48	43	37	46	45	43	41	44	46	41
215	41	45	50	40	38	48	50	38	43	43	50	39
Mean									41.4	46	48.2	41.6
Standard deviation									1.36	2.28	1.60	1.74
LSD(5%)									3.49	5.86	4.11	4.48

1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	45	43	48	47					46	47	51	42
29	33	36	43	38	43	42	49	45	44	47	48	45
57	48	43	48	41	45	46	50	44	45	48	51	46
84	47	44	50	47	42	50	50	45	43	49	50	45
113	48	41	51	45	44	43	51	47	45	46	47	41
194	35	39	46	43	48	45	47	48	46	45	53	44
Mean									44.8	47.0	50.0	43.8
Standard deviation									1.07	1.29	2.00	1.77
LSD(5%)									2.61	3.16	4.90	4.34

1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	32	49	46	36					34	47	46	45
44	35	52	48	46	34	49	46	37	32	47	47	36
65	39	53	52	31	35	49	47	37	35	52	49	37
96	32	47	49	38	36	49	48	38	36	51	47	37
158	32	50	53	28	35	47	50	37	34	49	45	44
247	29	43	48	37	34	50	47	39	36	51	51	37
Mean									34.5	49.5	47.5	39.3
Standard deviation									1.38	1.98	1.98	3.68
LSD(5%)									3.39	4.85	4.85	9.02

Table 4: Effect of storage on particle size (% greater than 32 microns) for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	83	84	90	86					86	86	89	85
41	85	86	89	84	84	87	88	83	84	85	88	83
73	84	82	87	83	82	85	85	84	83	87	86	84
151	82	85	90	84	85	84	89	83	83	84	85	83
215	80	84	88	84	84	85	88	85	84	85	85	86
Mean									84.0	85.4	86.6	84.2
Standard deviation									1.1	1.0	1.6	1.2
LSD(5%)									2.82	2.62	4.18	3.00

1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	83	83	87	85					85	87	82	90
29	81	84	87	83	84	83	88	84	83	87	88	84
57	84	81	89	86	83	85	90	85	82	85	88	84
84	81	85	87	83	85	83	89	88	84	86	86	88
113	84	87	90	88	82	84	87	84	85	85	83	85
194	82	82	87	87	85	86	91	86	85	89	83	89
Mean									84.0	86.5	85.0	86.7
Standard deviation									1.15	1.38	2.45	2.43
LSD(5%)									2.83	3.39	6.00	5.95

1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	83	90	89	85					84	89	90	89
44	83	90	90	88	83	83	89	85	83	89	90	85
65	82	90	90	83	84	90	90	85	84	90	90	85
96	82	89	90	86	84	90	90	86	84	90	90	85
158	83	90	91	79	83	89	91	85	83	89	89	88
247	81	87	89	86	83	90	89	87	84	90	90	85
Mean									83.7	89.5	89.8	86.2
Standard deviation									0.47	0.50	0.37	1.67
LSD(5%)									1.15	1.23	0.91	4.10

Table 5: Effect of storage on ash content (% dry matter basis)for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	0.56	0.55	0.64	0.59					0.57	0.56	0.64	0.60
41	0.67	0.62	0.67	0.63	0.58	0.57	0.65	0.61	0.58	0.57	0.65	0.60
73	0.55	0.58	0.58	0.58	0.58	0.56	0.63	0.60	0.56	0.56	0.64	0.60
151	0.52	0.54	0.60	0.53	0.55	0.55	0.65	0.60	0.58	0.57	0.65	0.61
215	0.56	0.54	0.59	0.56	0.57	0.57	0.65	0.61	0.57	0.57	0.64	0.60
Mean									0.572	0.566	0.644	0.602
Standard deviation									0.007	0.005	0.005	0.004
LSD(5%)									0.019	0.013	0.013	0.010
1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	0.64	0.64	0.61	0.59					0.64	0.69	0.59	0.58
29	0.69	0.65	0.62	0.62	0.63	0.63	0.57	0.57	0.62	0.57	0.58	0.57
57	0.66	0.64	0.65	0.60	0.64	0.62	0.57	0.56	0.62	0.55	0.56	0.56
84	0.65	0.63	0.61	0.59	0.64	0.61	0.58	0.59	0.64	0.64	0.59	0.58
113	0.65	0.61	0.58	0.58	0.63	0.60	0.59	0.59	0.63	0.55	0.59	0.59
194	0.65	0.61	0.58	0.58	0.63	0.66	0.59	0.58	0.60	0.60	0.61	0.59
Mean									0.625	0.600	0.587	0.578
Standard deviation									0.014	0.051	0.015	0.011
LSD(5%)									0.036	0.125	0.037	0.026
1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	0.57	0.54	0.60	0.62					0.57	0.55	0.61	0.63
44	0.59	0.59	0.59	0.64	0.56	0.54	0.61	0.63	0.56	0.54	0.60	0.62
65	0.63	0.55	0.68	0.71	0.57	0.54	0.61	0.63	0.56	0.54	0.60	0.62
96	0.62	0.61	0.64	0.67	0.59	0.54	0.63	0.63	0.56	0.53	0.61	0.63
158	0.66	0.56	0.63	0.61	0.56	0.54	0.61	0.62	0.55	0.53	0.60	0.60
247	0.66	0.62	0.67	0.70	0.56	0.55	0.61	0.63	0.57	0.54	0.61	0.63
Mean									0.562	0.538	0.605	0.622
Standard deviation									0.007	0.007	0.005	0.011
LSD(5%)									0.018	0.017	0.012	0.026

Table 6: Effect of storage on flour colour grade (GCF units) for freshly milled,stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	1.61	0.46	3.76	3.19	1.61	0.46	3.76	3.19	1.42	0.46	3.61	3.19
41	3.22	1.31	3.71	3.27	1.46	0.55	3.56	3.09	1.31	0.32	3.56	2.96
73	1.6	1.06	2.95	2.95	1.5	0.4	3.65	3.1	1.42	0.34	3.56	3.1
151	0.83	0.33	3.8	2.5	1.65	0.75	3.6	3.2	1.45	0.55	3.5	3
215	1.5	0.56	3.5	3.05	1.58	0.6	3.7	3.15	1.38	0.38	3.64	3.15
Mean									1.396	0.410	3.574	3.080
Standard deviation									0.048	0.085	0.048	0.087
LSD(5%)									0.124	0.218	0.123	0.225

1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	2	0.3	0.7	0.6					1.95	0.1	0.7	0.7
29	2.8	1.2	1.5	1.2	2.1	2.1	1	0.95	2.4	0.3	1	1.2
57	2	0.7	1.6	0.6	2.1	2	0.9	1	2.1	0.3	0.9	0.9
84	2	0.85	1.05	0.7	2.35	-0.15	0.9	0.9	2	-0.5	0.8	0.75
113	2.05	0.5	0.5	0.6	2.2	-0.7	1.1	1	2.1	-0.5	0.9	0.9
194	2.1	0.5	0.4	0.45	2.35	0.4	1.15	1.1	2	0.4	0.9	0.8
Mean									2.09	0.02	0.87	0.88
Standard deviation									0.15	0.38	0.09	0.16
LSD(5%)									0.364	0.921	0.231	0.399

1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	1.8	-0.7	0.9	1.1					1.7	-0.9	0.8	0.7
44	2.15	-0.4	0.9	1.4	1.75	-0.7	1.1	1	1.8	-0.95	0.9	1.2
65	2.9	-0.7	1.35	2.25	1.7	-0.8	0.7	1	1.6	-1	0.6	0.9
96	2.8	0.3	1.3	1.35	1.7	-0.8	0.9	1.1	1.85	-0.9	0.7	1.1
158	1.65	-0.5	1.05	3.1	1.85	-0.75	0.9	1.05	1.5	-1.05	0.7	0.9
247	4	0.7	1.8	2.3	1.95	-0.7	1	1.1	1.6	-1.05	0.9	0.6
Mean									1.675	-0.975	0.767	0.900
Standard deviation									0.122	0.063	0.111	0.208
LSD(5%)									0.298	0.154	0.271	0.510

Table 7: Effect of storage on protein content (Nx5.7 at 14% moisture content) for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	9.9	9.9	9.2	9.2					9.5	9.6	9.3	9
41	10.8	10.6	9.7	9.1	9.3	9.5	9	8.8	9.4	9.5	9	8.9
73	9.9	10.8	8.9	9.4	9.3	9.5	9	8.9	9.2	9.4	8.9	8.8
151	9.4	9.8	9.4	8.9	9.3	9.7	9.6	9	9.3	9.6	9.3	8.9
215	9.4	9.9	9.5	9	9.5	9.7	9.5	9	9.4	9.8	9.3	9
Mean									9.36	9.58	9.16	8.92
Standard deviation									0.10	0.13	0.17	0.07
LSD(5%)									0.26	0.34	0.45	0.19

1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	11.1	11.7	11	11.1					11.1	11.7	10.9	11.2
29	11	11.6	11	11.2	11	11.2	10.9	11.2	11	11.4	10.9	11.2
57	11	11.4	11	11.2	11.2	11.1	10.9	11.1	11.1	11.4	10.9	11.1
84	10.9	11.5	10.9	11.2	11.1	11.4	10.9	11.1	11.1	11.4	10.9	11.1
113	11	11.4	11	11.1	11.1	10.8	10.9	11.1	11.1	11	10.9	11.1
194	10.9	11.4	10.8	11	11	11.5	10.9	11.1	11.1	11.3	10.8	11
Mean									11.08	11.37	10.88	11.12
Standard deviation									0.04	0.21	0.04	0.07
LSD(5%)									0.09	0.50	0.09	0.17

1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	10.7	10.4	11.4	10.6					10.6	10.4	11.5	10.5
44	11.1	10.7	12	10.8	11.2	10.6	12.1	10.8	10.7	10.6	11.9	10.9
66	10.7	10.4	11.6	10.7	10.7	10.3	11.7	10.6	10.7	10.4	11.5	10.6
96	10.8	10.3	11.5	10.4	10.7	10.3	11.7	10.4	10.5	10.6	11.5	10.5
158	10.5	10.5	11.4	10.7	10.7	10.4	11.5	10.5	10.5	10.4	11.3	10.9
247	10.7	10.6	11.6	10.7	10.7	10.5	11.5	10.5	10.7	10.4	11.3	10.6
Mean									10.62	10.47	11.50	10.67
Standard deviation									0.09	0.09	0.20	0.17
LSD(5%)									0.22	0.23	0.49	0.42

Table 8: Effect of storage on Falling Number (seconds) for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	264	306	192	329					267	297	200	327
41	253	261	176	320	257	314	187	328	248	295	173	320
73	255	298	183	321	269	326	193	353	253	316	178	338
151	244	308	179	349	262	332	192	345	247	286	172	320
215	248	337	168	353	261	316	192	343	247	308	177	313
Mean									252.4	300.4	180	323.6
Standard deviation									7.6	10.5	10.3	8.5
LSD(5%)									19.6	26.9	26.4	21.7
1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	371	374	365	393					379	373	357	400
29	389	379	375	412	373	371	361	384	363	387	384	388
57	373	400	383	406	394	402	385	397	378	383	370	380
84	402	404	395	416	397	418	394	416	387	389	370	414
113	372	393	388	417	420	390	395	424	392	402	377	407
194	369	375	364	417	395	404	386	417	378	383	364	367
Mean									379.5	386.2	370.3	392.7
Standard deviation									9.0	8.7	8.7	16.1
LSD(5%)									23.2	22.3	22.2	41.4
1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	334	393	345	313					335	398	353	357
44	309	391	364	328	341	413	364	332	340	400	362	331
65	301	362	328	296	353	359	349	335	332	394	349	331
96	311	400	337	309	342	386	355	342	323	372	326	305
158	318	419	361	337	327	411	336	370	339	394	319	352
247	382	443	397	364	373	453	387	325	319	397	346	303
Mean									331.3	392.5	342.5	329.8
Standard deviation									7.8	9.4	15.1	20.7
LSD(5%)									19.2	23.1	37.0	50.7

Table 9: Effect of storage on alpha-amylase content (Farrand units) for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	9	2	23	2					5	1	19	1
41	6	2	14	0	6	1	19	1	6	0	17	0
73	6	1	17	1	6	1	18	1	6	2	18	1
151	6	0	17	1	6	2	15	2	5	1	16	1
215	7	1	21	1	6	2	17	1	6	1	18	1
Mean									5.6	1	17.6	0.8
Standard deviation									0.5	0.6	1.0	0.4
LSD(5%)									1.3	1.6	2.6	1.0

1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	0	1	0	0					0	0	0	0
29	0	0	0	0	1	0	1	0	0	1	0	1
57	1	0	1	0	1	1	0	1	1	0	0	0
84	2	1	2	1	2	1	2	2	1	1	2	1
113	2	1	1	1	1	1	1	1	2	0	1	0
194	1	0	0	0	1	0	2	1	1	0	0	0
Mean									0.8	0.3	0.5	0.3
Standard deviation									0.7	0.5	0.8	0.5
LSD(5%)									1.7	1.2	1.9	1.2

1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	1	1	1	2					2	1	2	1
44	2	0	0	0	2	1	0	0	1	0	0	0
65	1	1	1	2	1	2	1	1	1	1	1	2
96	2	1	0	1	0	1	2	1	1	1	0	1
158	2	1	1	0	1	1	1	2	2	1	0	1
247	1	0	1	0	1	1	1	0	1	0	1	0
Mean									1.3	0.7	0.7	0.8
Standard deviation									0.5	0.5	0.7	0.7
LSD(5%)									1.2	1.2	1.8	1.7

Table 10: Effect of storage on starch damage (Farrand units) for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	35	42	44	58					38	44	45	59
41	40	49	39	51	36	44	44	59	38	44	47	58
73	34	43	35	50	36	43	44	56	37	44	45	58
151	29	34	42	48	35	42	43	55	36	43	44	54
215	31	34	39	45	36	44	44	56	38	43	44	56
Mean									37.4	43.6	45.0	57.0
Standard deviation									0.80	0.49	1.10	1.79
LSD(5%)									2.06	1.26	2.82	4.60

1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	26	27	32	30					27	28	31	26
29	32	34	34	30	27	26	30	27	27	30	30	27
57	26	30	34	27	28	27	31	29	28	30	33	28
84	25	26	30	24	26	29	29	27	26	30	31	27
113	25	26	28	27	27	31	33	27	27	33	30	26
194	29	29	30	28	26	31	31	27	27	30	32	26
Mean									27.0	30.2	31.2	26.7
Standard deviation									0.58	1.46	1.07	0.75
LSD(5%)									1.41	3.58	2.61	1.83

1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	28	23	29	37					29	23	29	38
44	27	23	26	35	29	25	27	39	28	23	27	38
65	37	22	29	50	27	23	26	37	28	24	29	39
96	31	28	26	36	27	18	27	37	28	22	28	37
158	43	22	27	39	27	25	28	37	30	23	32	33
247	34	33	35	41	29	24	29	39	30	25	30	40
Mean									28.8	23.3	29.2	37.5
Standard deviation									0.90	0.94	1.57	2.22
LSD(5%)									2.20	2.31	3.85	5.43

Table 11: Effect of storage on water absorption (Farinograph, %) for freshly milled, stored and control flour

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	59.2	60.4	60.9	62.3					59.2	60.5	60.3	62.6
41	61.2	62.4	60.6	63	59.2	61.1	61.3	62.8	59.5	61.7	62	63.4
73	58.9	61.3	58.4	62.1	59.2	60.8	60.8	62.7	59.9	61.3	61	63.9
151	58.1	59.1	60.4	60.7	58.4	60.5	60.2	62.3	58.2	60.6	60.8	63.3
215	57.1	57.9	58.1	59.8	58.8	60.4	60.6	62.4	59.2	61.2	61.1	63.1
Mean									59.2	61.06	61.04	63.26
Standard deviation									0.56	0.45	0.55	0.42
LSD(5%)									1.44	1.16	1.42	1.09

1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	56.6	56.7	56.1	54					58.2	56	54	56.1
29	59.3	57.7	56.4	53.5	56.2	56.9	56.5	54	56.5	56.4	56.9	54.3
57	56.2	56.5	58.5	56.2	56.2	55.7	55.5	53.7	56.7	57.6	56.7	54.1
84	57.5	55.4	56.9	53.7	56.2	55.2	56.1	54.2	56.4	56.4	56.4	54.3
113	58.1	55.4	55.5	54.5	56.6	55.2	56.5	53.9	57.1	58.5	56.8	54.1
194	58.6	56	54.9	54.2	56.3	56.8	56	53.8	56.8	55.6	56.7	53.8
Mean									56.95	56.75	56.25	54.45
Standard deviation									0.60	0.99	1.02	0.76
LSD(5%)									1.48	2.43	2.49	1.85

1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	60	56.5	56.5	60					60	57.6	57.7	60.6
44	58.1	57.2	55.7	59.4	59.1	57.7	57.1	59.5	59.2	57.3	57.7	59.8
65	61.4	57.2	58	65.5	58.8	57.3	57.8	60.4	59.3	57.1	56.7	60.2
96	60.3	58.7	56.5	59.6	59.1	56.9	56.1	59	59.9	57.7	57.1	60
158	61.8	57.5	56.6	63.2	59	57.4	57.4	60	59.2	57.4	58.5	58.4
247	60.2	60	58.2	60.5	58.4	57.1	56.8	59.1	59.2	56.9	57.2	59.9
Mean									59.47	57.33	57.48	59.82
Standard deviation									0.34	0.27	0.57	0.68
LSD(5%)									0.84	0.67	1.40	1.68

Table 12: Effect of storage on Resistance(Brabender Extensograph in BU)for freshly milled ,stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	335	250	177	248					325	280	190	265
41	330	238	195	260	340	199	151	280	309	170	110	245
73	245	202	185	260	343	205	195	292	286	295	158	245
151	323	186	157	355	320	216	169	263	375	180	195	280
215	333	220	143	325	335	230	163	325	283	150	135	253
Mean									315.6	215.0	157.6	257.6
Standard deviation									33.5	60.2	32.3	13.4
LSD(5%)									86.0	154.6	83.1	34.4
1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	118	85	185	354					88	155	205	405
29	116	115	211	405	160	165	203	338	113	195	190	322
57	128	105	140	365	133	125	245	433	108	165	208	426
84	110	85	176	305	135	140	226	480	100	100	173	400
113	108	120	176	396	150	195	193	441	120	105	155	380
194	120	109	202	355	155	186	206	316	105	139	179	374
Mean									105.7	143.2	185.0	384.5
Standard deviation									10.1	33.3	18.4	32.7
LSD(5%)									24.7	81.5	45.1	80.1
1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	108	120	189	147					110	115	175	130
44	160	116	215	100	130	120	190	128	130	117	172	115
65	110	138	190	136	150	113	219	150	130	113	209	135
96	105	90	265	190	145	142	290	190	105	120	230	145
158	165	130	296	115	215	165	279	180	115	118	197	119
247	110	105	194	165	200	173	235	255	125	120	186	145
Mean									119.2	117.2	194.8	131.5
Standard deviation									9.8	2.5	20.1	11.6
LSD(5%)									23.9	6.2	49.4	28.4

Table 13: Effect of storage on Extensibility (Brabender Extensograph in mm) for freshly milled ,stored and control flour.

1993	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	10.4	15.5	18.3	16.4					11	14.9	19.1	14.55
41	11.9	15.8	19.4	16	11.3	15	18	13.8	11.7	15.4	19.15	16.2
73	10.8	15.6	18.9	16.7	11	14.8	18.5	15.4	11.8	14.7	18.5	15.9
151	12.5	15.3	18.2	15.8	11.3	14.5	18.2	14.6	11.8	15	18.9	14.8
215	11.4	15.15	18.65	15.4	11.45	13.8	17	14.4	10.75	14.8	18.4	16.3
Mean									11.41	14.96	18.81	15.55
Standard deviation									0.45	0.24	0.31	0.73
LSD(5%)									1.14	0.62	0.79	1.88
1992	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	21.8	20.8	22.9	22.9					20.5	23.3	22.4	20.1
29	23.4	20.5	22.5	21.2	21.5	20.3	21.2	21.2	22.8	21	22.1	22.5
57	21.8	16.9	24.4	21.4	19.8	18.6	22.9	20.4	20.8	15.5	23.7	21
84	21.6	17.3	23.7	24.9	20.7	17.5	23.3	22.1	22.1	17.3	22.9	21.2
113	22.5	19.7	23.6	23.3	20.8	17.7	20.9	21.5	21.7	17.6	23.6	23.3
194	20.5	19.5	22	22	22.1	19	21.4	21.1	20.3	18.8	22.9	22.7
Mean									21.37	18.92	22.93	21.80
Standard deviation									0.84	2.38	0.54	1.03
LSD(5%)									2.05	5.83	1.31	2.53
1991	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	19.7	19	16.4	16.5					20.7	19.8	16.9	16.8
44	18.8	20	17.5	13	20.3	20	16.6	16.1	21	19	16.9	16.1
65	19.5	18.7	17.3	14.7	19.1	18.3	17.7	17.7	17	18.4	17	16.8
96	18.5	20.5	16.8	15.5	20.2	20.3	15.1	15.1	19.6	22	18.3	16.3
158	17.7	19.8	17.5	18.1	20.7	20.6	16.4	16.4	20.5	19.4	18	16.4
247	20.8	20.2	16	16.4	19.5	20	14.8	14.8	20.8	20.6	17.3	17
Mean									19.93	19.87	17.40	16.57
Standard deviation									1.39	1.17	0.55	0.32
LSD(5%)									3.39	2.87	1.36	0.78

Table 14: Effect of storage on Alveograph W (Joule x 10-4) for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	160	126	132	302					152	163	149	288
41	154	132	120	287	195	159	140	267	152	158	152	273
73	168	141	120	395	150	186	138	321	144	174	135	302
151	175	169	159	335	150	163	166	276	152	153	145	294
215	182	172	150	275	202	218	145	308	191	211	124	264
Mean									158.2	171.8	141.0	284.2
Standard deviation									16.7	20.8	10.3	13.9
LSD(5%)									42.9	53.5	26.4	35.6

1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	137	122	172	221	137	122	172	221	110	115	147	183
29	117	108	177	235	105	130	170	178	102	107	162	189
57	123	85	136	182	135	118	163	224	115	95	146	186
84	110	89	148	212	116	118	161	223	103	102	138	217
113	117	83	175	207	139	106	177	236	113	108	163	211
194	107	130	152	183	128	128	198	162	101	121	159	170
Mean									107.3	108.0	152.5	192.7
Standard deviation									5.6	8.4	9.4	16.3
LSD(5%)									13.6	20.6	22.9	39.9

1991												
	FRESH				STORED				GAS PACKEd (CONTROLo			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	124	95	149	127					121	109	163	139
44	102	108	157	130	113	104	149	127	125	117	172	115
65	121	121	145	140	121	114	147	137	130	108	146	145
96	120	107	133	125	131	122	130	101	138	107	158	127
158	154	128	160	143	131	134	156	149	119	126	142	130
247	112	119	158	119	140	136	174	159	106	120	134	144
Mean									123.2	114.5	152.5	133.3
Standard deviation									9.9	7.0	13.0	10.6
LSD(5%)									24.2	17.3	31.9	25.9

Table 15: Effect of storage on Alveograph P/L for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	3.3	1.18	0.73	4.26					2.89	1.32	0.82	4.23
41	4.1	0.99	0.92	4.32	3.38	1.28	1.43	4.05	3	1.65	1.35	3.57
73	3.8	1.29	0.69	3.77	3.5	1.65	0.98	3.91	3.2	1.46	0.98	3.95
151	2.95	1.22	0.87	4.22	3.05	1.57	1.37	4.25	3.06	1.32	1.57	4.34
215	2.58	1.3	0.84	4.08	3.74	1.89	1.12	4.7	3.27	2.03	0.95	4.55
Mean									3.084	1.556	1.134	4.128
Standard deviation									0.137	0.266	0.280	0.340
LSD(5%)									0.351	0.684	0.720	0.873
1992												
	FRESH				STORED				FROZEN (CONTROl)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	0.77	0.5	0.53	0.8					1.2	0.6	0.9	0.88
29	0.79	0.67	0.47	0.82	0.5	0.55	0.4	0.73	0.52	0.55	0.46	0.68
57	0.57	0.52	0.49	0.59	0.45	0.56	0.42	0.52	0.54	0.65	0.42	0.56
84	0.73	0.54	0.43	0.39	0.54	0.51	0.42	0.51	0.65	0.56	0.48	0.4
113	0.73	0.54	0.43	0.39	0.54	0.51	0.42	0.51	0.65	0.56	0.48	0.4
194	0.73	0.63	0.62	0.66	0.76	0.76	0.8	0.82	0.56	0.73	0.46	0.59
Mean									0.687	0.608	0.533	0.585
Standard deviation									0.235	0.064	0.165	0.166
LSD(5%)									0.576	0.157	0.405	0.406
1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	1.07	0.72	0.96	1.23					0.94	0.71	0.87	1.32
44	1.14	0.81	0.78	0.91	1	0.6	0.9	1.5	0.83	0.66	0.87	1.15
65	1.13	0.53	0.93	1.5	0.77	0.54	0.81	1.23	0.74	0.54	0.81	1.25
96	1.15	0.95	1.79	2.08	0.82	0.74	1.68	2.66	0.93	0.89	0.98	2
158	1.66	0.66	1.45	1.53	0.92	0.6	1.47	1.32	0.89	0.54	1.43	1.36
247	1	0.95	1.13	1.37	0.82	0.59	0.92	1.39	0.92	0.54	0.66	1.11
Mean									0.875	0.647	0.937	1.365
Standard deviation									0.070	0.127	0.240	0.297
LSD(5%)									0.173	0.312	0.589	0.728

Table 16: Effect of storage on CBP loaf volume (ml) for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	1464	1526	1524	1463					1463	1537	1537	1497
41	1408	1516	1512	1471	1450	1499	1517	1435	1437	1537	1521	1450
73	1436	1469	1528	1472	1429	1476	1437	1400	1482	1538	1459	1450
151	1418	1461	1466	1409	1375	1439	1444	1368	1386	1507	1445	1393
215	1404	1428	1462	1434	1368	1445	1428	1354	1409	1506	1462	1425
Mean									1435.4	1525	1484.8	1443
Standard deviation									34.9	15.1	36.9	34.2
LSD(5%)									89.6	38.8	94.8	87.8
1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	1622	1647	1837	1870					1681	1651	1869	1857
29	1627	1650	1849	1873	1660	1632	1820	1853	1605	1662	1811	1888
57	1562	1569	1750	1786	1557	1568	1748	1818	1549	1615	1818	1790
84	1597	1583	1768	1790	1526	1570	1740	1721	1566	1574	1807	1782
113	1546	1538	1671	1744	1507	1529	1686	1726	1554	1555	1703	1753
194	1466	1464	1650	1637	1440	1463	1565	1590	1495	1509	1652	1669
Mean									1575.0	1594.3	1776.7	1789.8
Standard deviation									57.3	53.9	74.5	70.9
LSD(5%)									140.5	132.2	182.5	173.7
1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	1492	1511	1600	1575					1470	1538	1604	1593
44	1512	1496	1627	1620	1511	1561	1653	1623	1553	1562	1702	1624
65	1481	1536	1647	1495	1476	1487	1540	1544	1527	1542	1668	1571
96	1540	1533	1653	1616	1534	1546	1631	1594	1486	1545	1676	1614
158	1635	1595	1702	1532	1548	1566	1644	1595	1590	1582	1711	1640
247	1469	1463	1552	1499	1437	1487	1510	1490	1522	1497	1598	1546
Mean									1524.7	1544.3	1659.8	1598.0
Standard deviation									37.0	24.0	40.8	29.7
LSD(5%)									90.6	58.7	100.0	72.6

Table 17: Effect of storage on gel protein weight (g/5g of flour) for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	8.25	8.52	8.52	8.19					9.33	10.14	8.03	9.03
41	7.64	8.91	7.52	8.31	6.49	8.65	8.16	8.12	6.56	9.04	9.88	7.51
73	9.53	11.26	8.79	10.46	9.64	10.47	9.99	10.07	9.45	10.96	10.20	9.31
151	8.93	10.24	9.32	9.72	8.99	10.85	9.49	10.15	9.28	10.72	9.30	10.18
215	8.53	9.95	8.56	9.46	8.79	10.21	9.07	9.84	8.67	9.82	9.60	10.06
Mean									8.658	10.136	9.402	9.218
Standard deviation									1.083	0.681	0.748	0.959
LSD(5%)									2.784	1.751	1.922	2.464
1992												
	FRESH				STORED				FROZEN			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	11.95	11.59	11.12	12.14	11.95	11.59	11.12	12.14	10.34	10.66	12.7	12.48
29	12.74	10.61	13.69	13.53	11.36	10.67	13.04	12.84	12.34	9.39	12.87	12.2
57	10.95	8.97	12.91	12.56	11.41	11.14	12.9	11.22	11.55	10.32	13.2	12.69
84	10.69	11.11	13.57	13.73	12.07	11.18	14.07	13.76	11.46	11	13.06	13.61
113	11.77	11.46	14.41	14.12	12.35	11.85	14.07	14.27	11.92	10.98	14.11	13.6
194	11.68	11.65	14.05	13.45	11.1	10.56	12.33	13.02	10.74	10.35	13	13.35
Mean									11.392	10.450	13.157	12.988
Standard deviation									0.676	0.544	0.454	0.557
LSD(5%)									1.655	1.334	1.112	1.364
1991												
	FRESH								GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	10.14	9.87	9.71	10.08	10.14	9.87	9.71	10.08	9.85	10.61	9.99	9.78
44	7.96	8.86	10.94	9.55	10.43	10.17	10.37	9.55	9.3	9.82	10.69	8.93
65	9.84	11.22	11.07	9.56	10.06	10.74	10.57	9.66	10.79	10.83	10.75	9.53
96	10.75	9.85	11.08	10.31	11.29	10.14	11.31	10.37	10.73	9.04	11.37	10.14
158	7.72	10.02	10.19	9.03	10.76	9.35	10.63	8.15	9.69	9.17	10.81	10.22
247	10.42	9.79	10.6	9.74	10.4	9.03	10.26	9.27	11.29	11.03	10.94	9.88
Mean									10.275	10.083	10.758	9.747
Standard deviation									0.704	0.788	0.409	0.430
LSD(5%)									1.725	1.930	1.003	1.055

Table 18: Effect of storage on gel protein breakdown rate for freshly milled, stored and control flour

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	0.25	0.95	0.83	0.23	0.25	0.95	0.83	0.23	0.24	0.47	0.87	0.19
41	0.38	0.41	0.74	0.20	0.15	0.39	0.78	0.33	0.18	0.45	0.96	0.18
73	0.30	0.53	0.76	0.15	0.23	0.39	0.73	0.21	0.25	0.52	0.85	0.19
151	0.34	0.36	0.65	0.11	0.18	0.29	0.48	0.24	0.22	0.37	0.84	0.17
215	0.36	0.44	0.69	0.15	0.24	0.33	0.43	0.18	0.24	0.42	0.76	0.18
Mean									0.226	0.446	0.856	0.182
Standard deviation									0.025	0.050	0.064	0.007
LSD(5%)									0.064	0.129	0.165	0.019
1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	0.87	0.76	0.58	0.31	0.87	0.76	0.58	0.31	0.76	0.96	0.72	0.31
29	0.79	0.87	0.79	0.27	0.66	0.82	0.61	0.32	0.89	0.83	0.78	0.29
57	0.81	0.82	0.81	0.23	0.71	0.73	0.59	0.36	0.97	0.9	0.68	0.32
84	0.81	0.84	0.66	0.32	0.77	0.72	0.61	0.22	0.79	1.04	0.55	0.31
113	0.91	0.95	0.65	0.29	0.93	0.82	0.54	0.27	0.83	0.89	0.8	0.29
194	1.15	0.77	0.67	0.25	0.81	0.67	0.51	0.27	1.09	0.93	0.59	0.34
Mean									0.888	0.925	0.687	0.310
Standard deviation									0.113	0.065	0.092	0.017
LSD(5%)									0.277	0.159	0.225	0.042
1991												
	FRESH								GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	1.18	1.11	0.61	0.77	1.18	1.11	0.61	0.77	0.8	0.91	0.63	0.77
44	0.67	0.8	0.57	0.8	0.8	0.74	0.48	0.65	0.71	0.77	0.59	0.74
65	0.83	0.67	0.47	0.74	0.67	0.77	0.43	0.63	0.87	0.74	0.43	0.61
96	0.71	0.83	0.39	0.71	0.67	0.63	0.34	0.42	0.77	0.74	0.47	0.74
158	0.74	0.55	0.33	0.63	0.61	0.59	0.42	0.41	0.78	0.85	0.53	0.45
247	0.84	0.76	0.37	0.43	0.62	0.67	0.21	0.46	0.84	0.89	0.46	0.65
Mean									0.795	0.817	0.518	0.660
Standard deviation									0.051	0.070	0.072	0.109
LSD(5%)									0.126	0.171	0.177	0.268

Table 19: Effect of storage on elastic modulus (G' in Pascal) of gel protein for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	27.70	17.60	2.64	30.40					26.80	17.40	1.36	30.10
41	24.40	22.80	5.08	32.80	24.60	18.80	4.64	35.60	25.90	20.80	4.22	32.30
73	29.40	20.30	6.02	34.70	26.70	20.50	2.85	30.10	25.00	18.40	1.60	24.10
151	30.50	18.90	4.27	34.20	24.70	17.50	3.06	35.80	26.40	18.70	2.50	32.40
215	26.50	20.60	5.37	33.60	27.30	19.80	4.56	33.50	24.50	20.90	4.31	31.70
Mean									25.720	19.240	2.798	30.120
Standard deviation									0.857	1.384	1.257	3.121
LSD(5%)									2.201	3.556	3.230	8.020
1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	11.3	10.6	11.4	33					8.18	6.71	16.1	27.4
29	7.53	9.95	14.7	34.9	10.7	11.8	11.2	22.1	6.72	9	12.7	24.1
57	10.1	9.33	14.9	37.6	10.3	13.3	14.8	35.4	8.69	10.5	15.8	39.8
84	7.94	8.42	15	27.6	9.58	10.2	15.5	34.3	10.7	9.95	14.9	34.3
113	8.86	8.74	10.7	26.9	7.64	7.43	14.9	30.9	9.57	7.61	12.8	28.9
194	6.94	6.64	10.7	24.3	7.39	7.36	14.6	26.7	7.57	7.15	10.9	23.3
Mean									8.572	8.487	13.867	29.633
Standard deviation									1.299	1.424	1.875	5.794
LSD(5%)									3.183	3.489	4.594	14.194
1991												
	FRESH								GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	18.6	22.2	23.7	25.6					15.5	16.2	27.7	21.3
44	16.6	16.5	23.4	22.3	18	16.9	22	21.4	18.7	16.2	20.6	16.9
65	12.8	18.2	31.8	17.5	12.6	16.9	27.7	22.1	14.7	15.9	21.4	20.9
96	13.4	15.1	37.3	19.7	20.9	18.7	31.1	17.4	18	19	26.9	17.3
158	17.9	17.2	28.3	16	16.6	18.1	23	17	12.4	19.5	19.1	21.6
247	9.56	18.5	23.9	23.9	17.2	22.5	18.7	17.7	16.4	20.3	22.9	11.3
Mean									15.950	17.850	23.100	18.217
Standard deviation									2.095	1.793	3.183	3.619
LSD(5%)									5.133	4.394	7.798	8.866

Table 20: Effect of storage on wet gluten content (%) for freshly milled,stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	24.8	27.6	28.4	22.0					24.2	27.1	28.1	21.7
41	25.3	29.0	27.5	21.6	24.0	27.3	27.4	22.7	23.9	27.5	27.6	22.4
73	25.0	28.1	27.8	20.8	23.5	27.1	24.9	21.5	23.7	26.6	27.3	22.6
151	25.3	28.7	27.3	21.2	23.3	27.5	26.4	22.1	23.8	28.1	26.9	23.3
215	25.0	27.7	28.3	19.9	22.8	27.0	26.9	21.7	24.4	29.1	26.3	22.0
Mean									24.00	27.68	27.24	22.40
Standard deviation									0.26	0.86	0.61	0.55
LSD(5%)									0.67	2.22	1.57	1.41

1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	30.3	30.3	31.2	28.5					29.9	30.7	31.4	31.5
29	30.9	31.3	30.9	27.7	30.6	30.5	30.3	28.5	29.4	29.9	29.1	27.1
57	30.2	31.3	30.5	28.2	30.4	30.3	29.9	28.0	29.9	31.6	30.0	28.4
84	30.1	30.6	29.9	27.9	29.8	29.2	29.8	27.7	30.1	29.5	30.2	27.8
113	30.4	30.7	30.0	28.1	29.7	29.2	29.4	27.6	30.0	29.9	29.9	27.8
194	30.4	31.8	28.8	28.6	29.2	29.4	29.5	27.5	30.5	31.6	30.0	28.8
Mean									29.97	30.53	30.10	28.57
Standard deviation									0.32	0.83	0.68	1.41
LSD(5%)									0.80	2.04	1.66	3.47

1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	30.2	30.8	31.9	28.7					30.2	30.6	31.2	29.3
44	29.1	30.6	30.5	28.8	30.7	30.3	30.5	27.8	30.6	29.7	29.1	28.6
65	30.4	30.6	30.3	28.8	31.1	30.6	31.0	28.9	31.0	30.8	31.4	28.6
96	30.4	31.2	30.7	28.6	30.1	30.6	31.4	28.6	31.1	31.2	31.6	28.8
158	27.7	29.7	30.1	29.6	30.8	28.9	30.9	28.1	30.6	30.3	31.0	28.7
247	30.7	31.0	30.8	28.7	30.4	30.4	31.2	28.5	30.3	30.0	31.9	29.0
Mean									30.63	30.43	31.03	28.83
Standard deviation									0.33	0.50	0.91	0.25
LSD(5%)									0.81	1.22	2.23	0.61

Table 21: Effect of storage on elastic modulus(G' in Pascal) of gluten for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	17.18	11.50	10.06	15.68					18.12	11.06	11.51	19.65
41	13.75	8.60	9.06	24.30	15.20	10.75	8.43	18.30	17.90	10.45	8.69	23.35
73	14.95	10.50	12.70	16.90	18.75	10.08	11.60	18.70	16.85	9.01	12.75	13.75
151	11.90	8.00	10.25	14.55	14.65	8.96	9.74	17.90	11.40	8.97	9.94	13.80
215	11.50	7.30	8.19	12.10	12.95	7.52	10.52	14.05	9.31	6.76	7.00	11.24
Mean									14.716	9.250	9.978	16.358
Standard deviation									3.647	1.487	2.028	4.456
LSD(5%)									9.373	3.821	5.211	11.451
1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	11.7	9.54	15.85	25.55					11.3	8.94	15.95	24.5
29	7.6	7.7	13.3	21.4	9.6	8.13	12	20	8.36	8.08	12.2	20.76
57	7.2	5.9	11.6	15.3	5.9	5.7	9.7	16.2	6.5	5.7	10.1	17.6
84	7.1	5.7	10.3	14.8	7.1	5.3	9.9	15.3	7.6	6.1	9.8	13.6
113	9.20	6.4	10.2	21.8	7.9	5.9	10.9	19.5	7.8	7.1	11.8	19.1
194	5.3	4.2	7.1	13.6	4.8	4.7	6.8	13.9	4.6	4.5	6.2	15
Mean									7.693	6.737	11.008	18.427
Standard deviation									2.019	1.487	2.940	3.617
LSD(5%)									4.947	3.644	7.204	8.862
1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	6.97	7.48	7.89	8.34	6.97	7.48	7.89	8.34	8.06	8.29	9.78	12.5
44	5.56	4.82	6.28	5.07	5.65	5.59	5.57	5.32	5.55	4.85	6.6	5.76
65	4.64	4.94	5	4.87	4.31	4.5	4.77	4.79	4.5	3.72	4.84	4.66
96	7.17	6.99	9.27	7.1	6.91	7.25	7.78	7.85	7.16	6.35	8.38	6.95
158	10.6	8.6	12.1	10.95	9.41	9.17	11.65	11.05	9.94	8.55	11.9	9.66
247	10.8	10	13.65	11.55	12.55	12.45	14.75	15.4	10.07	9.98	10.97	9.42
Mean									7.547	6.957	8.745	8.158
Standard deviation									2.073	2.189	2.448	2.650
LSD(5%)									5.078	5.362	5.998	6.493

Table 22: Effect of storage on dough stickiness as measured by Dough phase angle for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	23.60	23.75	25.25	22.05					23.35	24.30	23.75	22.50
41	22.20	23.20	24.05	22.85	25.05	24.30	25.35	22.40	23.35	25.85	24.30	22.05
73	26.70	26.70	29.60	22.80	23.60	26.30	26.50	23.60	26.30	24.60	24.20	24.80
151	24.30	23.90	22.90	23.20	25.10	23.90	24.40	24.40	23.90	23.40	25.00	22.30
215	17.45	17.95	18.40	18.85	20.95	20.00	19.35	18.90	19.95	18.80	18.65	19.00
Mean									23.370	23.390	23.180	22.130
Standard deviatio									2.028	2.425	2.300	1.849
LSD(5%)									5.212	6.233	5.911	4.752
1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	24.2	24.5	22.5	21					25.06	22.86	21.45	21.9
29	25.1	28.1	23.6	24.2	26.3	26.4	24.2	23.9	27.1	25.9	24.65	23.81
57	26.3	25.3	25.05	23.9	27.1	25.7	24.8	26.1	26.2	27.1	25	23.59
84	25.3	25.4	23.6	24.35	27.2	26.3	25	23.1	26.64	26.8	23.55	23.5
113	26.50	27	23.5	25.4	27.1	27.3	26.1	25	26.7	26.1	25.2	22.9
194	29.4	30.8	29.1	27.9	29.4	31.6	27.6	28.6	32.9	30.75	27.8	30.3
Mean									27.433	26.585	24.608	24.333
Standard deviation									2.527	2.318	1.906	2.742
LSD(5%)									6.191	5.679	4.669	6.717
1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	25.1	28.25	24.15	24.05	25.1	28.25	24.15	24.05	25.5	25.5	24.1	24.45
44	25.35	25.9	24.75	24.15	25.5	26.05	25.15	24.3	25.95	25.95	24.4	23.65
65	15.15	16.35	15.25	14.35	16.5	16.8	14.75	16.2	16.3	26.3	15.6	16.45
96	22.9	24	21.8	21.75	23.85	24.4	23.25	23.35	24.3	24.3	22.8	22.3
158	23.3	26.05	24.25	25	25.8	25.75	24	25.2	27.05	27.05	23.55	25.2
247	25.4	25.05	24.2	24	25.45	25.85	24.65	24.5	26.7	26.7	25.25	24.5
Mean									24.300	25.967	22.617	22.758
Standard deviation									3.685	0.896	3.226	2.962
LSD(5%)									9.029	2.196	7.904	7.258

Table 23: Effect of storage on sulphydryl content of freshly milled,stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	0.67	0.71	0.70	0.74	0.67	0.71	0.70	0.74	0.71	0.72	0.72	0.73
41	0.81	0.84	0.76	0.76	0.68	0.72	0.71	0.73	0.72	0.82	0.75	0.77
73	0.72	0.77	0.68	0.69	0.67	0.72	0.70	0.72	0.70	0.75	0.74	0.74
151	0.62	0.70	0.67	0.60	0.63	0.66	0.64	0.67	0.69	0.74	0.69	0.71
215	0.65	0.67	0.64	0.61	0.64	0.60	0.63	0.64	0.65	0.71	0.70	0.71
Mean									0.694	0.749	0.717	0.733
Standard deviation									0.023	0.037	0.022	0.023
LSD(5%)									0.060	0.094	0.058	0.059
1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	0.74	0.74	0.75	0.7	0.74	0.74	0.75	0.7	0.8	0.75	0.72	0.63
29	0.78	0.78	0.75	0.67	0.7	0.71	0.7	0.68	0.73	0.69	0.73	0.69
57	0.68	0.67	0.73	0.65	0.64	0.57	0.67	0.62	0.66	0.6	0.67	0.67
84	0.71	0.68	0.71	0.64	0.64	0.59	0.65	0.62	0.68	0.68	0.7	0.65
113	0.70	0.64	0.66	0.62	0.57	0.58	0.63	0.59	0.63	0.64	0.66	0.64
194	0.59	0.53	0.54	0.54	0.5	0.48	0.53	0.51	0.57	0.55	0.59	0.55
Mean									0.678	0.652	0.678	0.638
Standard deviation									0.073	0.065	0.047	0.044
LSD(5%)									0.179	0.158	0.114	0.108
1991												
	FRESH				STORED				GAS PACKED (CONTROL)			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	0.68	0.62	0.72	0.76	0.68	0.62	0.72	0.76	0.68	0.6	0.72	0.74
44	0.73	0.67	0.73	0.8	0.7	0.66	0.75	0.78	0.72	0.68	0.78	0.82
65	0.74	0.63	0.78	0.82	0.68	0.62	0.73	0.74	0.68	0.63	0.7	0.75
96	0.73	0.72	0.74	0.76	0.66	0.62	0.71	0.73	0.7	0.65	0.75	0.79
158	0.79	0.67	0.72	0.75	0.64	0.63	0.69	0.71	0.72	0.68	0.76	0.77
247	0.78	0.7	0.75	0.82	0.58	0.58	0.66	0.66	0.67	0.61	0.72	0.75
Mean									0.695	0.642	0.738	0.770
Standard deviation									0.020	0.031	0.027	0.028
LSD(5%)									0.048	0.077	0.067	0.068

Table 24: Effect of storage on paste viscosity [Brabender units(1991) and % (1992 and 1993) for freshly milled, stored and control flour.

1993												
	FRESH				STORED				FROZEN (CONTROI)			
DAY	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA	AVALON	MERCIA	HEREWARD	TORFRIDA
15	84	165	34	187					78	155	36	180
41	71	137	34	171	94	180	39	202	78	143	34	172
73	74	130	34	178	102	187	41	222	76	155	34	176
151	80	157	35	203	127	213	50	245	84	160	34	188
215	78	165	34	203	127	221	54	247	80	155	34	180
Mean									79.20	153.60	34.40	179.20
Standard deviation									2.71	5.64	0.80	5.31
LSD(5%)									6.97	14.50	2.06	13.64

1992												
	FRESH				STORED				FROZEN (CONTROL)			
DAY	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO	AVALON	MERCIA	HEREWARD	FRESCO
10	261	271	245	323					254	281	241	321
29	206	244	212	290	258	255	251	326	245	275	233	302
57	217	242	217	263	274	288	266	336	245	274	238	312
84	222	246	226	319	284	302	272	343	243	262	254	309
113	195	258	219	204	296	302	280	352	239	264	231	307
194	252	286	258	337	317	334	305	374	274	286	262	329
Mean									250.00	273.67	243.17	313.33
Standard deviation									11.63	8.54	11.22	9.07
LSD(5%)									28.50	20.92	27.48	22.22

1991												
	FRESH				STORED				GAS PACKED			
DAY	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B	AVALON/M	AVALON/A	MERCIA/BG	MERCIA/B
18	595	1290	910	660					540	1200	895	610
44	380	1170	915	375	455	1285	705	480	545	1220	915	610
65	370	900	625	480	500	1000	720	520	380	890	670	475
96	380	915	665	475	555	1030	780	565	460	930	680	490
158	600	1220	980	550	835	1620	1250	895	590	1230	910	650
247	735	1150	990	710	960	1605	1240	1050	630	1250	925	645
Mean									524.17	1120.00	832.50	580.00
Standard deviation									82.79	149.67	111.76	70.77
LSD(5%)									202.82	366.68	273.80	173.39

Table 25: Effect of storage on total lipid, glycolipid and free fatty acid content for freshly milled, stored and control Mercia flour.

% Lipid				% Glycolipid in lipid			% free fatty acids		
Days	Fresh	Stored	Control	Fresh	Stored	Control	Fresh	Stored	Control
1993									
15	0.944		0.944	11.22		12.5	5.40		5.41
41	0.942	0.943	0.927	10.39	12.33	9.76	6.22	8.60	6.79
73	0.936	0.937	0.949	11.57	13.45	14.02	4.60	12.61	5.90
215	0.94	0.937	0.93	11.2	11.95	12.02	4.99	14.00	5.71
Mean			0.937			12.075			5.949
Standard deviation			0.055			1.527			0.609
LSD(5%)			0.141			3.924			1.565
1992									
10	0.917		1.034	12.86		11.07	7.90		4.59
29	0.981	0.905	0.896	12.03	12.19	14.36	3.55	11.89	4.68
57	0.917	0.865	0.862	12.52	12.7	14.31	2.21	10.80	2.65
84	0.937	0.855	0.953	12.65	12.32	11.62	2.32	11.04	4.50
113	0.931	0.874	0.859	12.68	11.54	13.62	3.79	15.09	2.61
194	0.916	0.866	0.976	12.39	11.5	14.01	3.88	19.68	4.63
Mean			0.936			13.122			4.063
Standard deviation			0.065			1.469			0.955
LSD(5%)			0.159			3.599			2.340
1991									
18	0.956		0.952	11.48		12.06	5.15		4.17
44	0.866	0.909	0.785	7.43	3.37	9.25	2.29	7.01	5.50
65	0.994	0.92	0.905	6.39	7.17	7.07	2.95	9.29	5.23
96	0.885	0.918	0.938	12.17	11.72	12.6	2.91	11.38	4.59
158	0.895	0.861	0.898	11.82	10.51	11.85	2.28	15.67	4.00
247	1.045	0.904	0.937	11.43	11.46	13.01	4.39	22.72	5.73
Mean			0.902			10.973			4.870
Standard deviation			0.057			2.139			0.754
LSD(5%)			0.140			5.241			1.847