PROJECT REPORT No. 283

PROCESSABILITY OF MALTS MADE FROM UK-GROWN BARLEY (2001/2002)

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PROCESSABILITY OF MALTS MADE FROM UK-GROWN BARLEY (2001/2002)

by

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1. EXECUTIVE SUMMARY

1. Nine commercial malts, each of which conformed to a typical premium lager malt specification, manufactured in Europe, North America or Australia, were obtained from international brewers who routinely sourced their malts from these areas.
2. Each sample was subjected to a battery of standard and non-standard tests, some of which were designed to predict some aspect of processability during brewing.
3. Six of these malts were selected for pilot brewing trials on the basis of their standard analyses. At least one malt was chosen from each of the growing areas described above. Where possible, two malts from the same brewer were selected.
4. Each of the selected malts was brewed in BRi's pilot brewery according to three different brewing regimes;
    (a) BRi's standard premium lager protocol, which is very well characterised and utilises a high proportion of malt in the grist
    (b) A recipe based on those used by commercial brewers who regularly use a high proportion of unmalted adjunct (maize grits) in their grists. The intention here was to investigate the fermentability of the malt.
    (c) A recipe containing a significant proportion of undermodified malt, to investigate the cytolytic capabilities of the malt
5. The brews were monitored for indices of processability during brewing and fermentation. Worts and beers were analysed by standard industry methods.
6. **The brewing results showed that although the malts had similar standard specifications, their processability in the brewery differed significantly, particularly in terms of ease of lautering in the brewhouse.**
7. Overall, the two UK malts had the highest processability scores. However, the number of samples processed was insufficient to draw any firm conclusions as to whether there is a real link between geographical origin and processability.
8. The high malt grist protocol gave the most useful information. The other two brewing regimes supported this but did not add any new information. If this work were to be extended, it is recommended that a larger number of malts should be processed by a single brewing regime.
9. None of the predictive tests used gave a totally reliable indication of processability. Some parameters showed a higher correlation with processability than others, but a larger number of samples would need to be processed in order to make firm recommendations. However, it was apparent that several of the tests currently used gave redundant information and there were indications that a combination of two or three carefully selected tests would be most useful for predicting processability.
10. There were indications that malts from some laboratory tests, particularly those involving cell wall modification, gave anomalous results with certain non-European malts. It is recommended that this should be taken into account in the development and calibration of predictive laboratory tests.

2. BACKGROUND AND SCOPE OF PROJECT

Factors influencing the quality of malting barley

It is well recognised that the quality of malting barley is governed by both genetic and environmental factors. A third, overlying parameter, the malting technology used, can also influence the quality of the finished malt for processing. Until relatively recently, the UK had an advantage in each of these respects. Collaboration between the malting, brewing and distilling industries, the barley breeders and the official bodies responsible for varietal evaluation and registration (in the past particularly NIAB, and now CEL), has resulted in a robust and widely recognised system for assessing new varieties and identifying those particularly suitable for malting[1]. Climate can affect several aspects of malting quality, particularly protein and β-glucan content[2], and there has been a general perception that barleys grown in a maritime climate tend to produce better and more evenly modified malts[3]. Another indirect advantage of the UK climate is that, because grain moisture at harvest frequently exceeds that required for safe storage, most of the malting barley harvested is dried prior to long term storage and processing. It is suggested that this drying process results in more homogenous grain, with a more even distribution of water, both within the grain and between individual grains. This in turn is thought to improve the uptake of water at the beginning of steeping[4]. Efficient water uptake early in steeping is crucial for malt quality, an observation which has been well documented[5, 6].

The importance of malt processability

Brewing companies set specifications against which they purchase malt. Some of these specifications, such as malt colour, and specific flavour-related compounds (for example the dimethyl sulphide precursor, S-methyl methionine) relate to the style of beer being brewed. Other parameters specified relate to the efficiency of processing, in particular to

(1) the potential amount of fermentable carbohydrate,
(2) the ease with which that fermentable carbohydrate can actually be extracted from the malt in the brewhouse and
(3) the capability of the malt to convert that carbohydrate to fermentable sugars.

While the first and the third of these parameters can now be predicted from laboratory scale tests with a reasonable degree of accuracy, prediction of the second point, that of the actual ease and efficiency with which fermentable extract can actually be obtained in a commercial brewhouse, remains difficult. Factors affecting mash filtration are complex and range from physical effects such as particle size and bed porosity to biochemical effects such as gum and gel protein content. The separation of sweet wort from the mash is usually the main rate-limiting step in the brewhouse in terms of cycle and turn-around times, and so is of considerable importance to the brewer. While use of lightly but evenly modified lager malts will very often give trouble free separation, this is not always the case. Barley cell walls contain substantial quantities of high molecular weight β-glucan (gum) which must be digested during malting. The amount of β-glucan in the barley is affected by the climate and the variety. The amount remaining in the malt depends not only upon the amount in the original barley, but also upon the

extent of breakdown during malting. If β-glucan is not adequately broken down during malting, it can reduce the rate and efficiency of lautering in the brewhouse and can also lead to filtration and haze problems with the resultant beer. Thus measurement of the viscosity and β-glucan content of laboratory worts[7] can give some indication of lautering performance. A number of bench-scale filtration tests, using laboratory worts, have been developed[8,9,10], and these also are claimed to have some value in predicting brewhouse performance.

Another approach to the prediction of brewhouse performance has been the Light Transflectance Meter, developed at BRi as part of an HGCA funded project. [11,12,13] This instrument assesses endosperm structure by its ability to transmit or reflect light, and quantifies the relative proportions of mealiness and steeliness. A significant advantage of this machine is that it also measures the homogeneity of a sample. The relationship between malt homogeneity and ease of processing has been recognised in recent years[14] and indeed is the subject of another current HGCA-funded project[15].

The transflectance value has been show to correlate well with a visual assessment of mealiness, using a traditional farinator.[13] Since this technique utilises whole malt kernels it assesses the extent of modification which has occurred during malting only, whereas measurement of β-glucan and filtration on laboratory worts will also be influenced by the amount of enzyme activity during mashing.

None of these methods however, are infallible, since lautering can be affected by so many factors, and to date, pilot scale brewing trials remain the most accurate means of predicting brewhouse performance.

The current project

Perhaps as a result of the factors mentioned above, UK malt has, in the recent past, developed a reputation for quality, particularly with regards to the ease and efficiency of processing, most importantly in the brewhouse but also, to a lesser extent, during fermentation.

However, more recently the technology gap between the UK industry and its major overseas competitors has narrowed. In particular, a strong focus in many countries on the breeding of barley varieties suitable for specific end-uses has eroded the competitive position of UK malting barley and UK malt. In order to establish whether this reputation for premium quality is still justified, it is essential to obtain concrete evidence comparing the processability of malts made from UK barleys with non-UK malts. Currently there is a lack of such information, and the aim of this project was therefore to compare the brewing performance of a number of commercial malts from different growing regions of the world, each prepared to similar specifications. Actual brewing performance in the pilot brewery would also be compared with that predicted by a range of laboratory tests.

3. METHODS

3.1 Sourcing suitable malts.

A number of major brewing companies, all manufacturers of premium lagers, who were known to source their malts from around the world were asked to supply samples of the premium lager malt they purchased, preferentially from each of the main malt producing areas (North America, Europe and Australia). The specifications of such malts are generally very similar, even between different brewing companies, although it is recognised that malts from some geographical areas will be acceptable at slightly higher protein contents than malts from other areas. At BRi, each malt was mixed, sampled and re-analysed for standard quality parameters, in order to eliminate inter-laboratory variations. Analyses were carried out according to the methods published in EBC Analytica[16]. BRi has UKAS accreditation for these methods. Measurements of β-glucanase activity in selected malts were provided by a commercial maltings, using the IRV method[17].

3.2 Bench-scale methods for predicting brewhouse performance.

In addition to the standard quality parameters, each malt was tested using several laboratory techniques which have been developed to predict brewhouse performance.

3.2.1 Light Transflectance meter (LTm)

This technique depends upon the observation that grains with a dense, steely endosperm reflect more light than do grains with a loose, mealy endosperm[12]. (Mealy endosperm will absorb water more readily and modify better during malting than will steely grain). The test can also be used with malt, and a more mealy malt would be expected to better modified and to be easier to process in the brewhouse. Barley or malt grains (97) are placed ventral side down in the carousel of the LTm and illuminated with laser light at 680nm. Sensors in the instrument detect the reflected and transmitted light and the integral computer uses this information to give a transflectance value for each grain. An example of the data obtained from the LTm is given in **Figure 1.** Grains with a value below 200 mV are considered to be mealy. For convenience, the LTm values for all grains are presented as a single value representing the % mealiness (Figure 1A).

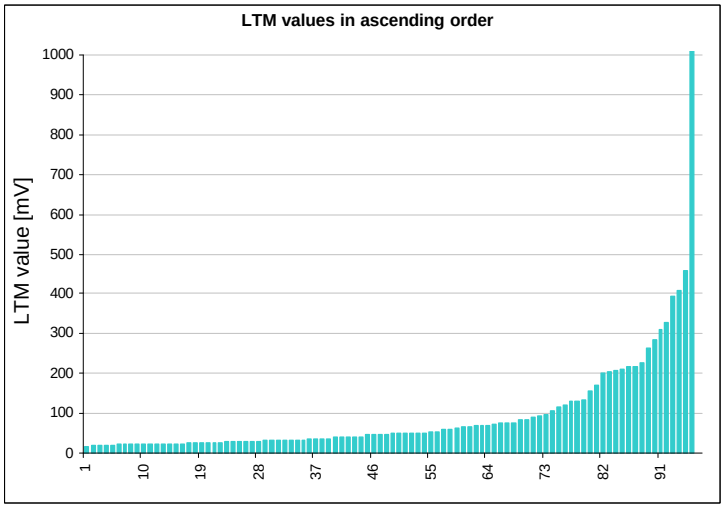
The homogeneity of modification in a malt sample is also an important parameter which has an influence on processability[14]. Homogeneity is most commonly measured commercially using the friability meter. This method is fast and relatively reproducible but, since it involves crushing the kernels, gives limited information of the differences between individual kernels. The LTm, however, gives a reading for each kernel and can thus be used to give an estimate of the homogeneity of the sample. This can be illustrated by the frequency plot shown in **Figure 1B**. These values cover a wider range of values than do homogeneity scores by friabilimeter and thus allow better discrimination between samples.

For example, Figure 1B shows a significant difference in homogeneity between Malt UK4 and Malt D, although there is only 1% difference in homogeneity by friabilimeter (**Table 5**).

A quantitative value for homogeneity can be obtained from the LTm v frequency graph for the first 80 mealy grains, as shown in **Figure 1C** for Malt D. Then homogeneity as a percentage is obtained from the equation

H (%) = 1/ y x 100 where y = the gradient

Figure 1. Example of results from Light transflectance meter.
1A LTm scores for a sample of Malt UK4
Percentage of mealy grains = 84% where mealy grains are defined as <200mV



LTm scores for Malt D Percentage mealiness = 80%

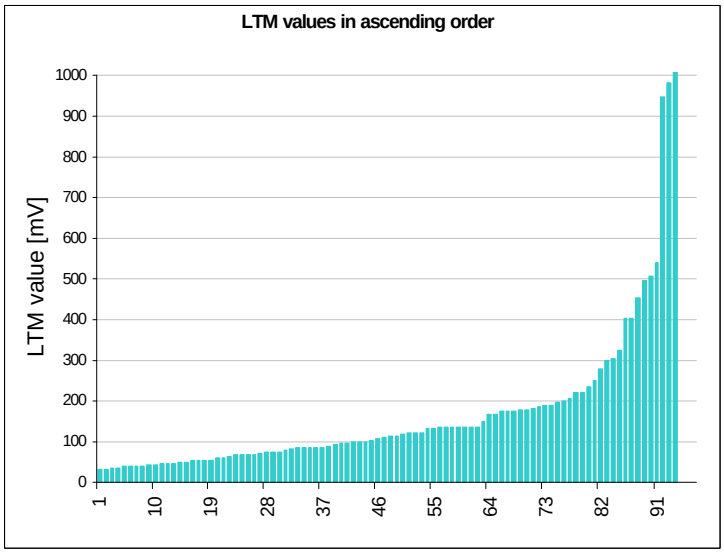


Figure 1B Frequency diagrams and trend lines for the grains < 200mV

Malt UK4 **Malt D**

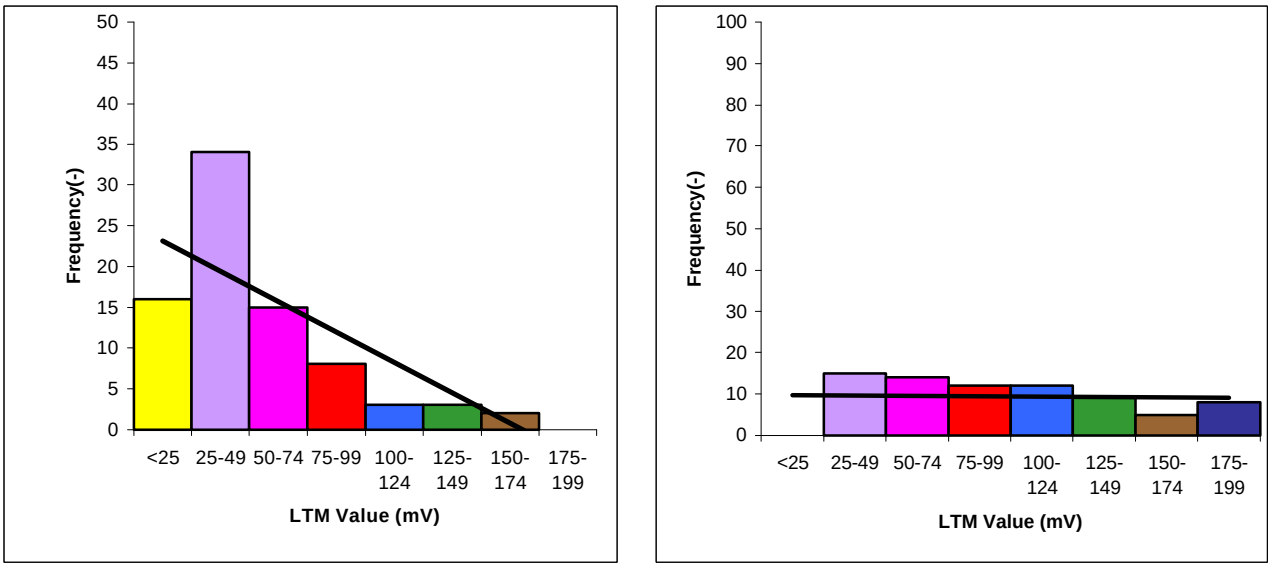
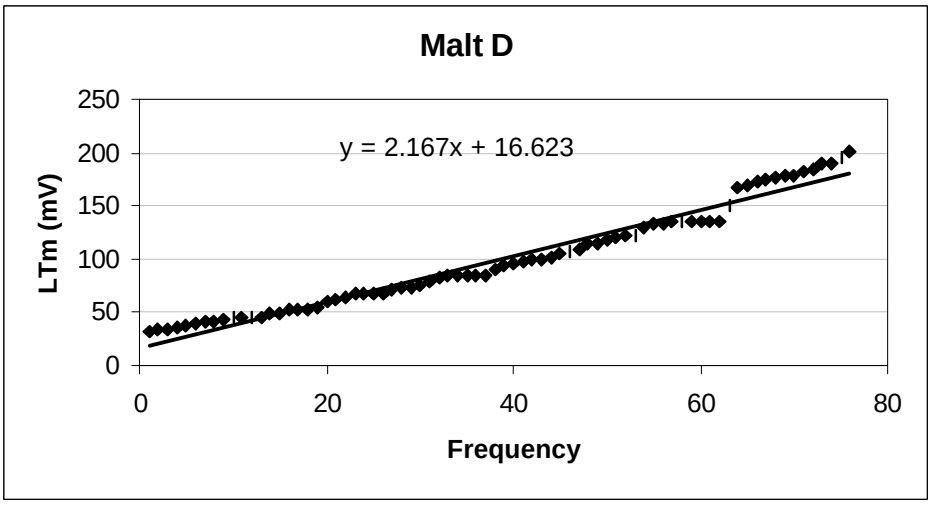


Figure 1C Quantitative estimation of homogeneity from LTm scores



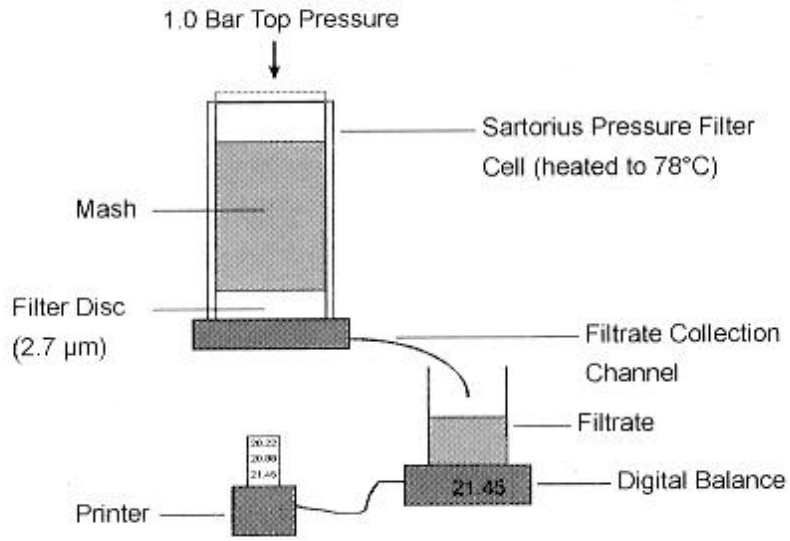
$$\text{Homogeneity} = \frac{1}{y} \quad X \quad 100$$

3.2.2. Malt β-glucan. The amount of un-degraded cell wall material remaining in the malt was estimated by the Carlsberg sanded slab technique.[18] In this method half grains are stained with calcofluor, which causes β-glucan to fluoresce. Results are expressed in terms of modification and homogeneity.

3.2.3. Wort β-glucan. In commercial practice, relatively under-modified malts which still contain significant amounts of β-glucan would be brewed using a temperature programmed mash, in which the wort is held at around 45°C in order to allow further digestion of glucan by the malt enzymes. In these current trials, therefore, β-glucan was measured in laboratory worts prepared from the test malts using a similar mashing schedule. The β-glucan was analysed according to the McCleary method.[18] This is an enzymatic method which involves the precipitation of β-glucan from the wort, followed by enzyme hydrolysis to release glucose. Analyses of laboratory wort β-glucan using a SKALAR instrument were provided by a commercial maltings. The instrument depends upon staining of β-glucan in the wort by calcofluor.[18] The Skalar technique generally gives higher values than the McCleary method, most probably because it also picks up lower molecular weight β-glucans which would not be precipitated and would not therefore be detected by the McCleary method. Thus the McCleary value relates to the high molecular weight fraction of β-glucan whilst the Skalar method will include high and medium molecular weight glucans.

3.2.4. Bench-scale filtration.
Malt is milled in a Miag disc mill, gap setting 0.2mm to give a fine grist composition[8]. 50g of malt is then mashed with 150ml water at 64 degrees C for 1 hour in the BRI Mashing Bath. The temperature is then ramped to 78 degrees C at the rate of 1°C/min before transfer to the filter Cell which is preheated to 78°C. The filter set up is illustrated diagrammatically in Figure 2. The mash is filtered for 20 minutes after which filtration performance is measured by the calculation of Vmax[21], the theoretical mass of filtrate that would be collected from the system in infinite time. The higher the Vmax, the better the filtration.

Figure 2. Filter Set up for measuring mash filtration



3.3 Pilot brewing trials

Each of the six selected malts was used to brew standard BRi lagers in BRi's pilot brewery[22]. Three brewing schedules were used for each malt (see **Table 1**).In each case, the run-off from the lauter tun was "manipulated" by the brewer in order to obtain a consistent run-off, by raking whenever the differential pressure across the plates started to rise above a certain level, causing the rate of run-off to slow down. This is routine practice in commercial breweries and is essential if sufficient good quality wort is to be obtained for fermentation even with malts which are more difficult to process. However, it has the disadvantage that there is no single quantitative measure of run-off rate. Instead, the differential pressure, wort turbidity and frequency of raking are used to give a measure of the ease or difficulty of run-off.

The same yeast was used to ferment all the worts. Ideally, for studies of this nature, all the worts being compared should be fermented using the same generation of yeast, since different generations may give slightly different fermentation profiles. In many (although not all) breweries yeast will be discarded after a set number of generations in order to obtain a more consistent fermentation behaviour. In this case the time constraints of the project and the delayed arrival at BRi meant that malts UK4 and E were brewed later than the other 4 malts, using a different generation of yeast. We have therefore only compared fermentation behaviour between the sets of malts which were fermented using the same generation of yeast (Malts UK2, A, C and D in one group and Malts UK4 and E in the other.

3.3.1 High malt grist

This is the standard protocol used at BRi for brewing premium lager beers, and is based on commercial brewing schedules. It was chosen for this project because it

is well characterised, both in terms of wort and beer analysis and process parameters, and also contains a high proportion of malt, thus accentuating any effects of malt quality.

3.3.2 High maize adjunct.

Each of the six selected malts was also used to brew a similar lager beer, but using a substantial proportion of maize grits as an adjunct. This is a standard practice for brewing companies in many parts of the world where maize is readily available. The maize is not malted and contains relatively little in the way of enzyme activity. The malt used must therefore be rich in enzymes, particularly amylolytic enzymes (to provide sufficient fermentable sugars). The gelatinization temperature of maize starch is significantly higher than that of malt starch. The maize must therefore be cooked with a portion of malt at 70° - 100°C in order to gelatinize the starch before adding to the main mash. The mash schedule used (see **Table 1**) was based on those used commercially for maize brewing.

3.3.3. Under-modified malt "adjunct"

The third set of brews included 15% of under-modified malt as an "adjunct" (for analysis see **Table 2)**. The aim of this was to simulate the situation which exists in some parts of the world where brewers have to use a proportion of locally grown barley malt regardless of its suitability for processing. The malt was prepared at BRi using a low casting moisture to restrict the activity of hydrolytic enzymes during malting. The laboratory wort made from this malt had a high β-glucan content (259 mg/litre by the McCleary method). Malts which did not provide sufficient β-glucanase activity to deal with this high molecular weight material might be expected to give lautering problems when used with such adjuncts. A temperature programmed mash programme was used. This was based on the type of mash schedule likely to be used commercially with this type of under-modified malt. This mash schedule incorporates a temperature stand at 45°C to encourage enzyme activity and cell wall digestion. It would tend, therefore, to minimise differences between the malts

Table 2. Analysis of Under-modified malt

HWE_{10} (%)	79.9	**DP (°WK)**	165
TSN (%)	0.55	**β-glucan (mg/L) (McCleary)**	259
Viscosity (mPa)	1.74	**Mealiness (LTm) (%)**	90
Friability (%)	68	**Vmax (g)**	17
Homogeneity (%) (By Friabilimeter)	86	**Kolbach (%)**	38

Table 1. Brewing process conditions .

Brewing Stage	High malt grist	High maize grist	Undermodified malt grist
Grist:	13.5 kg test malt 1.6 kg Cara malt 0.5 kg wheat flour liquor/grist ratio 3:1	12.9 kg test malt (in total) 8.6 kg maize grits	11.5 kg test malt 1.6 kg Cara malt 2 kg under-modified malt (866P)
Cereal cooker	none	3kg test malt 8.6 kg maize grits 55°C - 70°C at 1°C/minute Hold at 70°C for 10 minutes Ramp to 100°C, boil for 10 mins	none
Mash Conversion	Infusion mash at 64°C for 60 mins. Sparge temperature 78°C	9.9kg test malt liquor:grist of 3:1, hold at 45°C for 60 mins. Add maize mash Hold at 67°C for 60 minutes Sparge at 78°C	45°C for 30 minutes Increase to 70°C at 1°C/min Hold at 70°C for 60 mins Sparge at 78°C
Copper Boil	Boil time 90 mins Hop grist; 12.5 g $HOPCO_2N$ 20g Saaz pellets after 80 min boil 1.5 kg Fermentose syrup		
Fermentation	12°C for 6 days or until PG < 1010° gravity Yeast strain BRYC 32		
Maturation	3 days at 13° 1-2 days cold rest at 3°C minimum of 7 days cold maturation at 0°C		
Packaging	DE filter sheets, type XE 200 275 ml bottles		
Pasteurisation	15 min at 60°		

4. RESULTS

4.1. Analytical data for the commercial malts

After arrival at BRi, each commercial malt was re-homogenised by thorough mixing, sub-sampled and re-analysed for basic quality parameters, common to most brewers' specifications.
On the basis of the results of all nine malts, six (two from the UK and four from the other major malting barley producing areas of the world (north America, Australia and mainland Europe), were chosen for brewing trials. The standard analyses for these six malts are shown in **Table 3,** together with the typical specification for a premium lager malt, as advised by the MAGB. All values are BRi analyses, with the exception of the Apparent Attenuation, where the brewer's own value is used, since at BRi the real rather than the apparent attenuation is measured.

Table 3. Standard analyses of malts chosen for brewing.

Parameter	Typical specification Min	Max	UK2	UK4	A	C	D	E
Moisture (%)		4.5	5.3	6.5	6.0	4.5	6.4	4.6
Extract (fine) (% dry)	80.5		83.1	81.5	81.9	81.5	82.2	83.2
Fine /coarse difference		2	0.7	0.3	1.3	0.3	0.9	0.9
Colour (° EBC)	3.0	4.0	3.7	4.4	3.7	4.9	3.7	4.1
Apparent Attenuation (%)	78		83	NA	78	84	82	NA
P (°WK)	230		298	326	372	253	285	274
TN (%)	1.65	1.85	1.64	1.68	1.84	1.63	1.69	1.64
TSN (%)	0.65	0.80	0.69	0.75	0.73	0.77	0.76	0.72
Kolbach (%)	38	45	42	44	40	48	45	44
Wort β-glucan (mg/l) Skalar		230	85	15	185	NA	60	145
Friability (%)	80		81	92	72	82	78	84

The aim was to choose malts which would be within the normal specifications for premium bottled lagers. The 6 malts chosen largely fell within the typical specification range, except for moisture, which was frequently higher than specified. This was most probably due to moisture pick-up during transport. Malt UK3 was particularly high in moisture and was therefore rejected for brewing trials. The differences in moisture between the other malts was not considered

likely to have a significant effect on brewing performance. Malt A had a higher total nitrogen content than did the other samples, although it was still within the typical specification range, and was considered by the brewing company involved to be suitable for use alongside Malt B as part of the grist for its' brands production. This is not unusual for malts from some geographical locations. Although there was some variation in wort β-glucan levels, all 6 malts were well below the specified maximum.

The malts were also analysed for a wide range of quality parameters, not all of which would be regarded by brewers as standard specifications. However, some brewers would include some of these analyses in their specifications. Results for all analyses for all 9 malts are shown in Annex 1 **Table 4.** There was more variation between the malts with these parameters. For example, Malt UK4 and Malt A were particularly high in amylolytic enzymes (DP) while Malt UK3 and Malt C were below the average. All the malts, however, were above the minimum specification and would be generally acceptable commercially. It was also noted that malts A and B were particularly high in β-glucanase activity, while UK2 was well below the average. Since this enzyme is heat labile, it is easily destroyed during kilning, thus the activity in commercial malts is a reflection, not only of the amount developed during malting, but also of the kilning conditions and specified moisture content.

4.2. Predictive tests for brewhouse performance

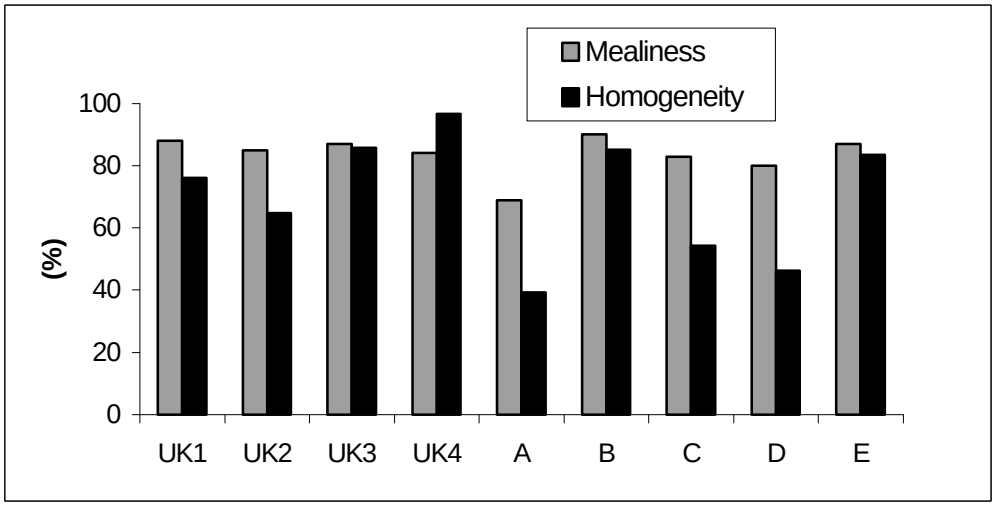
All 9 malts were also analysed using tests which are considered to predict brewhouse performance (see BACKGROUND AND SCOPE OF PROJECT).

4.2.1. Light Transflectance Meter (LTm)

With the exception of malt A (which had a higher nitrogen content), all the malts were relatively mealy, with scores between 80 and 90% (**Figure 3)**

Somewhat larger differences were apparent in the homogeneity scores. The malts UK 3, UK4 , B and E were noticeably more homogenous than the others, while malts A, C and D were below average.

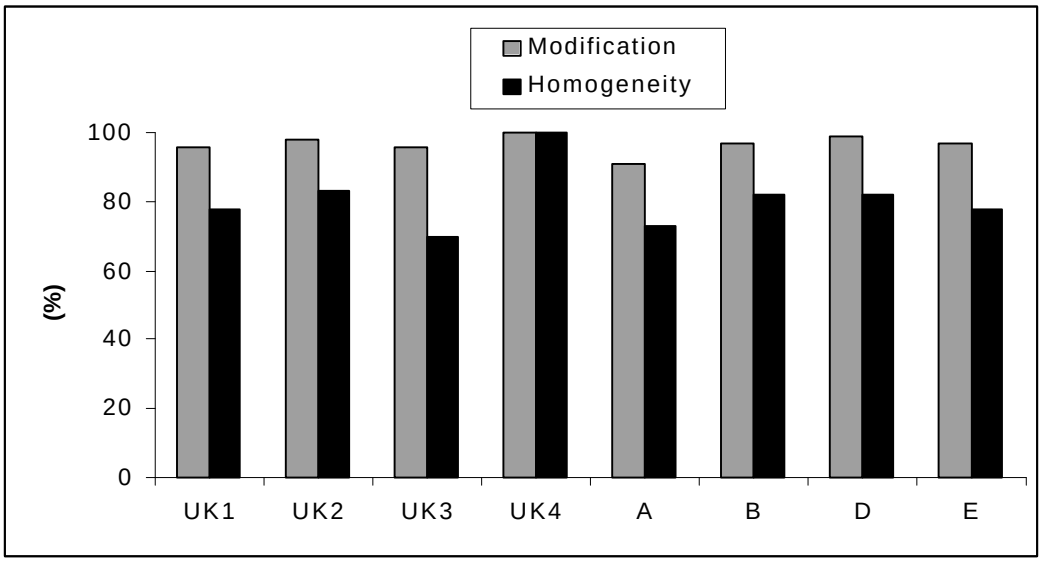
Figure 3. LTm scores



4.2.2. Malt β-glucan

The sanded slab technique gives values for both extent and homogeneity of modification of endosperm cell walls (**Figure 4**). There was little difference between the malts in terms of the extent of modification, with all except Malt A being over 96% modified. There was somewhat greater variability in homogeneity, although less than was evidenced with the LTm technique. In both cases Malt A displayed poor homogeneity whilst UK4 was the most homogeneous.

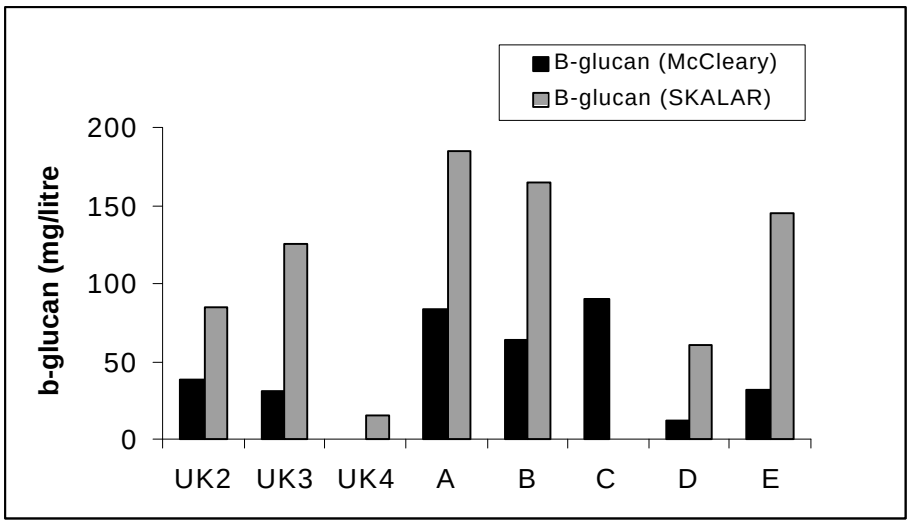
Figure 4. Malt β-glucan



4.2.3. β-glucan content of laboratory wort

The β-glucan content of the worts prepared in the laboratory mashing bath from each of the malts are shown in **Figure 5.** The SKALAR method gave values from 2 – 4 times as high as the McCleary method (see Methods) but there was a strong correlation between the two methods and they generally ranked the samples in the same order. The difference between the two values gives an indication of the amount of small to moderate sized β-glucan molecules. For both methods UK4 gave the lowest β-glucan content and Malt A the highest. Unfortunately there was insufficient malt C to obtain a SKALAR analysis, but extrapolation from the McCleary results suggests that it would be high.

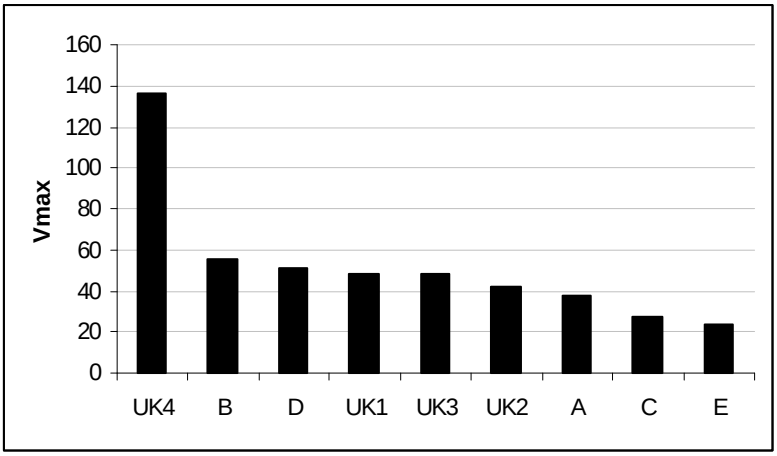
Figure 5. β-glucan content of laboratory wort



4.2.4. Bench-scale filtration (Vmax)

As with β-glucan content, there was a wide range of filtration behaviour (**Figure 6**), from very fast (UK4) to slow (malts C and E).

Figure 6 . Filtration (Vmax)



4.2.5 Correlations between predictive tests

The results for each of the predictive tests were compared with each other (**Table 5**). The strongest correlations were found between the β-glucan content and modification by calcofluor staining, as might be expected, since calcofluor primarily stains β-glucan cell walls. There was also a good correlation between laboratory filtration (Vmax) and homogeneity by Calcofluor staining. Perhaps surprisingly, there was little correlation between the homogeneity as measured by the three different techniques (LTm, friability and calcofluor staining), suggesting

that they were detecting different characteristics. However, with such a small number of samples, all of which were relatively well modified, no great reliance can be placed on these correlations. The general lack of strong corrrelations between most of the tests is perhaps not surprising, given the number of factors involved. For example, β-glucan content of the wort will be affected not only by the mealiness of the endosperm, but also by the β-glucanase activity during the laboratory mashing stage. Likewise, the Vmax will also be affected by enzyme activity during mashing in addition to endosperm mealiness and other factors. However, the general lack of significant correlations between the different predictive tests supported the argument, derived from practical experience, that the different laboratory tests available are each influenced by a different set of factors and can therefore give differing results.

4.3 Brewing trials

4.3.1 Standard brews using grist with a high malt content

Brewhouse performance

Each of the six selected malts was used to brew a standard lager, using an infusion mash schedule (see Methods). Brewhouse data are shown in **Table 6**.

Table 6. Brewhouse data for brews with a high malt grist

	UK2	UK4	A	C	D	E
Brew number	67/01	82/01	69/01	66/01	68/01	81/01
Mash pH	5.56	5.49	5.66	5.58	5.57	5.47
Lauter time (mins)	83	83	84	84	82	81
Re-circulation time (mins)	16	23	22	35	16	31
Time before first rake	13	None needed	64	None needed	16	6
Gravity of last running (°)	1005.8	1004.1	1006.9	1005.8	1003.1	1003.8
Sweet Wort clarity	Very good	Good	Very good	Fair	Very good	Good
Extract yield (litre ° Plato at fermentation gravity)	1102.9	1086	1048.8	1044	1081.6	1124.5

Malt E gave the highest yield of extract overall, followed by Malt UK2. Extract yields from Malts A and C were below average for the malt set.

The time which elapses before raking is required is an indication of the ease with which the wort could be run off. The results shown above in Table 6 suggest that malts A, C and UK4 ran off very readily, while malt E was much more difficult. Another quantitative measure of ease of run-off is the differential pressure which was need to maintain a steady run-off rate. This is shown in **Figure 7.** The sharp rises in pressure show where raking was required. These data confirm that malts UK4 and C ran off very easily, while run-off problems were experienced with malts D and E.

The clarity of the sweet wort is another important quality parameter. Wort turbidity was therefore monitored during run-off and the data shown in **Figure 8.** Both of the UK malts (shown in red) had relatively low turbidity throughout most of the lautering period, as did malt A. Malt C, on the other hand, which had run off very readily (**Figure 7**), was very turbid throughout. Malt E, which had not run off well, was also very turbid, although Malt D, which had also experienced run-off problems, was quite clear

Wort Quality

Each wort was analysed for standard quality parameters. The results (given in **Table 7**) were very similar for all six brews. This would be expected, since all six malts had similar standard analyses. The exception was Malt A, which gave higher values for free amino nitrogen and total soluble nitrogen. Again, this is to be expected, given the higher protein content of this malt.

Figure 7. Differential pressures during run-off for all malt brews

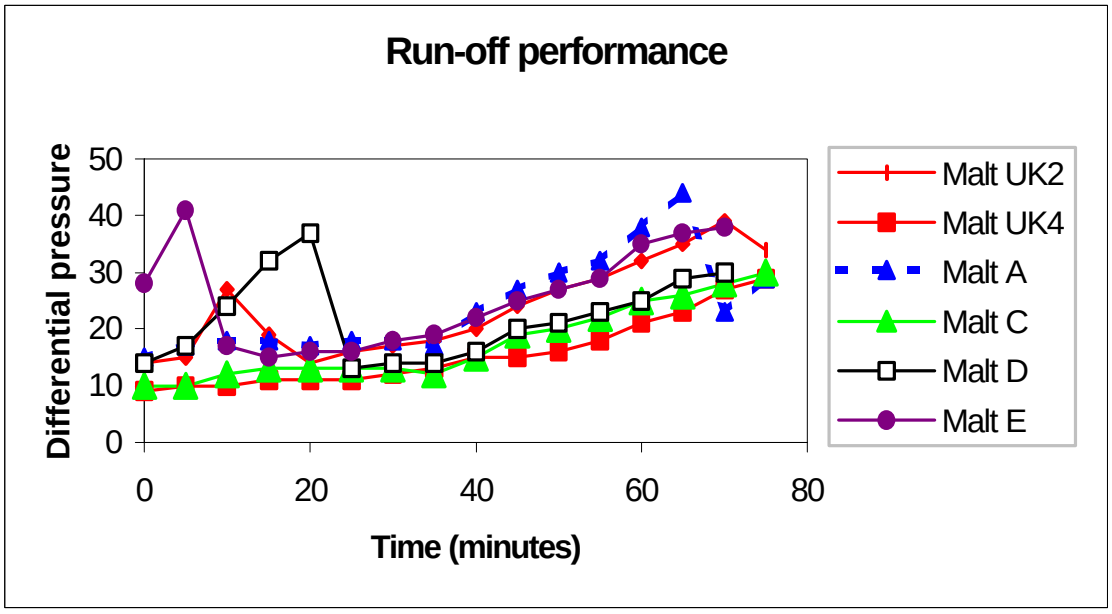


Figure 8. Wort turbidity during run-off for all malt brews.

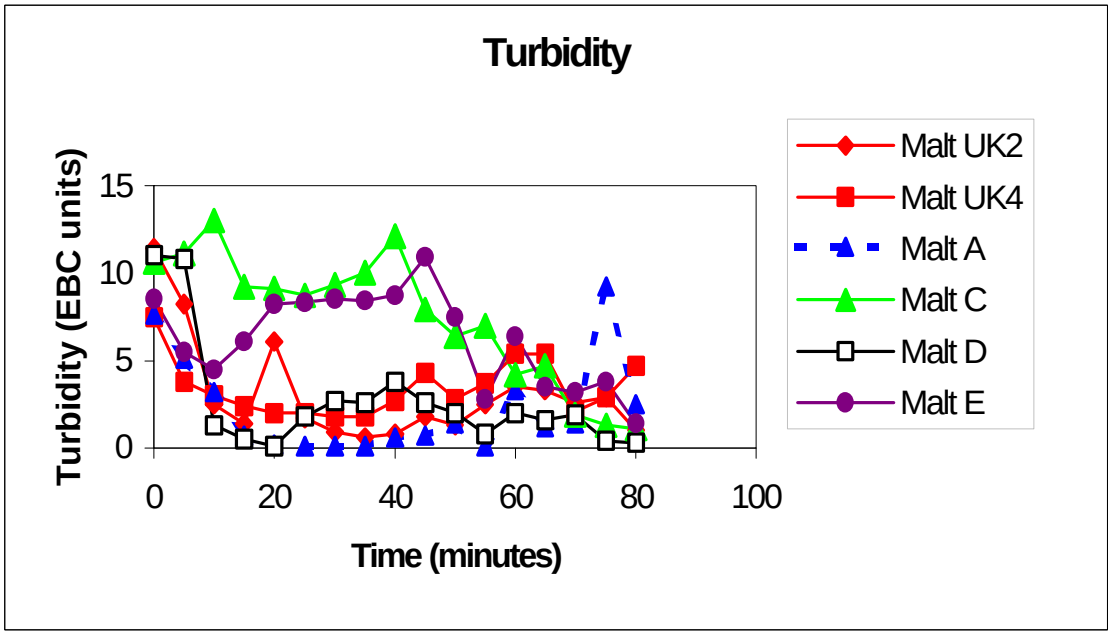


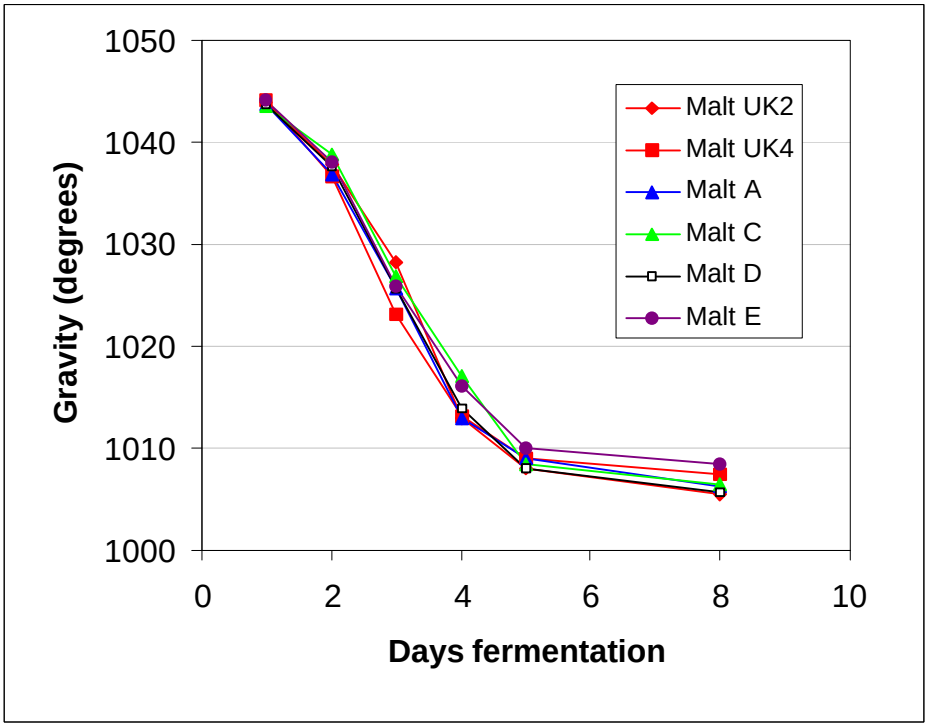
Table 7. Wort analyses for all malt brews

	UK2	UK4	A	C	D	E
Brew number	67/01	82/01	69/01	66/01	68/01	81/01
QA Ref. No.	3042/01	3657/01	3084/01	3001/01	3057/01	3640/01
PH	5.55	5.52	5.50	5.58	5.58	5.40
Colour (°EBC)	12.0	12.5	12.3	13.1	11.9	11.5
Present gravity (°)	43.29	43.41	43.23	42.64	43.14	43.78
Bitterness (BU)	32	32	33	33	32	31
Free amino N (mg/litre)	146	157	182	164	161	148
Forced fermentation (%)	68	75	71	69	69	71
Total soluble nitrogen (mg/litre)	828	855	944	894	890	832

Fermentation performance

The fermenting worts were monitored daily for gravity. The results, shown in **Figure 9,** indicate that all six worts fermented satisfactorily and that there were no major differences between them in their ability to support yeast growth and fermentation. Final attenuation for Malt UK4 and Malt E was slightly higher than for the other 4 malts. However, this is most likely to be due to the fact that these two malts were brewed later than the first set of 4, and therefore were fermented with a later generation of yeast.

Figure 9. Fermentation performance for all malt brews



Beer quality

Final beers were analysed for a range of key quality parameters and the results are shown in **Table 8**. As expected, these did not show any major differences between the malts, other than the slightly higher nitrogen content of beer from Malt A. UK2 and UK4 gave above average levels of ethanol, while both Malt E and Malt C were below the average ethanol concentration for this set of malts.

The total yield of ethanol from the grist was calculated from the total volume of wort obtained at fermentation gravity and the concentration of ethanol in the final beer. The highest yields of ethanol overall were obtained from Malts UK2 and UK4. Malt E, although it gave the highest yield of extract in the brewhouse, gave slightly below the average yield of ethanol, suggesting that some of the extract was not fermentable.

Table 8. Analysis of beers from all malt brews.

Malt	UK2	UK4	A	C	D	E
Brew No.	**67/01**	**82/01**	**69/01**	**66/01**	**68/01**	**81/01**
QA Ref. No.	**3536/01**	**3849/01**	**3586/01**	**3535/01**	**3585/01**	**3848/01**
PH	4.00	4.14	4.21	4.08	4.14	4.09
Colour (°EBC)	9.5	9.7	9.4	9.4	9.0	8.2
Present Gravity (°)	6.10	4.23	5.49	5.50	4.97	6.76
Attenuation limit (°)	5.69	4.04	6.11	5.97	5.51	5.87
Head Retention Value (Nibem) (sec)	75 164 246	78 156 231	73 153 234	78 165 238	72 149 225	83 161 235
Bitterness (BU)	21	21	21	22	21	20
Free Amino Nitrogen (mg/litre)	43.6	40.6	59.4	57.1	52.2	39.8
Total Soluble Nitrogen (mg/litre)	582	631	716	630	661	590
Ethanol (%)	5.13	5.21	5.05	4.84	5.01	4.75
Total yield of ethanol (kg)	5.156	5.132	4.848	4.646	4.960	4.845
Haze	0.2	0.33	0.18	0.17	0.18	0.14

4.3.2. Brews using maize grits as adjunct

Brewhouse performance

Table 9 shows the brewhouse data. As with the all-malt brews, Malt UK2 and Malt E gave the highest yield of extract. Extract yield from Malt D was below average for the set.

Table 9. Brewhouse data for brews with maize adjunct

Malt	**UK2**	**UK4**	**A**	**C**	**D**	**E**
Brew number	**72/01**	**85/01**	**74/01**	**71/01**	**73/01**	**84/01**
Mash pH	5.7	5.7	5.72	5.56	5.62	5.38
Lauter time (mins)	93	93	91	92	89	91
Re-circulation time (mins)	16	15	13	17	15	24
Time before first rake	63	Not needed	Not needed	61	Not needed	70
Gravity of last running (°)	1005.8	1007.3	N/A	1006.5	N/A	1016.9
Sweet Wort clarity	Good	Good	Very good	Good	Very good	Fair
Extract yield (litre ° Plato at fermentation gravity)	1463.9	1342	1322.5	1371.1	1287	1454.2

Differential pressures for these brews are shown in **Figure 10**. All brews ran off well initially, but malt UK2 and Malt C (which had given good run off in the high malt brews) showed some pressure build up later on and required raking. Malt E, which had not run off well in the all-malt series of brews, showed a particularly high build of pressure towards the end of run-off and required raking. Although this malt gave a good yield of extract, the gravity of the last runnings was unusually high. Possibly the raking encouraged materials to leach out of the spent grains. Malt D (which had not performed well during the high malt brews), and Malts A and UK4 each ran off well and did not require raking. In general there was less difference between the malts in terms of run of performance than there had been with the high malt mashes.

There was also less differentiation with turbidity (**Figure 11**). All malts behaved similarly, in that turbidity was relatively low for the first 40 minutes of lautering, but then fluctuated rapidly, even with those malts which did not require raking. Malt E, however, was very turbid throughout run-off.

Figure 10. Differential pressures during run-off with maize brews

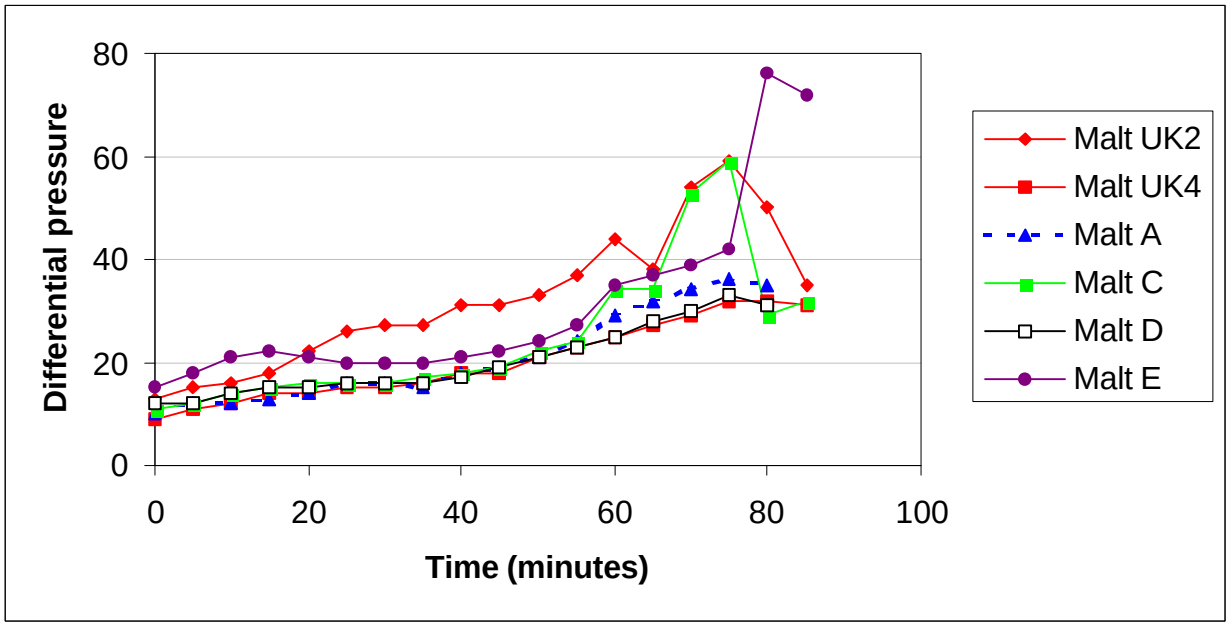
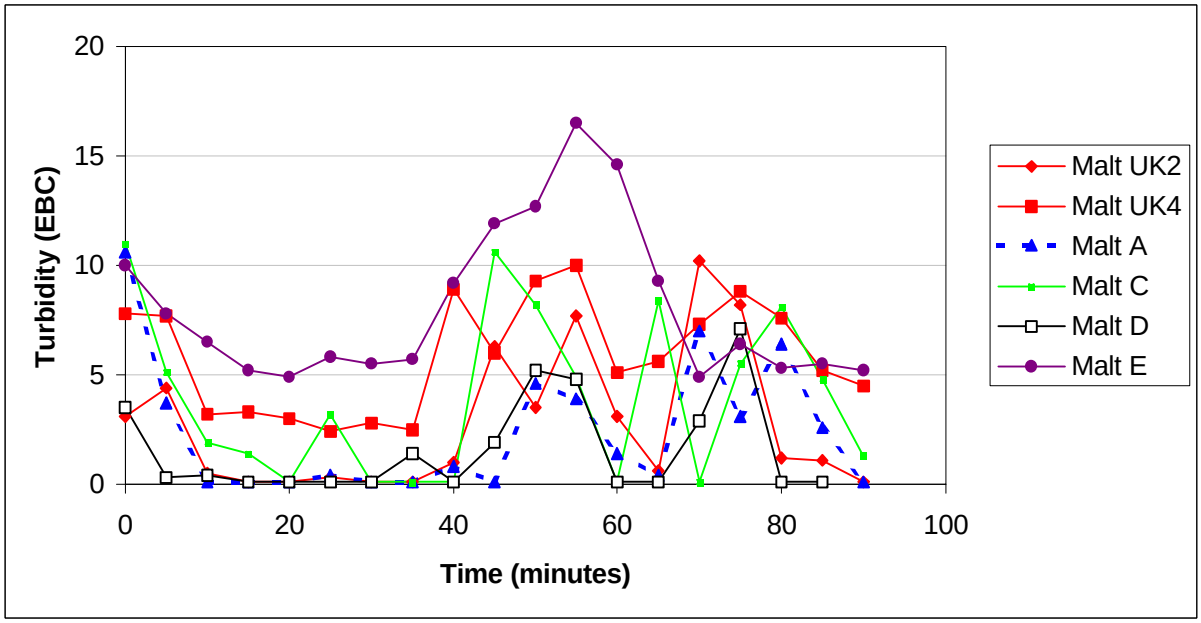


Figure 11. Turbidity during run-off with maize brews



Wort quality

Standard analytical data for the worts, given in **Table 10**, was similar for all six brews, with the exception, already noted, of the higher total and free amino nitrogen values for Malt A. Wort colours and soluble protein content were lower than for the all-malt beers, as would be expected from the proportion of maize (which imparts less protein and colour than malt) in the grist.

Table 10. Wort analyses for maize brews

Malt	UK2	UK4	A	C	D	E
Brew number	**72/01**	**85/01**	**74/01**	**71/01**	**73/01**	**84/01**
QA Ref. No.	**3181/01**	**3795/01**	**3275/01**	**3159/01**	**3218/01**	**3759/01**
PH	5.52	5.60	5.52	5.72	5.55	5.54
Colour (°EBC)	6.1	6.8	6.8	7.2	6.3	5.8
Present gravity (°)	43.38	43.55	43.47	43.23	43.33	43.58
Bitterness (BU)	26	33	35	32	33	27
Free amino N (mg/litre)	120	131	131	142	132	119
Forced fermentation (%)	67	70	68	66	68	67
Total soluble nitrogen (mg/litre)	542	622	674	594	615	583

Fermentation Performance

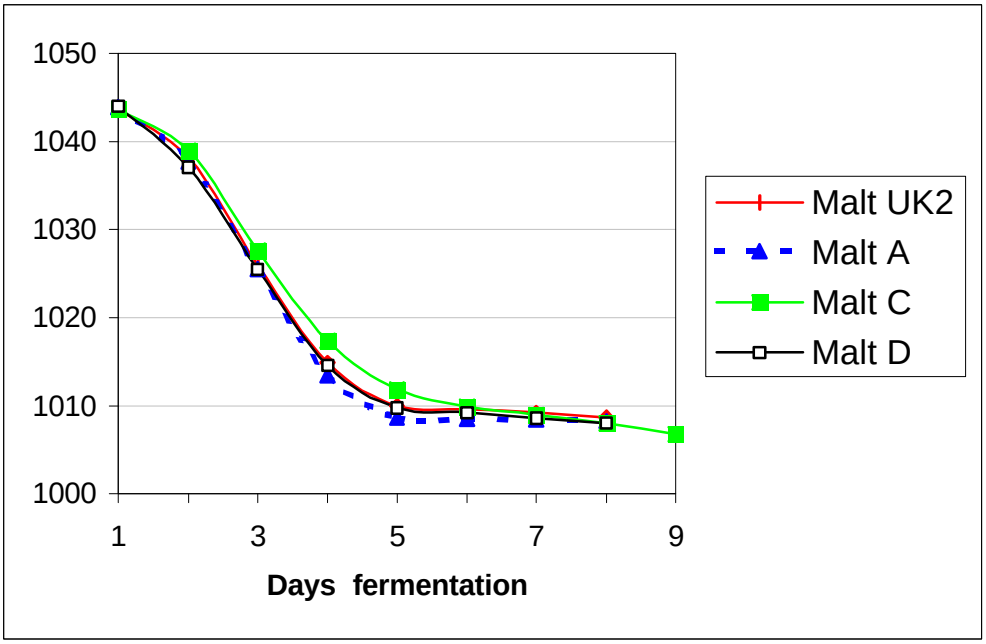
As before, the fermenting worts were monitored daily for gravity and in this case also for yeast cell numbers. The results are for Malts UK2, A, C, and D are shown in **Figure 12** and suggest that, although there was little difference between worts from malts UK2, A and D, yeast growth in wort from Malt C was somewhat limited. This was reflected in the slightly slower attenuation with Malt C, which needed an extra 12 – 24 hours to achieve final attenuation.

The fermentation results for Malt UK4 and Malt E are shown separately from the other 4 (see **Figure 13**), since these two were brewed as a pair, but 4-5 weeks later than the first four, and are therefore using a later generation of yeast. Older generations of yeast frequently display slightly longer lag periods, and thus the overall fermentation period is longer. If Figures 12A and 13A are compared, it can be seen that all of the first batch (with the exception of Malt C) had reached the threshold gravity at 1010 by five days, while neither of the second batch had. (Once the threshold gravity is reached, the temperature of the fermenter is increased to 13°C for three days. This is described as the warm maturation period).

Although both Malt E and Malt UK4 fermented more slowly than the first batch, Malt E took significantly longer to attenuate than did Malt UK4, and yeast growth was also noticeably reduced.

Figure 12. Fermentation performance for maize brews – Malts UK2, A,C and D

12A. Gravity



12 B. Yeast cell numbers

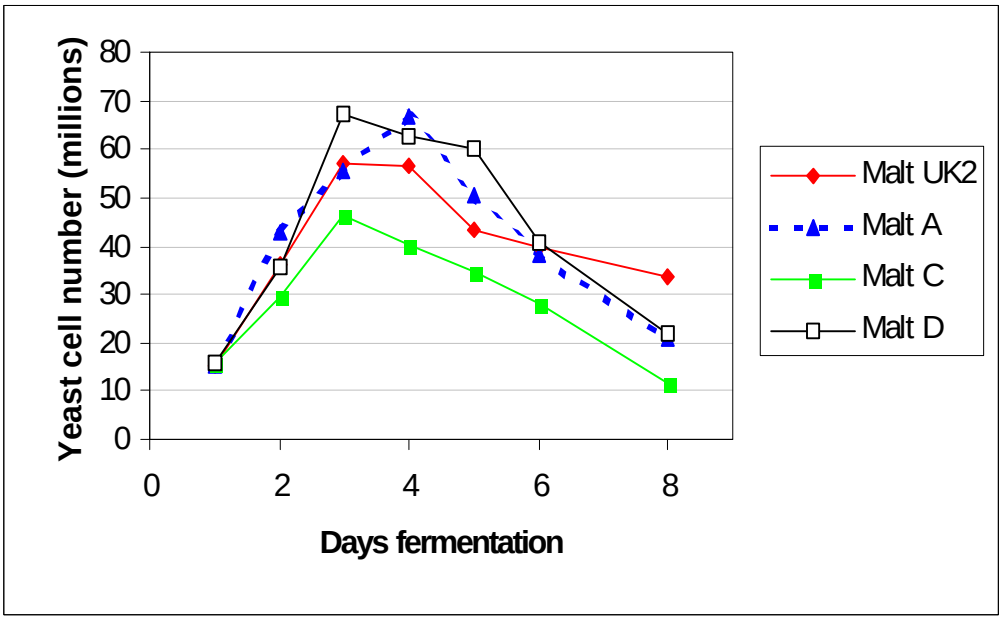
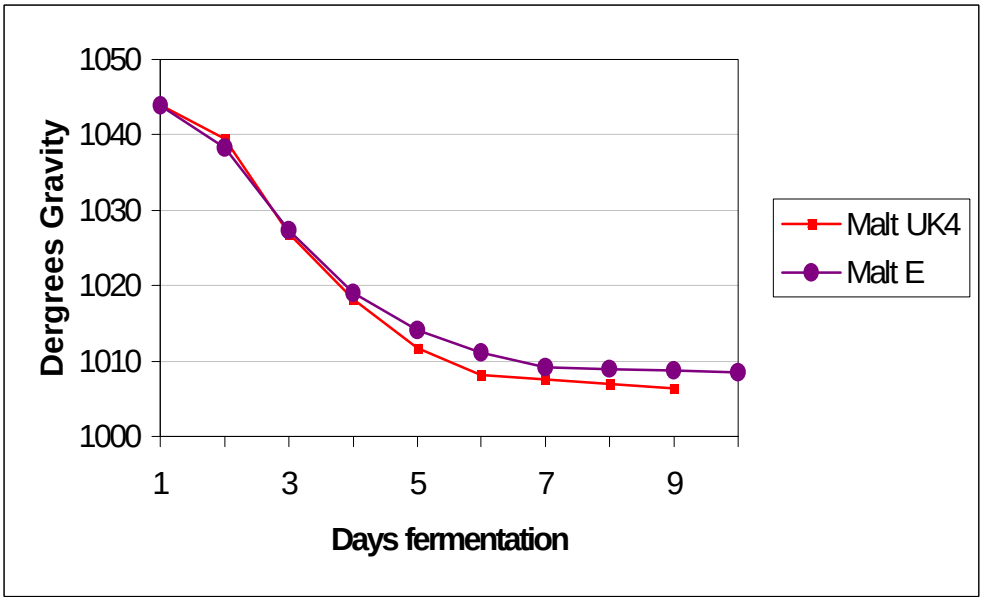
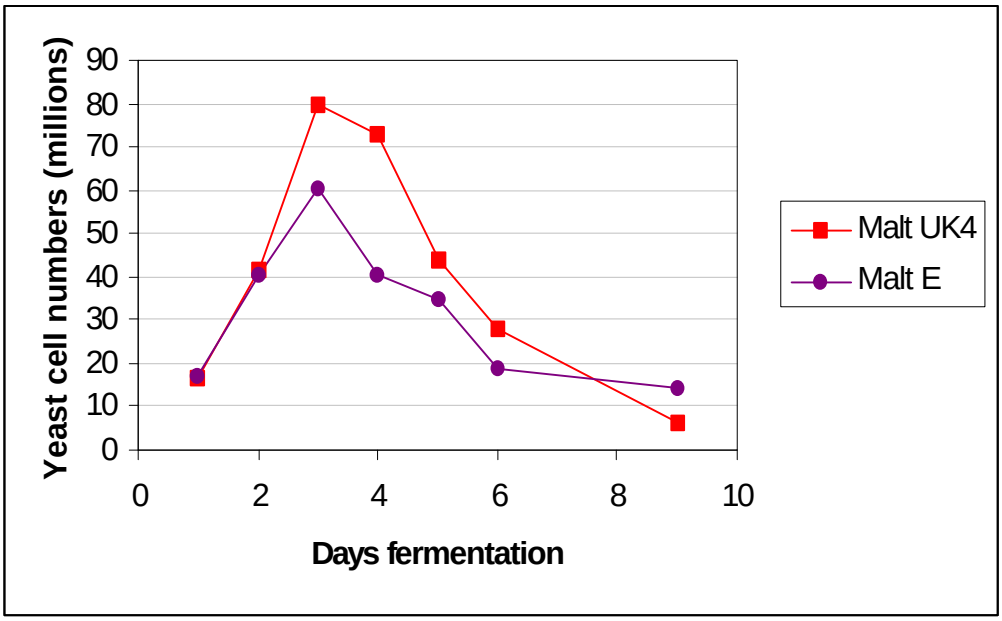


Figure 13. Fermentation behaviour - Malt UK4 and Malt E

13A. Gravity



13B. Yeast cell numbers



Beer Quality

The finished beers were analysed for key quality parameters. Results are given in **Table 11**. As with the all-malt brews, there was little difference between the beers for most standard parameters, as would be expected. Ethanol concentrations were in general lower than for the all malt brews, suggesting that the extract was not as fermentable. This was supported by the higher attentuation limits for the maize beers and is probably related to the temperature programme used in the cereal cooker. The concentration of ethanol from UK4 was slightly above average for this set of brews, while that for malts C and E was below average, indicating poorer fermentability. However, the total calculated yield of ethanol from Malt E was still good because of the high yield of extract. Malts UK2, UK4 and Malt E all gave above average yields of ethanol, while that from Malt D was below average for this set of brews.

Table 11. Analysis of beers from maize adjunct brews.

Malt	**UK2**	**UK4**	**A**	**C**	**D**	**E**
Brew No.	**72/01**	**85/01**	**74/01**	**71/01**	**73/01**	**84/01**
QA Ref. No.	**3682/01**	**4084/01**	**3693/01**	**3681/01**	**3692/01**	**4083/01**
PH	3.76	3.84	3.79	3.82	3.80	3.89
Colour (°EBC)	5.0	4.8	4.8	7.9	3.9	3.8
Present Gravity (°)	7.43	5.71	7.04	7.69	7.35	7.54
Attenuation limit (°)	7.76	6.12	7.54	7.54	7.76	7.66
Head Retention Value (Nibem) (sec)	86 166 242	59 125 186	75 147 221	76 154 234	70 144 217	74 149 223
Bitterness (BU)	18	20	23	20	21	17
Free Amino Nitrogen (mg/litre)	23.8	23.4	25.9	31.5	22.9	22.4
Total Soluble Nitrogen (mg/litre)	347	376	429	407	384	368
Ethanol (%)	4.78	4.97	4.85	4.67	4.75	4.58
Total yield of ethanol (kg)	6.405	6.063	5.844	5.861	5.558	6.069
Haze	0.18	0.14	0.22	0.2	0.22	0.20

4.3.3. Brews using under-modified malt as adjunct

Brewhouse Performance,
Brewhouse data for these mashes is shown in **Table 12**. No raking was required for any of the brews, and in fact run-off was satisfactory for all the malts except for Malt E. The differential pressure data, given in **Figure 14**, confirms that there was little differentiation between the malts UK2, UK4, C and D in ease of lautering. Malt A was a little poorer. Malt E displayed the poorest run-off performance, with a high build-up of differential pressure. Both Malt E and Malt C required extensive re-circulation prior to run-off and the clarity remained poor. The turbidity data in **Figure 15** confirm that Malt C and particularly Malt E had distinct problems with clarity. However, Malt E did give a good yield of extract. The extract yield from Malt UK2 was rather low compared with the other malts.

It had been expected that the under-modified malt adjunct would accentuate any processability differences between the malts. In fact, the run-off performance for some of the malts was better than that for the all malt brews. The result may have been due to the gentler mashing conditions afforded by the Congress mash, which allowed further digestion of β-glucan to take place during mashing. It is also possible that the endosperm structure of the variety used (a UK malting variety) meant that it was less likely to give mashing problems.

Table 12. Brewhouse data for brews with under-modified malt adjunct

Malt	**UK2**	**UK4**	**A**	**C**	**D**	**E**
Brew number	**76/01**	**88/01**	**79/01**	**75/01**	**78/01**	**87/01**
Mash pH	5.52	5.64	5.68	5.52	5.61	5.52
Lauter time (mins)	97	83	83	81	84	83
Re-circulation time (mins)	23	26	18	>45	25	>45
Time before first rake	No raking	No raking	No raking	No raking	No raking	No raking
Gravity of last running (°)	1008.2	1006.6	1004.9	1008.1	1006.3	1005.6
Sweet Wort clarity	Very good	Good	Very good	Fair	Good	Poor
Extract yield (litre ° Plato at fermentation gravity)	1030	1069.4	1059.7	1055.3	1056	1116.5

Figure 14. Differential pressures for brews with high under-modified malt adjunct

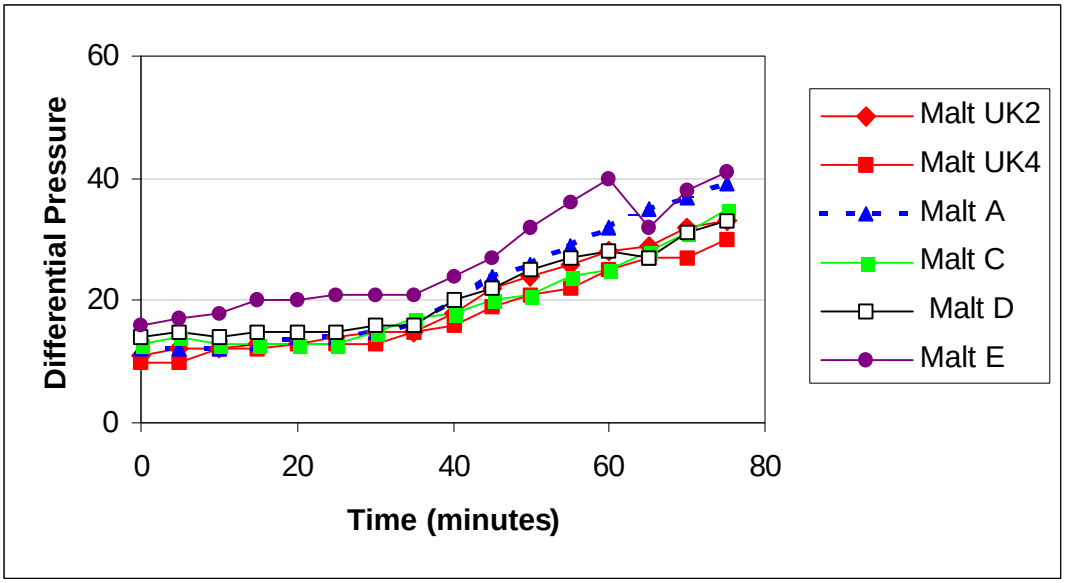
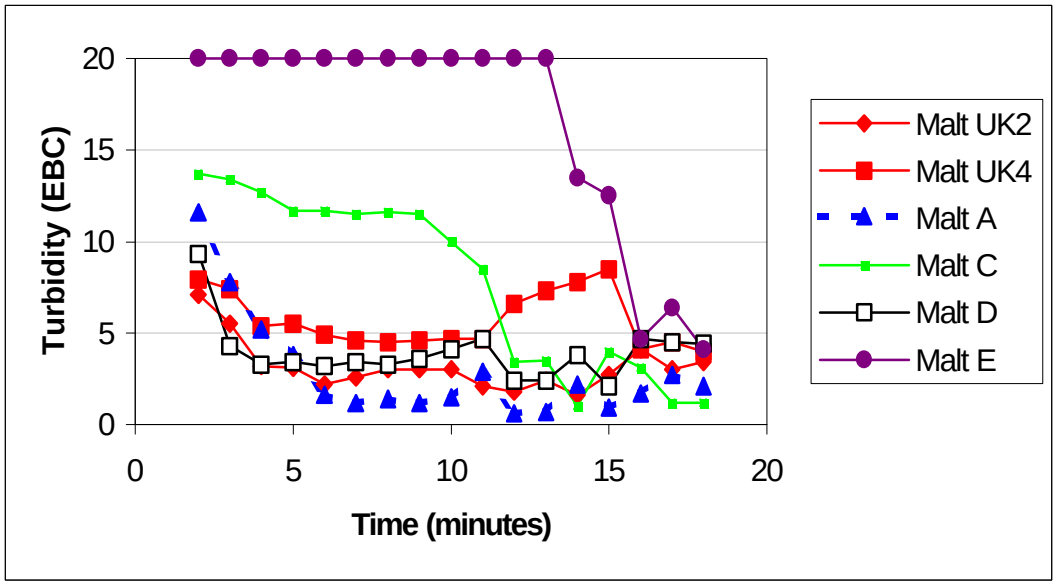


Figure 15. Turbidity for brews with high under-modified malt adjunct



Wort Quality

Results of the wort analyses for these brews are given in **Table 13.** As with the other sets of brews, these do not exhibit any significant variations other than the higher soluble nitrogen values from Malt A already noted with the earlier brews.

Table13. Wort analyses for brews with under-modified malt adjunct

Malt	**UK2**	**UK4**	**A**	**C**	**D**	**E**
Brew number	**76/01**	**88/01**	**79/01**	**75/01**	**78/01**	**87/01**
QA Ref. No.	**3436/01**	**3899/01**	**3508/01**	**3403/01**	**3500/01**	**3892/01**
PH	5.43	5.53	5.54	5.53	5.53	5.53
Colour (°EBC)	12.2	12.7	13.1	13.5	12.0	11.9
Present gravity (°)	43.16	43.50	43.24	43.68	43.49	43.49
Bitterness (BU)	31	33	32	32	32	29
Free amino N (mg/litre)	196	173	191	209	177	160
Forced fermentation (%)	67	69	67	67	67	67
Total soluble nitrogen (mg/litre)	827	906	948	903	888	847

Fermentation Performance

The fermenting worts were monitored daily for gravity and the results are shown in **Figure 16.** These show that there was little difference between any of the malts in fermentation performance.

Beer Analyses

These are shown in **Table 14.** As with the earlier brews, UK4 was highly fermentable, giving an above average ethanol concentration, while Malts C and E were below average. However, the overall yield of ethanol from malt E was good, because of its high yield of brewhouse extract. Malt UK4 gave the highest total yield of ethanol, while Malt C gave the poorest yield.

Figure 16. Fermentation performance for worts from brews with under-modified malt adjuncts

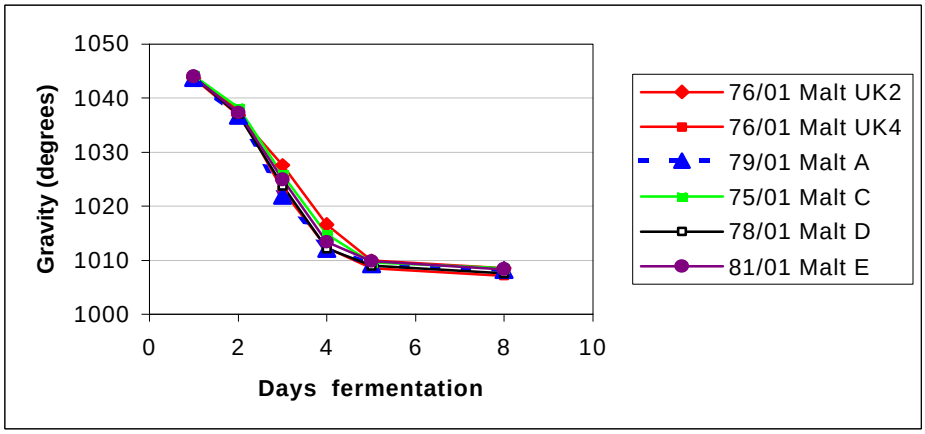


Table 14. Beer analyses - under-modified malt "adjunct" brews

Malt	UK2	UK4	A	C	D	E
Brew No.	**76/01**	**88/01**	**79/01**	**75/01**	**78/01**	**87/01**
QA Ref. No.	**3719/01**	**4187/01**	**3734/01**	**3718/01**	**3733/01**	**4186/01**
PH	4.09	4.09	4.06	4.15	4.07	4.12
Colour (°EBC)	9.3	9.4	9.7	8.8	8.4	8.1
Present Gravity (°)	7.76	6.83	7.59	7.82	7.15	7.52
Attenuation limit (°)	8.14	7.17	7.97	8.20	7.58	7.67
Head Retention Value (Nibem) (sec)	78 171 222	88 168 244	27 146 169	75 153 221	68 196 223	70 150 236
Bitterness (BU)	21	21	21	23	22	21
Free Amino Nitrogen (mg/litre)	56.0	53.0	57.0	61.0	53.8	45.1
Total Soluble Nitrogen (mg/litre)	609	639	690	621	642	570
Ethanol (%)	4.72	4.87	4.73	4.60	4.70	4.56
Total yield of ethanol (kg)	4.460	4.724	4.588	4.393	4.512	4.628
Haze	0.24	0.33	0.26	0.26	0.22	0.21

5. DISCUSSION

The basis of selection of the six test malts was that all had standard analytical specifications (for those quality parameters most widely used in commercial trading) within a relatively narrow band, although they were produced from barleys grown in different areas of the world. All were used commercially to produce similar premium lager beers with similar profiles for standard chemical analyses, although with some differences in flavour, largely due to the different yeasts used by the individual brewing companies. Many of the brewers provided at least two malts, both from different growing areas.

In spite of the similarity in standard analyses, the malts behaved very differently during processing when judged by a number of processability indices, both in the brewhouse and during fermentation. Malt UK4, on the one hand, was very easy to process and gave good yields of ethanol, while Malt E gave lautering difficulties and a less fermentable extract. The behaviour of each malt is summarised below and also in **Table 15** (see Annex 1).

Malt UK2

This malt was average in the predictive tests (β-glucan, mealiness, LTm homogeneity and filtration rate).
Run-off in the all-malt brew was fair, but wort clarity was excellent and the yield of extract was also very good.
In the maize brews, run-off was again fair, but wort clarity and extract yield were once again very good.
With the under-modified adjunct brews, both run-off and clarity were very good and the extract yield was moderate.
Fermentation performance was good in all the brews. The yield of ethanol was good or very good for all brews.
Summary – good all-round performance

Malt UK4

This malt did extremely well in the predictive tests. It had the lowest β-glucan content and the fastest filtration. Mealiness was average, but it was the most homogenous of the malts tested.
Run-off performance was excellent for all brews and there were no problems with wort turbidity .
Extract yield was good in all three sets of brews.
Fermentation performance was good in both all-malt and maize brews. The yield of ethanol was very good for each brew.
Summary – an excellent all-round performance.

Malt A

This malt had a higher nitrogen content than the other malts and did not perform as well in the predictive tests. Its β-glucan content was next to the highest, mealiness and homogeneity were low, and filtration was slow. However, it performed well in the brewhouse in all cases. Run-off and wort clarity was good for all the brews and extract yield was generally good, although only fair for the all-malt brew. Possibly the very high glucanase activity of this malt compensated

in part for the higher glucan content. Fermentation performance and yield of ethanol was also good for all brews.
Summary – a good all-round performance.

Malt C
Malt C did not perform well in the predictive tests. It had the highest β-glucan content of all the malts. Mealiness and homogeneity were average, but filtration was slow. Run-off performance was good in the all-malt and under-modified malt brews, but only fair with the maize brew. There were distinct turbidity problems in both the all-malt and the under-modified adjunct brews. Fermentation performance in the maize brew was significantly poorer than for the other malts. Extract yields were average but yields of ethanol were poor.
Summary- some processing problems, particularly with clarity and possibly with fermentation also.

Malt D
Malt D's performance in the predictive tests was mixed. β-glucan content was very low, and it filtered quickly. It did not do so well in the LTm tests - mealiness was relatively low and it was the least homogenous of the malts tested. In the actual brews, performance was generally good, except for run-off in the all malt-brew, which was relatively poor. Extract yield was lower than the others for the maize brew but yields of ethanol were good for all brews.
Summary – generally good performance but there could be problems with run-off

Malt E
Malt E's performance in the predictive tests was fairly average, with moderate β-glucan content, and average scores for mealiness and homogeneity. Filtration was , however, very slow. This was reflected in the brewing trials, where this malt gave the poorest performance. Run-off was poor in the all-malt brew and turbidity was high throughout lautering, although the clarity of the final sweet wort was quite good. Extract yield was very good, but this did not translate through to a good yield of ethanol. There was evidence of similar run-off and turbidity problems with the maize brew. Extract yield was again very good but ethanol was low, suggesting that the extract was not completely fermentable..
With the under-modified malt brews run-off and turbidity were again poor. As before, there was no correlation between extract yield, which was good, and ethanol yield, which was below average.
There were indications of potential fermentation problems with the maize brews.
Summary – processing problems with both run-off and clarity and potentially also with fermentation. Below average yield of ethanol.

A numerical value can also be assigned to these descriptors in order to obtain an overall "processability" score;

- Poor = 0
- Fair = 1
- Good = 2
- Very good = 3

Using this scoring method, the six malts are ranked as follows;

- UK4 = 39
- UK2 = 37
- A = 33
- D = 30
- E = 19
- C = 16

Predictive tests

The test malts showed more variation when subjected to certain non-standard tests which are designed to predict, to a greater or lesser extent, the behaviour of the malt during processing. Part of the objectives of this project were to identify which laboratory tests, whether standard or non-standard, were most useful for such predictions. Correlation coefficients for several standard and non-standard malt parameters with the overall processability scores are shown in **Table 16.** These values support the accepted view that standard trading specifications such as Hot Water Extract do not predict processability, and indicate that "functional" parameters such as viscosity and Vmax are more useful in this respect. However, statistical interpretations based on such a small number of samples can only be regarded as tentative. It is most probable that the parameters in the middle of Table 16 (that is, the ones giving neither a significant correlation nor an obvious lack of correlation) were heavily influenced by the particular samples in this sample set. The table does suggest, however, that a combination of a parameter influenced by enzyme activity (eg Vmax) with one which relates to physical endosperm structure (such as nitrogen, homogeneity or mealiness) might be a useful predictive tool.

Table 16. Correlations for a number of malt parameters with overall processability

Parameter	Correlation coefficient	Type
Viscosity	0.7162	linear
Vmax	0.6046	exponential
DP (WK)	0.4776	linear
KI	0.4156	linear
Homogeneity (Calcofluor)	0.3035	linear
β-glucan (SKALAR)	0.2649	linear
Total nitrogen	0.1359	linear
LTm mealiness	0.0566	linear
Modification (Calcofluor)	0.0207	linear
LTm homogeneity	0.0197	linear
β-glucan (McCleary)	0.0102	linear
Friability	0.0079	linear
HWE coarse	0.0067	linear
β-glucanase	0.0002	linear

An attempt was made to examine the proportion of variation which could be explained by certain combinations of parameters using multiple regressions. However, it soon became evident that the small sample set was generating spurious results and this approach was abandoned for generating quantitative correlations. Nevertheless, there were some qualitative indications. Results of principal components analysis are shown in **Figures 17 and 18.**

Figure 17 gives an indication as to which tests give the most information. Tests which lie in the same sector are giving similar information, and those which lie further from the centre give more information than those in the centre. As would be expected, those tests which measure physical modification of the endosperm (Calcofluor staining, LTm and friability) lie close together in the same sector. They are also at the opposite end of the x-axis to TN, with which they are negatively correlated. Similarly, the enzyme-based tests (β-glucanase, DP and DU) all lie in the same sector. This figure also suggests that Vmax and viscosity measurements are amongst the most useful, agreeing with the correlations shown in Table 17. However, as already mentioned, it must be emphasised that these can only be regarded as tentative suggestions, due to the small number of samples.

Figure 18 provides some indication as to how different the samples were from each other. Again, these must be treated with caution because of the small number of samples. This approach identifies Malt UK4 (which had the best processability score) and Malt A, and to a lesser extent, Malt B (which was not brewed with) and Malt C (which had the lowest processability score) as being the most different from the rest of the set. Combining the two figures suggests that the main distinguishing feature of Malt UK4 is its homogeneity and physical modification. Malt A is distinguished by its high nitrogen content and comparatively poor physical modification.

6. CONCLUSIONS

The findings of this project support the concept (widely held in the industry but without a great deal of firm evidence) that malts which appear similar by standard analytical parameters can nevertheless vary significantly in the ease and efficiency with which they can be processed. Within the limitations imposed by the necessarily small numbers of samples which could be accommodated within this project, the results suggest that a combination of a small number of tests, chosen to measure quite distinct aspects of processability, would be of most value in predicting processability. Many of the tests currently demanded within a typical malt specification are providing the same information as each other and thus of extra little value to the brewer. Where a number of available tests are influenced by the same factors, the speed and reliability of the test should be the main factors influencing the choice of test.

Any comparison of this nature is inevitably limited by the number of malt samples which can be processed. This study was limited to 9 commercial malts, of which only 6 were brewed under each set of conditions. The results cannot therefore be

regarded as a statistical survey of commercial malts. However, some conclusions can be drawn.

- Malts which are similar with regards to standard specifications can behave differently during processing
- It is encouraging to note that the two best performing malt were from the UK. However, significantly more samples would need to be tested in order to draw any firm conclusions as to any relationship between the geographical origin of a barley and its inherent “maltability”.
- None of the predictive laboratory tests used was foolproof. However, each gave some useful predictions concerning processing performance. The malt which performed best in the brewing trials (UK4) was also the best in 3 out of the 4 predictive tests. The malt which had the poorest brewing performance (malt E) was picked up by the filtration test (Vmax). Malt C, which also displayed problems with processing, was picked up by the filtration test and the β-glucan analysis.
- A combination of two or three tests which were based on different aspects of processability (for example, enzyme activity and physical modification) should provide a more useful basis for predicting processability than a battery of tests which give overlapping information. A larger number of malts would need to be processed in order to identify the most suitable tests.
- Some predictive tests, in particular those like friability and LTm which assess endosperm structure, can give misleading results with barleys from certain geographical areas. For example, malt A, which performed well in all the brewing trials, did not score highly in any of the predictive tests. This could be due to differences in grain shape or in endosperm structure. Possibly calibrations for such tests could be adapted or extended to include varieties from different growing areas. On the other hand, it is possible that some other characteristic of these malts (for example, high enzyme levels) could render physical modification less of a barrier to processability.

Study design

- The current study utilised 3 different brewing protocols in an attempt to investigate different aspects of processability. Analysis of the results indicates that the maize and under-modified brewing protocols did not, in fact, provide any additional information beyond that gained from the high malt protocol, although they did support and re-enforce those findings. If this work were to be extended or repeated , it is recommended that a single, high malt, regime would be sufficient, which would allow significantly more malts to be compared.
- Further information on brewhouse performance could be obtained by comparing brews in which lautering was managed in order to obtain sufficient good quality wort for fermentation (as in the present study) with ones in which run-off was allowed to proceed without intervention.

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ANNEX 1. **Table 6.** **Analytical data for a range of quality parameters (denotes used for brewing)**

Malt	**UK1**	**UK2**	**UK3**	**UK4**	**A**	**B**	**C**	**D**	**E**
Supplier (brewer)	1	2	3	4	5	5	2	3	4
Moisture (%)	5.9	5.3	8.2	6.5	6.0	4.8	4.5	6.4	4.6
HWE_2 (%)	81.7	83.1	82.8	81.5	81.9	81.2	81.5	82.2	83.2
HWE_{10} (%)	80.8	82.4	82.5	81.3	80.6	80.2	81.2	81.3	82.3
Fine/coarse diff. (%)	1.0	0.7	0.4	0.3	1.3	1.1	0.3	0.9	0.9
Colour (EBC)	3.8	3.7	3.5	4.4	3.7	4.2	4.9	3.7	4.1
Total soluble Nitrogen (%)	0.71	0.69	0.71	0.75	0.73	0.68	0.77	0.76	0.72
Total nitrogen (%)	1.62	1.64	1.65	1.68	1.84	1.75	1.63	1.69	1.64
Kolbach Index (%)	44	42	43	44	40	39	48	45	44
Free amino nitrogen (%)	0.14	0.14	0.13	0.14	0.14	0.14	0.16	0.15	0.13
pH	5.98	5.90	5.87	5.87	5.98	5.87	5.97	5.92	5.92
Fermentability (%)	72	72	71	72	72	73	71	72	71
β-glucanase (IRV units)	681	169	884	679	1103	1542		785	482
Viscosity (mPa)	1.53	1.53	1.52	1.49	1.52	1.50	1.56	1.53	1.54
β-glucan of lab wort (mg/litre)	40	38	31	0	83	64	90	12	32
β-glucan by SKALAR	125	85	125	15	185	165		60	145
Vmax (g)	48	42	48	136	38	55	27	51	24
DP (°WK)	291	298	268	326	372	286	253	285	274
DU dry	39	41	43	46	50	61		47	59
Friability (%)	75	81	84	92	72	82	82	78	84
Homogeneity by friabilimeter (%)	92	95	96	99	92	96	99	98	97
Mealiness -LTm (%)	88	85	87	84	69	90	83	80	87
Homogeneity – LTm (%)	76	65	86	97	39	85	54	46	84
Modification by calcofluor (%)	96	98	96	100	91	97		99	97
Homogeneity by calcofluor (%)	78	83	70	100	73	82		82	78

Table . Correlation between predictive tests

	Vmax	β-glucan Skalar	β-glucan McCleary	LTm mealiness	LTM homogeneity	Calcofluor modification	Calcofluor homogeneity	Friability modification	Friability homogeneity
Vmax	1	0.52	0.36	<0.01	0.25	0.27	0.73	0.39	0.30
β-glucan (Skalar	0.52	1	0.81	0.02	0.06	0.68	0.60	0.36	0.38
β-glucan (McCleary)	0.36	0.81	1	0.10	0.25	0.74	0.35	0.27	0.06
LTm (mealiness)	<0.01	0.02	0.10	1	0.59	0.36	0.03	0.26	0.03
LTM homogeneity	0.25	0.06	0.25	0.59	1	0.25	0.13	0.56	0.05
Calcofluor modification	0.27	0.68	0.74	0.36	0.25	1	0.51	0.52	0.50
Calcofluor homogeneity	0.73	0.60	0.35	0.03	0.13	0.51	1	0.43	0.33
Friability modification	0.39	0.36	0.27	0.26	0.56	0.52	0.43	1	0.58
Friability homogeneity	0.30	0.38	0.06	0.03	0.05	0.50	0.33	0.58	1

Table 16. Summary of brewhouse and fermentation performance

Parameter	UK2			UK4			A			C			D			E		
	High malt	Maize	Under-mod. malt	High malt	Maize	Under-mod. malt	High malt	Maize	Under-mod. malt	High malt	Maize	Under-mod. malt	High malt	Maize	Under-mod. malt	High malt	Maize	Under-mod. malt
Run-off	fair	fair	good	good	good	good	good	good	good	good	fair	good	poor	good	good	poor	poor	poor
Wort clarity	good	good	good	good	fair	fair	good	good	good	poor	fair	poor	good	good	good	poor	poor	poor
Extract yield	very good	very good	Fair	good	good	good	fair	fair	good	fair	good	good	good	poor	good	very good	very good	very good
Fermentation Performance	good	good	good	good	good	good	good	good	good	good	fair	good	good	good	good	good	fair	good
Specific Ethanol yield /litre	very good	good	good	Very good	Very good	Very good	good	good	good	poor	poor	poor	good	good	good	poor	poor	poor
Total ethanol yield / brew	Very good	Very good	fair	Very good	good	Very good	fair	good	good	poor	good	poor	good	fair	fair	fair	good	good

Figure 17. Principal Components Analysis of analytical and processability data . (1) analytical parameters

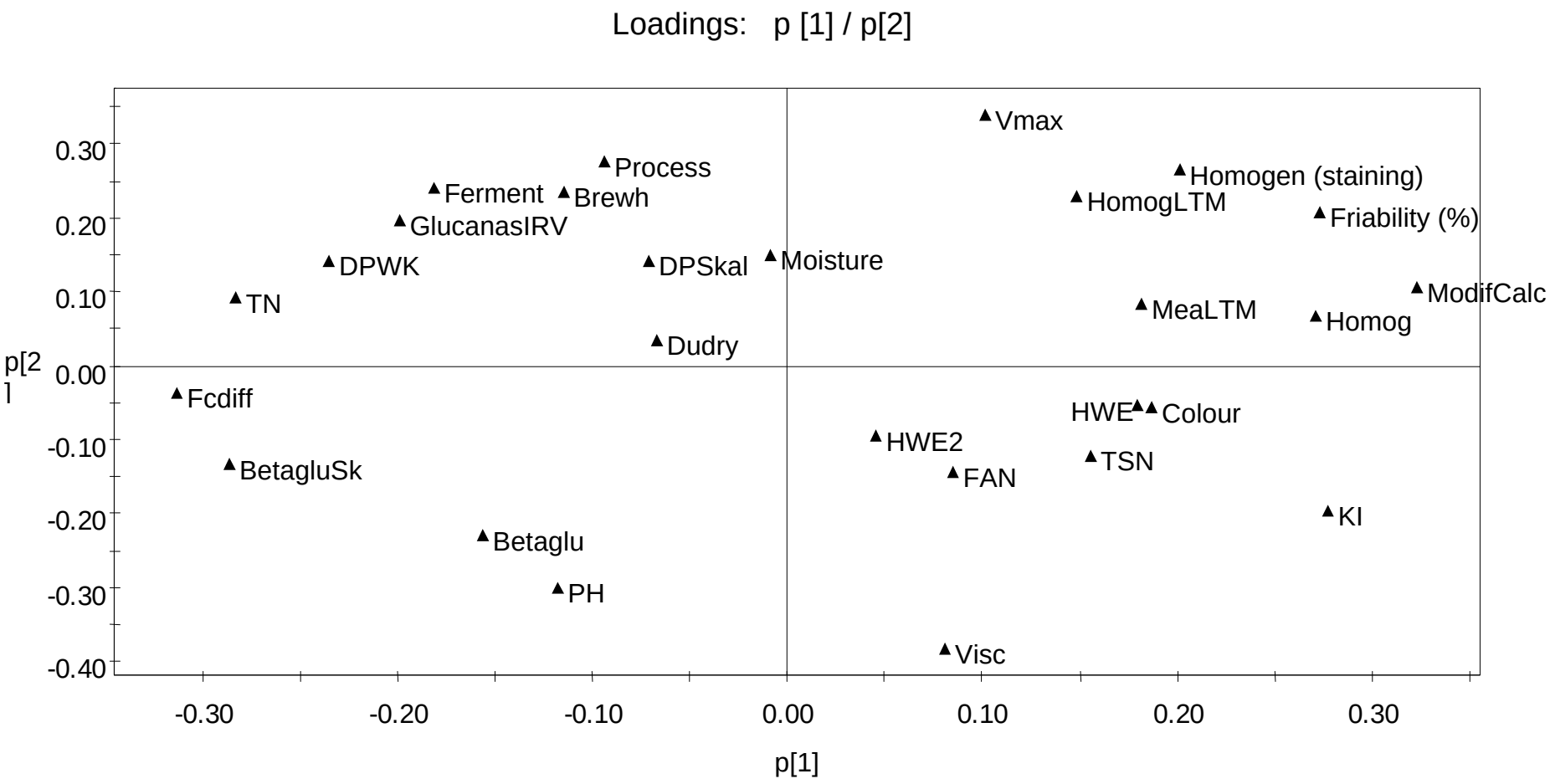

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Figure 18. Principal Components Analysis of analytical and processability data. (2) Malts