Creating markets for recycled resources

Colourite Project – Maximising Cullet Additions in the Glass Container Industry

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Final Report

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Executive Summary

Glass in an eminently recyclable material. The UK's waste stream is estimated to contain upwards of 2.5 million tonnes of the material, principally containers used to package food and drink. Efforts to recover this valuable resource began over 35 years ago with the introduction of the first bottle bank. The importance of recycling in achieving a more sustainable lifestyle is now government policy and a number of legislative instruments are in place to promote the activity. Whilst recovered glass has many potential uses, redirecting it back to the melting furnaces represents perhaps the best environmental option as significant raw materials and energy savings are made if this route is adopted. Unfortunately several factors conspire to frustrate this desirable outcome. One of the major barriers preventing recovered glass being directed to the melting furnaces centres on the mode of collection and the economics thereof. Essentially the environmentally favourable re-melting option is best served by colour separated collection schemes whilst other, less environmentally sound options, are able to accept colour mixed glass collected by schemes which are generally perceived to be cheaper to operate.

The work reported here represents an 18 month long WRAP supported collaboration from project partners which included glass processors, container glass manufacturers and retailers and various technical organizations aimed at providing a solution to the apparent conflict of interest between high collection rates and lower environmental benefits. Essentially the project is designed to maximize the amount of furnace ready cullet that can be recovered from glass waste streams collected in an increasingly colour-mixed form. In simple terms the UK has a large unsatisfied demand for clear glass but an oversupply of green glass. Mixed colour collection systems are effective in collecting large quantities of glass but, once mixed, separating the valuable clear glass is problematic and cross contamination with green glass becomes a major issue.

The project took a pragmatic view of the glass collection and recycling market and, accepting that glass would increasingly be collected by mixed colour schemes, sought ways to maximise the amount of cullet that the container glass manufacturers could incorporate in their furnaces from these predominantly mixed sources.

The project initially looked at technical solutions which would allow clear glass furnaces to produce an acceptable product from a feedstock containing colour-contaminated cullet. This technical phase of the project began with a detailed literature search, progressed through laboratory-scale melting and culminated in full-scale manufacturing trials.

The work was not however confined to a purely technological solution to decolourising glass. The container glass manufacturers are providing containers for the food and drink market and as such in fierce competition with other packaging materials. In this field glass has some distinct advantages over its rivals and the manufacturers obviously play to their strengths in promoting their product. The glass marketers have long stressed that the clarity and perceived purity of glass is its main selling point and the manufacturers continually strive to improve the colour quality of their products. The project took the bold step of challenging the container glass manufacturers long held beliefs in the overriding importance of colour integrity. To this end the expertise of the Psychology Department of University of Leeds was enlisted and a series of customer perception studies completed to determine the actual importance of clarity or otherwise of the glass packaging in relation to the product it contains.

The project could thus be seen as approaching the problem from both ends of the quality spectrum. How good a glass can be made by the use of decolourants and how good does that glass really need to be to satisfy the buying consumer as opposed to the marketers?

The outcome of the work is that technical solutions can help maximise cullet addition. Clear glass of an acceptable quality can be produced from feedstock that contains significant proportions of colour-contaminated flint cullet. The desired quality can be achieved cost effectively by the addition to the melt of commercially available decolourisers.

However a prerequisite to effectively countering the effects of colour tainted cullet is a measure of the degree of its colour contamination. Obtaining a representative sample of cullet for quality assessment is a difficult and labour intensive process and as a consequence the container glass manufacturer often merely assumes that the cullet is "up to spec" and accepts the consignment without any further quality checks. This work was able to demonstrate that for the purposes of colour determination a much smaller sample would provide adequate information and a rapid test procedure could be developed which would allow the container glass manufacturer to accurately calculate the appropriate level of decolourisers. A specification for colour contamination of processed glass was developed making use of this sampling procedure and was agreed by both container manufacturers and glass processors.

Predicting the effects of adding decolourises to an already complex batch recipe involves some very intricate calculations. An important output from the project is a very user-friendly Excel based programme that will quickly guide busy furnace managers through this procedure. The programme was the subject of an industry workshop training session and the programme has proven to be popular with users and a further workshop has been called for.

The customer perception work has proven to be a vital element in the project as it has demonstrated that in many cases the glass industry has been over-engineering its products in respect of colour integrity. The container glass manufacturer's eye for a brilliant glass is not usually matched by that of the consumer's whose focus is more often drawn to the container's label or other feature. In many instances the container glass manufacturers' or brand owner's concerns for the importance of a pristine container in which to best show their products are misplaced.

Contents

1 Introduction

This report concludes the work undertaken in an 18 month project supported by glass processors, container glass manufacturers and retailers. Glass Technology Services Ltd (GTS) undertook the project management and glass technology research, with additional support from the following organisations:

- University of Leeds, School of Psychology
- Faraday Packaging Partnership
- University of Sheffield, Department of Materials Engineering
- Society of Glass Technology
- British Glass

This project was aptly referred to as 'Colourite' with a full project title of 'Maximising Cullet Additions in the Glass Container Industry – GLA0039', its primary objective being "to continue and bring to fruition the potential to increase glass recycling by further understanding of the possibility of controlling glass colour with increased levels of post consumer glass."

This project was a continuation of a previous WRAP supported project 'Feasibility Study for the Reduction of Colour within the Glass Furnace – GLA0032" which investigated the feasibility of using several possible techniques to neutralise/reduce perceived colour in clear glass furnace production. This earlier project was research orientated and addressed a key issue which has traditionally restricted growth in glass recycling - the imbalance between the colour mix of glass collected and the actual colours produced by the UK container industry. The project was carried out jointly by GTS and the University of Sheffield's Engineering Materials Department. The project was guided by a steering committee which included a number of the UK's leading glass container manufacturers.

A worldwide literature survey was completed which reviewed reported methods for reducing the colour of clear container glass, including possible methods from other industries such as metal extraction. A series of laboratory-scale trials was then undertaken to assess the viability of a more comprehensive research programme. The six techniques below were then chosen for examination:

- dilution, decolourising and colour balance
- crystallisation followed by phase separation
- alkali fusion (separating out pure silica)
- alternative colouring – irradiation (the use of x-ray energy)
- reductive melting
- electrochemistry

The project concluded that the first four options offered both short and long term potential, with dilution, decolourising and colour balance identified as having the most potential for increasing primary recycling and thus being the priority for further research.

This current project was subsequently commissioned to develop and explore the possibility of industrial implementation of the dilution, decolouring and colour balance approach. The aim was to increase the use of post consumer waste glass in the melting process. The project initially reviewed current industrial practices and identified any barriers to increased cullet use. The project then sought to develop practices and understanding which would allow the container glass manufacturers to strive towards maximum utilisation of available recycled glass. Finally the project considered the consumer perception of glass colour and whether this is a potential barrier to maximising cullet additions if the quality of glass colour was sacrificed.

1.1 Project Objectives

This research and development project has the objective of maximising the level of post consumer glass used in container glass production. This objective is consistent will one of WRAP's glass priorities in promoting closed loop recycling.

Customer acceptance of a new product is critical to success. Whilst is possible to control the colour of glass some degree of detriment to light transmission may be inevitable. The initial study had suggested that it was possible to present some products in glass containers that were slightly coloured or had lower light transmission, without affecting the product's market position. Gaining a better understanding of market psychology and customer perception was thus a key objective of the current project.

Several technical barriers prevent the maximisation of the level of post consumer cullet used in glass production. The identification of these barriers and the provision of technical or marketing solutions to overcome them was another important objective

1.2 Project Work Packages

In order to address the project objectives the project was split into two major work areas, as follows:

A. Technical and commercial barriers;
B. Industrial implementation.

The project objectives were delivered by undertaking the following sub tasks:

1.2.1 Technical and Commercial Barriers - Task Details

This work area considered technical and commercial barriers including the buying decisions of consumers in respect to the glass colour quality and practical considerations of the commercial cullet collection schemes and their ability to deliver good quality product to the glass manufacturers. This work area was sub divided into the following tasks:

1.2.1.1 European Glass Survey

This task involved obtaining glass container samples produced in other European countries and assessing the colour quality and variation that is found between regions and product type. The task involved physical colour measurements which were then used as the subjective basis for colour perception comparison testing.

1.2.1.2 Consumer Perception of Colour

This task involved gaining an understanding of the market psychology in respect of consumer perception of colour as it impacts on glass packaged products. The study aimed to quantify how changes in colour, often seemingly very subtle, can influence customers buying intentions. The task was conducted by University of Leeds, School of Psychology under the guidance of Dr Steve Westerman.

1.2.1.3 Prediction of Future Demands

This task entailed predicting the UK manufacturers' future colour demand and was based on a comprehensive review of consumer tends and markets.

1.2.1.4 Prediction of Future Collections

This task involved predicting the future volumes and colour profile of the glass that will comprise the UK's waste glass stream. The quality and availability of flint glass is critically dependant on the mode of collection. The task sought to quantify the effects that the rapid growth in kerbside collection, with its attendant increase in mixed glass, would have on available cullet quality.

1.2.2 Industrial Implementation - Task Details

This work area entailed full-scale factory trials and the necessary preparatory stages leading to those trials. The work area was sub divided into the following sub tasks:

1.2.2.1 Benchmarking of Current Practice

This task involved a review of the decolouriser systems that have been used in the past and currently used systems including an examination of their effectiveness. This information was used as a benchmark to further develop suitable decolouriser systems. This task initially involved the collation of historical operating data from the project partners to understand what has been tried before and reasons why it was not adopted.

1.2.2.2 Specification of Furnace Ready Cullet

This task involved the development and validation of a specification for furnace ready cullet by utilising previously adopted specifications such as Society of Glass Technology (SGT) specification and specifications used between cullet suppliers and container glass manufacturers. Before this project the limitation to using higher levels of post consumer in container glass production was the quality of available recycled glass in terms of its contamination in respect of colour, organic and inorganic matter content. This project readdressed the issue of colour contamination with information and guidance on the critical contaminants such as organic and inorganic. A method of cullet sampling was developed utilising knowledge gleaned from previous WRAP supported work to develop a suitable cullet sampling method.

The output from this task will act as a precursor for an industry-wide accepted specification and testing method. Eventually this could be adopted into a more formal publication such as one of the Publicly Available Specifications (PAS).

This task was conducted in conjunction with the Society of Glass Technology with the guidance of Alan Reynolds.

1.2.2.3 Investigation of Colour Control

This task involved a practical investigation of the ability to control colour by existing and new chemical additions to the batch recipe. Making such experimental changes on a working furnace is not practical as they typically have a melting capacity in excess of 250 tonnes per day. Therefore, GTS undertook a number of melting trails on a laboratory-scale, to determine the effect of such variables as:

- Cullet sources
- Cullet level
- Cullet specification including colour, organics and inorganics contamination
- Decolouriser system including different chemicals and minerals
- Batch compositional changes required to counteract higher levels of cullet
- Furnace parameters

The information and data from this task was used for the development of a predictive model and for the industrial trials.

1.2.2.4 Predictive Colour Model

This task involved the development of a model for the prediction of glass colour, based on information and data gathered during the course of the project. The model will promote the adoption of the colouring or decolourising systems developed in the course of this project and act as a tool to give managers/operatives responsible for batch formulation the confidence to utilise the maximum level of available cullet. The model takes into account the concentrations of various colouring ions present, their absorption spectra and their redox interactions. The aim of the model is to enable the calculation of the optimum concentrations of additives needed in the batch in order to produce a neutral absorption spectrum, based on the level of added cullet.

This task was conducted by the University of Sheffield, Department of Materials Engineering under the guidance of Dr John Parker.

1.2.2.5 Industrial Trials

This task involved undertaking industrial trials of decolouriser systems on working container furnaces. The trials included extensive monitoring of all inputs to the furnace, and were the first opportunity to trial the cullet sampling method and the furnace ready cullet specification.

1.2.2.6 Impact of Recycling

This task involved analysing data on the levels of heavy metals in container glass manufactured in the UK. The analysis included consideration of the consequences of mixed colours and their incorporation into different waste streams (for flint, amber, green etc).

1.2.3 Dissemination

During the course of the project quarterly project partners meetings were held to disseminate work plans and progress to date. Progress and interim reports were published and circulated to project partners. Training, aimed at furnace/batch managers from the container manufacturers, was delivered by means of practical sessions during which the predictive model and related work was explained. Dissemination will continue after the completion date of the project (section 5).

2 Technical and Commercial Barriers

This section relates to the work that was carried out to investigate the technical and commercial barriers to increasing cullet additions in container glass. The section reports on the colour of glass containers currently used for food and drink packaging in Europe, the consumer perception of glass colour and the prediction of future UK production and waste arisings of container glass.

2.1 European Glass Survey

This task included the collection of numerous containers from glass manufacturers and supermarkets. The International Technical Centre for Bottling and related Packaging (CETIE), via its working group (WG1) for specification of bottles & jars, assisted the project by requesting production samples from across Europe. As a result GTS received numerous samples from European glass container manufacturers and was able to make comparative colour measurements. The results of the colour survey will be shared with the WG1 committee to improve the understanding of the spread of colour across Europe.

Initially, containers of all three colours (flint, green & amber) were collected for the colour measurement study; however, it soon became apparent that the colour of green and amber were product and brand dependant and, as these glasses display such a large range of colour coordinates, it was agreed that there was no value in reporting the results for the green and amber containers. Therefore, only measurements of flint containers were undertaken.

2.1.1 Introduction – Glass Colour Mechanisms

2.1.1.1 Glass Colour Mechanism

Glass can be coloured by several different mechanisms. These include dissolved ions (predominantly transition metal and rare earth ions), metal-anion complexes such as the iron-sulphide amber (brown in colour) and finally combinations of different redox[1] species.

The most commonly occurring transition metals that generate colour in container glass are Iron (Fe), Chromium (Cr), Cobalt (Co) and Nickel (Ni). The precise colour introduced depends on the oxidation state of the colouring ion and this in turn can be influenced by the batch composition and melting conditions. Normally iron will give a dull greenish colour to the glass, chromium a brighter green, cobalt a blue and nickel a brown/grey shade. The intensity of the colour depends primarily on the concentration of the species. Table 1 shows the typical oxides that are responsible for the glass colour in the flint, green and amber container glass.

In green glass the colour is introduced by chromic and iron oxides. The concentrations required to introduce colour are relatively low; for example a chromium green glass may contain just 0.25 wt% chromic oxide as a colorant. Chromium can exist in a 3+ and 6+ states, the latter state is generally regarded as unacceptable in container glass since the free ion has been shown to be carcinogenic. In the absence of other species some Cr^{6+} will often form with typical melting conditions. However, the Cr^{6+} tends to oxidise any ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), and in so doing is reduced to the Cr^{3+} state, the green chromophore. Most Cr coloured green glasses therefore also have significant levels of iron addition which help to reinforce the green colour.

An amber glass derives its colour from an iron-sulphide balance brought about by the reduced state of the glass composition with the introduction of iron in the presence of sulphide species. Amber colour is difficult control as the batch chemistry and glass temperature need to be controlled within relatively tight limits.

[1] Term used to describe the balance between the reducing and oxidising species in a glass melt, positive redox is an oxidised state, whilst negative is a reduced state.

In clear glass low concentrations of the transition metals will cause a noticeable change of colour; this is particularly observable in the base of the container where the glass thickness is greatest. Iron is the most common impurity and must be maintained at low levels in the glass composition, the limits for which are typically set lower for containers aimed at higher value products. Iron, in its normal concentrations and oxidation states, produces a greenish hue although oxidation makes this a pale yellow and reduction gives a bluish hue (or amber in the presence of sulphate as a refining agent). In general a slightly oxidised state is preferred and the resultant iron colour is balanced by adding low concentrations of cobalt (blue) and selenium (pink) to produce a neutral colour. The cobalt and selenium are termed as decolourisers.

Glass Colour	Fe_2O_3 (%)	Cr_2O_3 (%)	SO_3 (%)
Flint	0.07	0.002	0.21
Green	0.36	0.24	0.07
Amber	0.42	0.02	0.07

Table 1: Typical level of colorants found in commercial container glass.

2.1.1.2 Container Glass Decolouriser Mechanism

Despite all the precautions taken by the glassmaker, the contamination of all but the most sophisticated optical glasses by iron and other transition metals is an inevitable consequence of glass melting. The iron is naturally present in some of the raw materials and cullet. In addition as the furnace refractory linings erode they can also introduce iron into the glass.

Decolourants act by masking the effects of colour imparting impurities in the batch materials and cullet. The most common colour causing impurities are chromium, iron and manganese. Increasingly the supply of clear glass cullet contains significant proportions of coloured glasses which obviously introduce their respective colorants to the clear furnace. Decolourisers produce complementary colours to mask those of the impurities[2], producing a grey shade which the eye perceives as colourless. This technique has only a limited effect and eventually a loss of light transmission becomes noticeable.

Glass is decolourised by two methods namely chemical and physical[3]. Chemical decolourising is usually taken to mean oxidising the iron to its ferric state (Fe^{3+}) from its ferrous state (Fe^{2+}). Iron can be present in a glass in both its oxidation states, Fe^{2+} and Fe^{3+}, each of which give rise to different optical absorptions, and hence, in addition to the overall Fe content, the relative levels of Fe^{2+} and Fe^{3+} ions will also affect the colour of the glass.

Figure 1 shows the light transmission for two container glasses melted under oxidised and reduced conditions[4]. Curve 2 represents the reduced ferrous form and its lower transmission is a result of its ability to absorb light, especially in the red region of the spectrum. As it removes the red portion of the spectrum the ferrous addition imparts a strong blue tint to the glass. The ferric form absorbs weakly in the red and blue ends of the visible spectrum, giving the glass a green yellow tint. As The oxidised ferric absorptions are weaker than their corresponding reduced ferrous counterparts the minimisation of colour is best achieved when the majority of iron in glass is present in its Ferric (Fe^{3+}) form. Generally the iron redox ratio in container glass is 20% Fe^{2+} and 80% Fe^{3+}.

The absorption by the ferrous form is between ten to fifteen times stronger than the ferric form. Chemical decolourisers act by producing oxidising glass melting conditions which drive most of the iron into the pale green ferric form. Oxidising agents such as arsenic oxide, antimony oxides, nitrates or sulphates are used as batch materials to achieve these conditions.

[2] M. Muhlbauer, Decolorizing crystal glass, *Bull. Amer. Ceram. Soc.* Vol. 74, No. 5, 1995, p.70.
[3] P.J. Doyle, Decolourising glass, British Glass Industrial Research Association, Literature Review No 12, 1981.
[4] Volf, M.B., Chemical Approach to Glass, Elsevier, 1984.

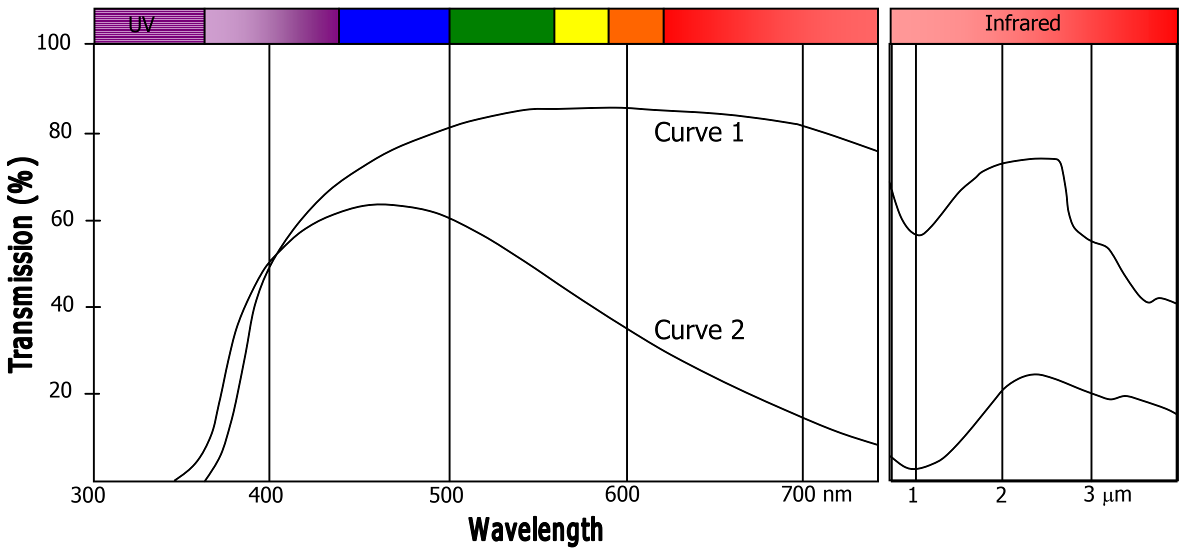

Figure 1: **Curve 1 Soda-lime-silica (typical container glass) glass melted under oxidised conditions with 2% Fe_2O_3 and Curve 2 same glass melted under reduced conditions.**

Physical decolourising depends on colouring the glass to cancel out the colour imparted by the iron and other impurities. The commonly used decolourisers in flint glasses[5] are selenium, cobalt, manganese, nickel and rare earth compounds such as neodymium and erbium. The physical decolourising of glass is achieved by adding a complementary colour to the glass to reduce the overall transmission of light but leave a neutral grey shade, something to which the eye is less sensitive. Figure 2 shows a complementary colour wheel used in the explanation of physical decolourising.

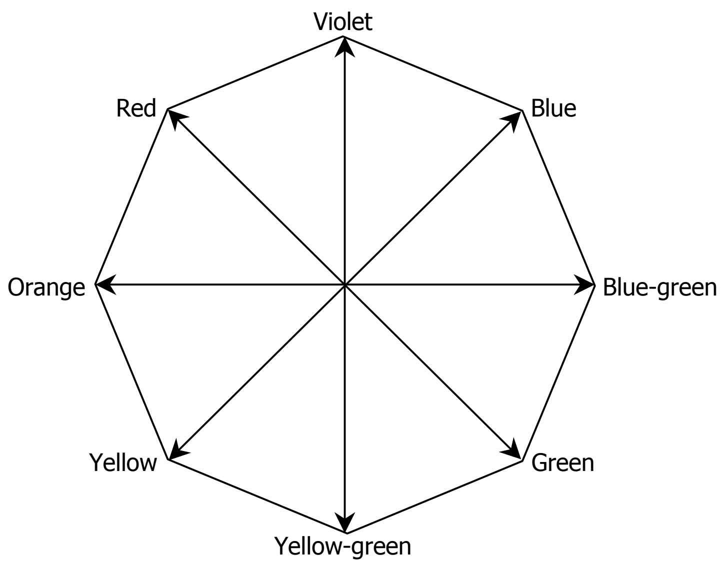

Figure 2: **Complementary colour wheel[6]**

The subject of decolourising glass is complicated by the various base compositions used in manufacture and there are a diverse range of approaches to decolourising. There are numerous publications that discuss the theory and practical approaches on glass decolourising. An excessive amount or inappropriate choice of some decolourisers can result in the glass being too dark or even sensitive to daylight (exhibiting solarisation).

[5] D. K. Hill, The decolourising of soda-lime-silica glasses, *BGIRA Information Circular*, No. 12, 1956.
[6] Muhlbauer, M., Bull. Amer. Ceram. Soc., v.74, 1995, p.70.

Selenium and cobalt are probably the most widely used decolourants for flint container glass. The selenium is typically added as elementary selenium (Se) between 0.001 & 0.005% and cobalt added as cobalt oxide (CoO) between 0.0001 & 0.0005%. Selenium introduces a pink colour that partially masks the green from the Fe^{3+}. Müller-Simon & Kircher[7] reported that 12% of the selenium was retained in the glass, with most evaporating from the batch pile as it enters the furnace and being lost in the waste gases from the furnace. It is also reported[8] that of the retained selenium only 10 to 20% is an effective decolouriser, due to the oxidation state of the selenium as shown Table 2. Selenium is a relatively expensive batch material and is classified as toxic. Selenium is required to counter the effects of green cullet in flint glass production and thus the issue raises cost and environmental concerns. There is the possibility of reducing elementary selenium additions by using selenium containing compounds such as zinc selenite[9] ($ZnSeO_3$), Elementary selenium is volatile at temperature above 400°C, whilst zinc selenite is thermally stable up to 850°C. Cobalt oxide shifts the colour towards a blue colour and is a relatively strong colorant. Cobalt oxide in combination with selenium will shift the perceived colour towards neutral (white).

← reduced		neutral	oxidised →	
Se^{2-} Colourless	Se^{2-} + Fe^{3+} Pink to amber	Se^{0} Pink	Se^{4+} Colourless	Se^{6+} Colourless

Table 2: Oxidation states of selenium observed in container glass

This project investigated practical and economic methods of decolouring flint to maximising cullet additions, which are reported in later sections of this report.

2.1.2 Colour Measurement

Ultraviolet visible (UV-Vis) spectroscopy measurements were carried out using a Camspec M350 Spectrophotometer. Prior to analysis the melted disks were polished to provide a good surface finish and a uniform thickness throughout the disk. The analysis was carried out in air between 190 nm to 1100 nm with a measurement taken every 0.5 nm.

The tristimulus values X, Y and Z are derived from the UV–Vis spectrum and are the basis for all further calculations. These values are used to calculate the chromaticity coordinates x, y and z which are a ratio of the tristimulus values and describe the hue and chroma of a glass. The chromaticity coordinates are calculated using the following equations

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z}$$

Where $x + y + z = 1$

[7] H. Müller-Simon & U. Kircher, Selenium flow in the meting of flint glass containers, Glastech. Ber., Vol. 69, No. 4, 1996, p. 107.
[8] H. Müller-Simon, J. Bauer & P. Baumann, Redox behaviour of selenium in industrial soda-lime-silica glasses, Glastech. Ber., Vol. 74, No. 10, 2001, p. 283.
[9] C. Merivale, Use of zinc selenite in glass manufacture, *Ceram. Eng. Sci. Proc.*, Vol. 17, No. 2, 1996, p71.

The chromaticity coordinates x and y along with tristimulus value Y are used to describe colour as shown in the chromaticity diagram in Figure 3. However, as the colour in flint glass is relatively faint, it is not appropriate to use such a method.

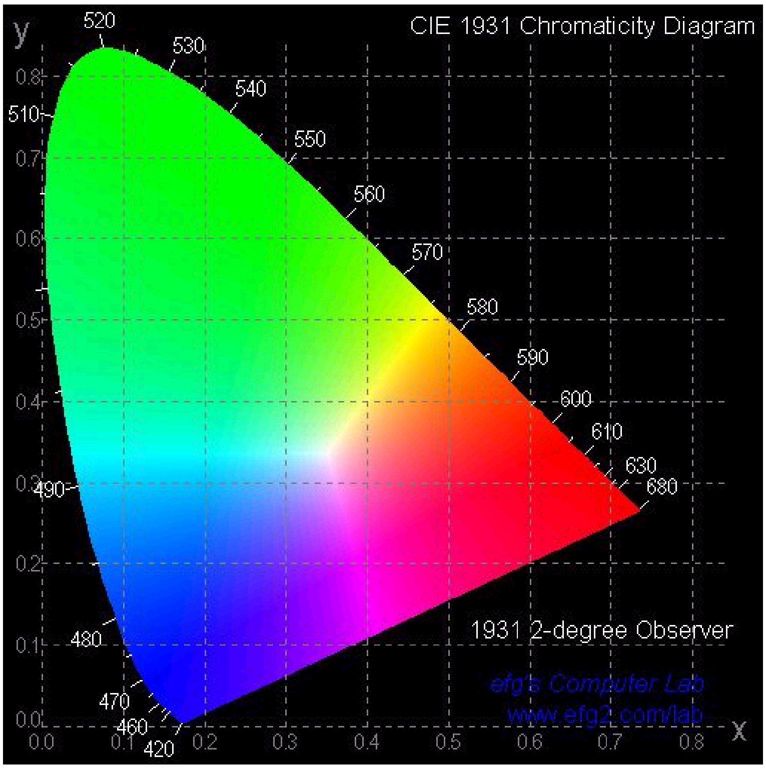

Figure 3: Chromaticity diagram for CIE (x,y,Y) colour co-ordinates.

Using data in the CIE (x,y,Y) form has drawbacks, the first is the non uniform nature of the plot, colours seen as equally different are not equally spaced on the chromaticity diagram, the second is the central region for faint or neutral colours is small. The uniform colour spaces measuring system is used to overcome the distortion of the CIE diagram. The two uniform colour spaces commonly used are the CIELUV and CIELAB systems. It is UK glass industry practice to use the CIELAB system for colour measurement including green and amber and therefore this method was adopted for reporting all colour coordinates within this project.

The CIELAB system transforms the (x,y,Y) from the chromaticity values into (L,a,b). The L axis is known as the lightness and extends from 0 (black) to 100 (white). The other two coordinates a and b represent red-green and yellow-blue respectively. Samples for which a = b = 0 are achromatic (colourless) and thus the L axis represents the achromatic scale of greys from black to white. Figure 4 shows the a & b coordinates that depict colour and the L is the vertical axis (z).

After the L*a*b coordinates have been defined it is possible to identify and locate any colour in a 3 dimensional space and to follow the progress of changes in colour.

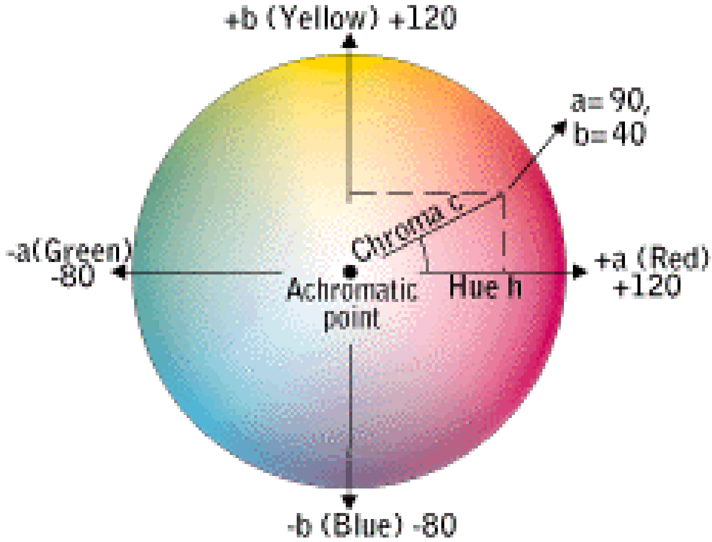

Figure 4: CIE colour space reference chart, in the a*b plane.

2.1.3 European Colour Measurement Survey

Numerous flint containers from UK and European manufacturers, the waste stream, brand owners and supermarkets have been collected and colour measurements conducted. The results are shown in Figure 5.

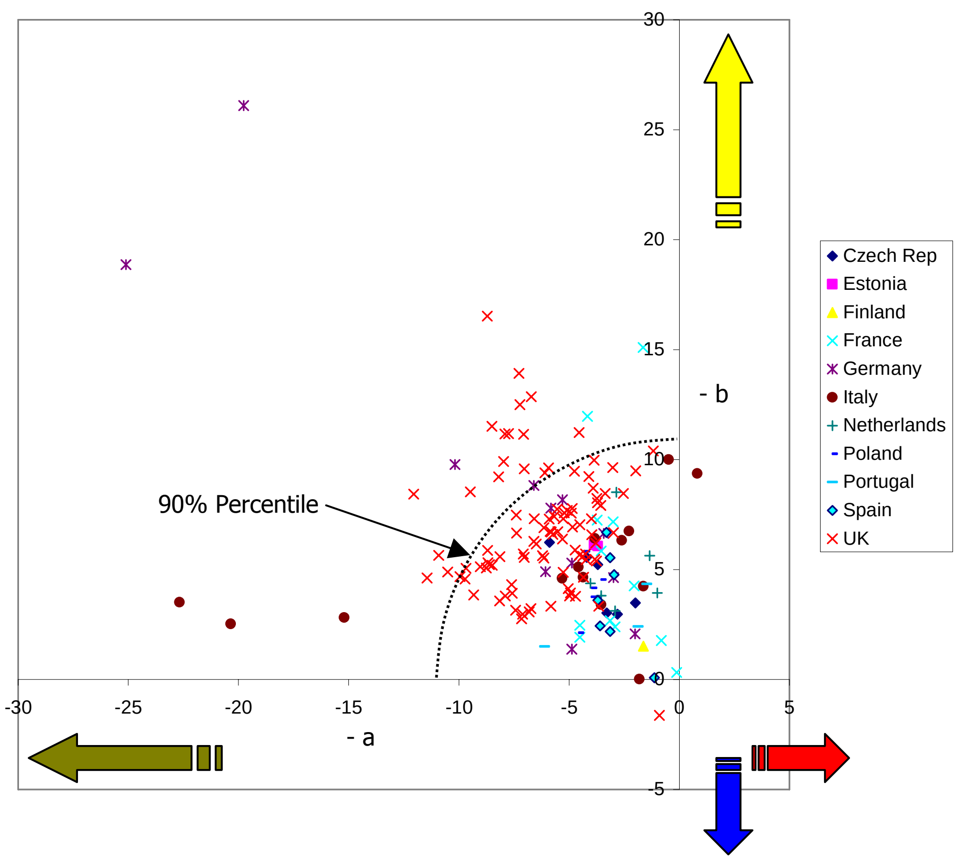

Figure 5: CIE colour space L*a*b colour measurements of a selection of European flint container glass.

As can be seen in Figure 5 there is a degree of scatter in these results. It must be stressed that most of the European containers were sent by glass manufacturers and they may have been selective in the containers sent for colour measurement. Also, a majority of these containers were bottles which tend to be manufactured to a higher colour specification than standard food containers. Conversely, a majority of the UK containers were randomly taken during factory visits and they were a mixture of bottles and jars. Therefore, the above results may not truly reflect the actual colour variation across Europe. On analysis of the data used in Figure 5, 90% of the colour coordinate measurements fall below and within -11 'a' and +11 'b'.

In addition, a comparison of the colour versus container type is shown in Figure 6 and demonstrates that tighter colour control for flint containers tends to be for spirit and food containers. The containers with a colour coordinates greater than -11 'a' and +11 'b' have been removed from the data for ease of interpretation, as most of these container were off white wine bottles. As the flint wine containers tend to be less restrictive on colour and therefore show more of a spread of colour. It would appear for a majority of product packed in flint containers the colour is probably not an issue unless it falls outside the -15 'a' and +15 'b' region. However the glass colour is product and brand sensitive and therefore it is not possible to independently specify colour coordinates for flint glass.

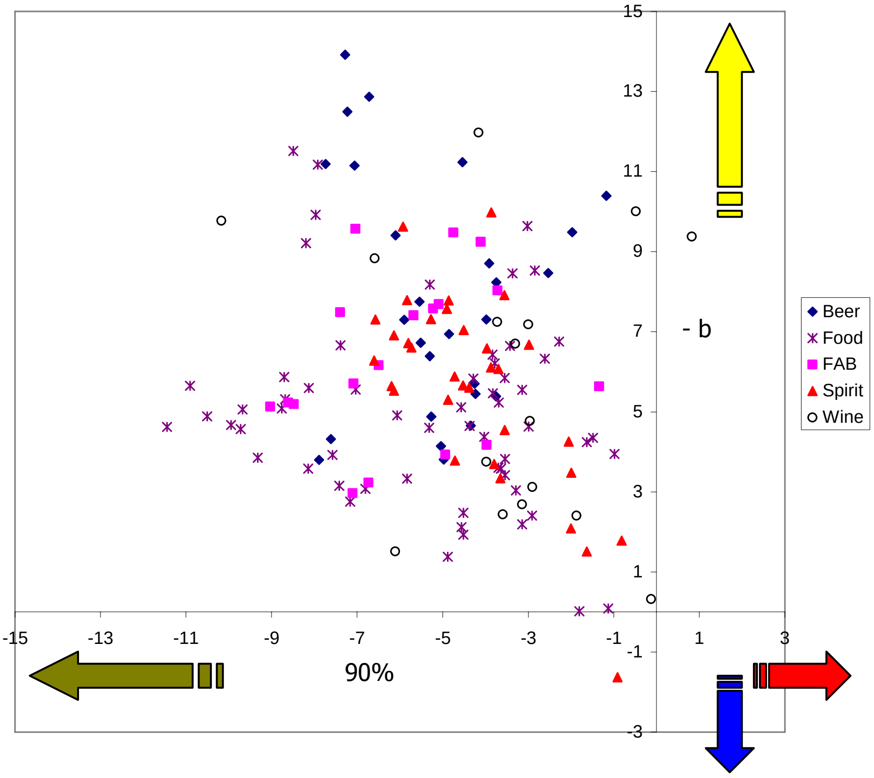

Figure 6: **CIE colour space L*a*b colour measurements of a selection of European flint container glass by container type.**

2.1.4 Colour Measurement – Consumer Perception Study

To be able to quantify the glass colour of the samples used in the consumer perception study (Section 2.2), the Department of Colour Chemistry, University of Leeds led by Professor Ronnier Luo, undertook an experimental study to quantify the colour of empty and filled glass containers. The method described for colour measurement in section 2.1.2 is a destructive method used for the colour measurement of glass containers, which is acceptable for production quality control in a glass factory. However, the Department of Colour Chemistry employed an innovative approach to glass colour measurement that has proven to be an appropriate method for assessing glass containers in situ such as on a supermarket shelf with artificial lighting. This research was additional work to support the consumer perception study and is described in full detail with conclusions in appendix A.

For the consumer perception study flint containers with varying shades of green were used for the consumer perception of glass colour both empty and filled. To obtain a range of green intensity, containers made during furnace colour changes (green to flint) were supplied by glass container manufacturers and also a series of different containers were spray coated with a different intensity of green shades. The purpose of this series of containers was to replicate flint containers with different cullet addition in the final glass and of varying degrees of quality. Based on information gained in the investigation of colour control (Section 3.3) it was possible to estimate the expected level of cullet addition (Table 3) to gain the colour in the containers used in the perception study.

Colour		**Cullet addition**	**Cullet quality (% green in flint cullet)**
Colour Change	**Coated**		
D	Flint	60% flint cullet	0.5% green
		(equivalent to 20% average quality flint cullet, 1.6% green)	
C		60% flint cullet	2.5% green
	Light	60% flint cullet	4% green
B		60% flint cullet	6.5% green
A	Dark	60% flint cullet	8% green

Table 3: The estimated level of cullet and quality for the flint containers used in the perception study.

2.2 Consumer Perception of Colour

This project task was concerned with consumers' perceptions of, and attitudes to glass containers of food and drink. There is a perception in the industry that consumers associate glass clarity with quality, and therefore clear flint glass is an important commodity. Certainly transparency is an important advantage of glass over many alternative packaging materials; this may arise because of product visibility[10] (although any advantage may depend on how attractive the product is). Through the use of decolourisers it is possible to 'absorb' certain levels of green cullet. However, this can be an expensive process and, if the decolouriser is used in quantity, clarity of the resulting glass can suffer. Moreover, fluctuations in cullet quantity or type, over time (within a product container run), can lead to slight variations in glass colour if the quantities of decolouriser and quantities of added recycled cullet are not well matched.

This project task was designed to provide a relatively broad perspective on these issues and to consider the impact that the use of various shades of glass (flint versus shades of green, given the availability of green glass for recycling) would have on consumers' perceptions of, and attitudes to, containers for foods and drinks. This work was undertaken by the Psychology of Design (PoD) group, at the Institute of Psychological Sciences, University of Leeds, with support from the Department of Colour Chemistry (Appendix A). It is hoped that the results will be of interest to brand owners and glass manufacturers when determining appropriate glass container colour, and also when deciding on colour tolerances that must be achieved.

In the context described, an important issue for empirical study is the ability of consumers to detect faint shades of green. The human visual system is not perfect and small variation in colour is likely to go undetected. The amount of colour required to exceed the detection threshold is likely to be influenced by a number of variables, including the thickness of the glass, shape of the container, size of the container, embossing on the container, type of lighting, the colour of the contents, the translucence of the contents, the nature of the background, and the colour of the label.

Another important variable, little studied in the psychophysics literature (i.e., relating to human ability to detect sensory differences), concerns whether the consumer is expecting the glass to be other than flint. It can be predicted that the ability of the consumer to detect colour differences will be greater when they are alerted (cued) to their existence than when they are not (un-cued). The first two studies reported, conducted as part of this programme of work, addressed this. The first study required participants to make a series of cued judgements as to whether two presented beer bottles varied in colour. The second study presented the same beer bottles and required participants to make other assessments (misdirecting attention) so that it was possible to assess the likelihood of consumers detecting colour differences when not specifically looking for them (an un-cued situation).

Following this, two studies are reported that provided detailed examinations of consumers' evaluations of different types of glass containers and different types of product when presented in containers of varying colour (flint, lighter green, or darker green). In both studies, presentation conditions approximated those that might be experienced in a supermarket. Previous research suggests that consumer responses to manipulations of packaging/container design are likely to be multi-facetted[11,12] and will be the complex amalgam of factors such as:

- Cognitive associations formed with both the container and the product (e.g., a green container in combination with certain products may trigger associations of unripe or mouldy food).
- More generic affective responses (e.g., a green tint may adversely affect aesthetic perceptions of container quality).
- Practicality concerns (e.g., a tinted container can make it more difficult to view the product).

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[10] Griffin, R.C., Sacharow, S., & Brody, A.L. (1993). Principles of Package Development. Second Edition. Malabar, Fl.: Krieger.
[11] Bloch, P.H. (1995). Seeking the ideal product form: Product design and consumer response. Journal of Marketing, 59, 16-29.
[12] Veryzer, R.W. (1999). A nonconscious processing explanation of consumer response to product design. Psychology & Marketing, 16, 497-522.

- Product context (e.g., coloured glass may be preferred if it is typical for a particular product type).

For this reason, a multi-dimensional approach to assessment was adopted. This was based on the CAPDeCO approach to design assessment that we (the PoD group) have been developing. This draws on existing research literature[11] and explicitly addresses the following components of consumers' responses:

- *Cognitive associations and evaluations:* People form cognitive associations between all sorts of things – people, places, things, feelings, even packaging designs. Understanding these associations can be informative when evaluating consumer perceptions (e.g. consumers might associate a design with a concept such as 'high class', or with being used in a particular setting, such as a party).
- *Affective responses:* This component can perhaps be thought of as emotional reactions to designs. Although different product designs are very unlikely to evoke strong emotion, mild changes in, for example, pleasure or boredom might be reported.
- *Perceptions of Practicality:* Functionality and ease of use are very important considerations when evaluating different product designs. For example, how easy is it to open a particular packaging design.
- *Design features:* Descriptions of fundamental features of design. These are necessarily design 'generic' (i.e., can be applied to a range of designs), and include, for example, consideration of the extent to which designs differ in their level of 'decorativeness' or 'orderliness'.
- *Context:* Product designs occur in a particular context and consumer perceptions may vary depending on this. For example, a consumer may like a packaging design because it is unusual in that particular marketplace.
- *Outcomes:* Consumers' perceptions of, and attitudes towards, product designs will tend to influence behaviour. These behaviours are obviously important to brand owners and manufacturers. For example, it is reasonable to assume that positive perceptions will increase the likelihood of sales. As part of our assessments of consumer perceptions we consider specific 'outcome factors' such as purchase intentions.

Although the approach to specific studies will vary, these components provide useful 'touchstones', helping to make sure that different aspects of the problem are being considered.

It is worth noting that consumers noticing that a glass container is tinted green (as opposed to flint) is not a prerequisite for a change in preference[13] or a change in affective response or consumption behaviour[14]. Therefore, it is important to consider consumers' responses to containers of different colour, regardless of the outcome of the detection studies. The corollary also applies. A difference in glass colour may be sufficient for the consumer to perceive its existence, but it may not translate into changes in product preference. It may be that a certain level of green-tint, even when detected, is considered acceptable and will not have a detrimental effect on consumer purchase behaviour.

Further potentially influential factors, in this context, include brand perceptions and product placement (e.g., premium versus value). However, the remit for this work was to investigate effects of glass colour, insofar as was possible, in a 'brand neutral' fashion. Therefore some of these considerations remain to be clarified by future work.

[13] Nisbett, R.E. & Wilson, T.D. (1977). Telling more than we can know: Verbal reports on mental processes. Psychological Review, 84, 231-259.
[14] Berridge, K.C. & Winkielman, P. (2003). What is an unconscious emotion? (The case for unconscious 'liking'). Cognition and Emotion, 17, 181-211.

2.2.1 A Market Survey of Products

A survey was conducted to determine which containers and categories of products would be the most appropriate to consider in research on consumer reactions to variations in flint glass colour. Not all could be tested in this programme of research, so this survey is useful in prioritizing areas of interest and could provide a basis for further consumer perception work in other projects. In the following sub-sections issues relating to specific product categories are identified.

2.2.1.1 Drinks

According to Mintel, glass packaging makes up 20 percent of all drinks packaging by value.

2.2.1.1.1 Spirits

A large proportion of the glass used for the packaging of spirits is made in the UK so there is a strong argument for examining consumer perceptions of spirit bottles. Effects of product colour on consumer perceptions of glass colour could be examined by contrasting a clear spirit (Vodka) with a darker spirit (Whisky). Rum would not seem to be an option for testing as the leading brand has a distinctive blue/green flint bottle.

- Whisky – The leading brands are Bells and Famous Grouse (available in 75 cl and 1 litre varieties).
- Vodka – The leading brands are Smirnoff and Absolute in the UK (available in 75cl containers).

2.2.1.1.2 FAB (Alcopops)

This is a growing market which, according to Mintel, is likely to increase supported by two of the largest manufacturers (Diageo and Bacardi-Martini). Most products are made and packaged in the UK. The two best selling varieties are:

- Bacardi Breezer – Available in watermelon, citrus, cranberry, etc. in 330 ml bottles.
- Smirnoff Ice – Available in Black, and original variations and in 330 ml bottles.

Some products in this market sector use plastic sleeves to add a range of graphics. This may be an important factor when considering relevance for testing.

2.2.1.1.3 Beer

There is a large range of bottled beers available, many of which come in flint glass packaging, e.g., Corona, Miller Genuine Draft, and Sol. All are available in 330 ml bottles. Miller bottles are manufactured in the UK so would be suitable for evaluation.

2.2.1.1.4 Water

The strongest market growth in recent years, in terms of soft drinks has been in the bottled water sector. There are a number of reasons why this would be a useful product to test. First, it will allow the testing of products where manufacturers clearly use the 'premium' nature of glass to add value to products. Second, the product (water) is relatively homogenous in taste and should not produce great variations in consumer preference. Third, it is a clear product, and so importance attached to transparency of the container may be maximised. Finally, there is strong competition from plastic containers. The leading suppliers of bottled water are Nestle and Danone, who own foreign sourced variations. It is unclear whether the water is bottled within the UK. The leading British company is Highland Spring with a ten percent market share in the retail market and the same in the on trade market to hotels and restaurants. It is available in 1-litre glass bottles.

2.2.1.1.5 Cordial

The market for dilute to taste soft drinks in the UK is the largest in Europe. In terms of packaging, this sector of the market has demonstrated a move away from PVC to PET bottles, while glass continues to command a significant share in the niche sectors of the market where the perceived quality of glass packaging is regarded as an important advantage. Although only a relatively small number of manufacturers utilise glass products in this market, those that do aim at the premium end and so any negative changes in glass perception (e.g., by virtue of colour change) would be very important. Possible products for consideration include:

- Cordial – Amè (available in variations similar to wine)
- High Fruit – J20 (this has a large share of the 'on trade' soft drinks market)

2.2.1.2 Food

According to Mintel glass packaging makes up approximately 5-6 percent of the food packaging market by value. There is stiff competition from other materials, which has increased over recent years. Manufacturers of glass-packaged products tend to either play on the premium nature of glass, utilise the material because it is the trend within a market area, or because of its inert properties (pickled products, and baby food). Mintel highlight sauces and dressings as the most commonly packaged in glass and so could be important to study, depending on country of manufacture.

2.2.1.2.1 Sauces

These can be further separated into table sauces and stir in sauces. The colour of the contents and its thickness may well be an important consideration in terms of consumer perception of the glass packaging here. A range of coloured products may well be required.

Table sauces

When considering which products consumer perceptions of glass colour change might be most damaging for, a potentially important factor is the context of use of. Glass table sauce containers may be used when social impression is important. These products also provide variety in the colour of contents. Heinz Tomato Ketchup, Hellman's Mayonnaise, HP Sauce and Coleman's Apple Sauce are possible containers for study.

Stir In Sauces

In this market sector there is increasing pressure from plastic and foil containers, which is beginning to erode into the share held by glass packaging. This is due to the increasing demand for single serve containers and the move towards fresh type sauces for pasta. The previous dominance of glass in the stir-in market (approximately 80+% share) suggests that this is a good potential stimulus for study. Italian pasta sauces account for 48 percent of the market so might be best to focus on. General sauces (e.g. Chicken Tonight, Sausage Casserole) and Indian sauces hold the next biggest market share so could also be considered.

- Italian – Dolmio (available in arrange of sizes and alternative packaging materials)
- General – Homepride Sauces
- Indian – Pataks (available in a range of sizes and alternative packaging materials)

2.2.1.2.2 Preserves and Honey

Mintel pinpoint jams and honey as another large user of glass packaging, ninety percent of conserves and honeys are found in glass. This glass varies in thickness, which could be an important factor. The products are also displayed on the table in some households, so aesthetic issues surrounding the packaging may be of importance.

- Jam – Robertsons'
Chivers Hartley
Bonne Maman — All share equal 12 percent market share.

- Honey – Rowse

2.2.1.2.3 Pickled Products

Glass is commonly used to store pickled vegetables as it offers a material that does not react with the vinegar, degrade, and is transparent so the contents can be viewed. The latter property would be of interest to study.

2.2.1.2.4 Olive Oil

The majority of olive oils are packaged in glass containers, as opposed to plastic. This may be a clever strategy of brand owners to promote an image of olive oil as health giving, associated with longevity, and a premium product more akin to wine than cooking oil. Olive oil also comes in square bottles that vary in thickness so potentially could offer insight into differences in consumer perception associated with thickness and shape. The leading brands are Fillipo Berio (16%) and supermarket own labels (55%). However, a range of shades of glass are available to consumers of olive oil and, for this reason, these containers may not be appropriate for study in this project.

2.2.1.2.5 Baby Food

This is a market where perceived inert and hygienic properties of glass may be most important to consumers when making purchase decisions. Changing the colour of the glass may damage these perceptions. The leading brands are Heinz (50 % share) and Hipp (23%). However, it would seem that most containers are not made in the UK.

2.2.1.3 Summary

A range of products has been described, issues related to glass colour considered, and information presented relating to their potential suitability for research. Spirit bottles are high quality/cost containers, manufactured in the UK, usually in flint glass, and would provide a useful opportunity to test effects of product colour with respect to manipulations of glass colour. In addition, vodka provides the opportunity to test effects of coloured glass with a transparent product. Similarly, bottled water would be an interesting product to test. Glass containers are used in this market sector for their associations with 'premium' and 'quality' products. Water also has the potential advantage of not producing large variations in preference for taste. Beer would be another useful product to test, particularly given the existing use of green glass for many examples of this product.

With regard to foods, these represent a smaller volume of glass manufacture. However, there are reasons to think that consumer responses to glass colour variations may be pronounced. The importance of consumer perceptions of food colour to purchase preferences is well established. In this context, associations with container colour may produce unwanted and particularly damaging effects. Table sauces, stir-in sauces and preserves would be potentially useful products for testing. They provide the opportunity to test a range of product colours. Issues relating to product visibility (the ability to assess product quality) would be important, and aesthetics (on table use) would be an interesting consideration for table sauces and preserves.

2.2.1.4 Information from Brand Owners

A series of interviews was conducted with Brand Owners to gather data for the WRAP ContainerLite project. However, these also provided an opportunity to discuss with brand owners their views on glass colour.

Four brand owners were interviewed, representing the product categories of alcoholic drinks (1), non-alcoholic drinks (1), and foods (2). Of these, one did not use flint glass. Although the brand owners expressed concern over container colour, and the effects that this would have on consumer perceptions of their product, generally they were not aware of precise specifications for colour or the amount of cullet additions used in manufacture. Representatives from one of the brand owners (food products) expressed strong dislike for the idea of 'tinted' flint glass, believing this would be contrary to key brand values, such as purity and quality. They were also concerned that cullet additions might lead to more inclusions and reduce the structural integrity of the containers. However, representatives of another food brand owner suggested that for some products, which were less appealing to look at (e.g., powders) strongly tinted glass was beneficial.

2.2.2 Focus groups

A series of six focus groups was conducted in the Psychology of Design Laboratory at the IPS to gather data for both the WRAP Colourite and ContainerLite projects.

2.2.2.1 Method

Two focus groups were recruited for each of three age groups (18-35; 35-55; and 55+ years). Each focus group comprised relatively equal numbers of males and females. In total 40 participants were tested. All focus groups were video recorded for later analysis. Two moderators were present for each focus group.

Each focus group began by soliciting participants views of glass packaging generally and container weight. These data are not reported here. Perceptions of variations in container colour were then examined. To facilitate this, samples of flint and green-tinted containers were used as prompts. Most of the green-tinted containers had been spray coated to replicate off white flint containers (Reef, WKD, Vodka, and Newcastle Brown). Two shades of green (varying in saturation) were available. In addition, colour change samples from when glass manufacturer project partners changed container colour, of which Bacardi and Miller beer bottles were available. These were obtained from glass manufacturers who were switching from flint to green glass (or vice versa) to begin a new production run. For some products of interest neither spray coated nor colour change samples were available. These products were placed in a colour change Miller bottle to enable participants to see the glass/contents colour combination. Participants were presented with and invited to discuss each of the products in turn.

2.2.2.2 Results

In the following sections, summaries of participants' comments are given for each product. This is followed by an overall summary of focus group findings, including consideration of age differences.

2.2.2.2.1 Alcopops

Reef: Participants associated the clear flint reef bottle with a natural and a fruit based drink such as J2O. One participant viewed the sediment in the bottom of the bottle as looking unattractive whilst another associated the presence of the sediment with the drink having juice in it. When shown the darkest green shade bottle, participants felt the hue detracted from the product making it look less like real fruit and unappetising. Almost all participants stated that they would not purchase a bottle this colour, but might consider a lighter shade if they had nothing to compare it to.

WKD: When presented with the WKD bottles (Figure 7) in the darkest shades the contents were not viewed favourably, being described as "dirty" "murky" and "a mix up on colours". The blue WKD was associated with spring water and the orange WKD iron brew. The green bottle colour was not considered successful for this particular brand, although the lighter shaded bottle was perceived less negatively. The orange WKD's in the green bottles were perceived as looking better than the blue WKD in the green bottle. The original flint glass was generally felt to be best.

Figure 7: WKD bottles in flint and two shades of green (spray coated).

2.2.2.2.2 Beer

A range of views was expressed when participants were presented with the green-tinted beer bottles. (These were much lighter in colour than the 'typical' green beer bottles.). There were no strong attitudes against the presentation of beer in glass with an obvious green colour (the darker shades tested). This may be partly due to context factors, with green being an 'expected' colour container for this product. Some participants viewed them as "more traditional", and as appearing to have more sediment. However, when first presented with the beer bottles in very 'light' shades of green–flint glass (from the colour change sample), some thought that the bottles made the beer look "wishy-washy" or like "washing up liquid". Some participants thought that it was the beer that was a different colour, rather than the bottle. This was seen to be a negative factor. Beer presented in the clear flint glass was viewed as being stronger and better tasting. Beer in the lighter green-tinted containers was thought, by some, to be cloudy. On closer inspection the middle age group of participants noted that the "head of the beer looks green", whilst other parts of the bottle do not show the glass colour as clearly.

2.2.2.2.3 Tomato sauce

Across the groups tested, attitudes were split with regards to the green–flint bottling for tomato sauce. One group disliked the green-tinted bottle, feeling that the colour had the potential to cover up the quality of the product, making it difficult to see. Participants in the middle age groups reacted most negatively, questioning whether the product was off or sour and stated that a clear bottle would be the most appropriate container for tomato sauce. In contrast other participants were less affected by the appearance of the sauce in the bottle, describing it as traditional and more natural looking. However, some participants found it hard to distinguish whether or not the product or the glass had changed in colour. One participant remarked that making the bottle a bit darker possibly made / could be used to make the sauce look spicier.

2.2.2.2.4 Salad cream

Salad cream was generally viewed negatively in the green bottles with participants stating:

"It's the wrong colour"

"Musty looking"

"Looks off in some way"

"Turned"

"I wouldn't think that it was the same product"

Participants tended to attribute the colour differences of the glass to the product and said they would assume that the product had expired. However, it was also remarked, with regard to a particular brand (Heinz) trust in the brand would mean that they would assume the perceived difference was not caused by the product and would attribute it to another situation / reason.

2.2.2.2.5 Sweet corn

Responses to the sweet corn in the green-tinted glass were generally reasonably favourable. A few participants did not like it and were concerned that the quality of the product was disguised. However, other participants preferred the green-tinted glass maintaining that it made the product look brighter and fresher. This was also considered to be the case for herbs in glass jars.

2.2.2.2.6 Vodka bottles

When compared to the clear glass bottle, the coloured vodka bottles (Figure 8) were viewed by the younger participants as "refreshing" "different" and more "classy". They did not feel the green bottle detracted from the product in that it still looked like vodka. Additionally some suggested that if the vodka was completely clear, it had cheap connotations. Older participants and some of the middle age group were more conservative in their opinions about the green–flint spirit bottles, saying that vodka has always been in a clear bottle. However, they thought that the colour of the darkest tint suited Gin bottles – probably because of the association with the market leader Gordon's.

Figure 8: Spirit bottles in two shades of green.

2.2.2.3 Summary

In this series of focus groups participants views of clear flint versus green tinted glass containers were solicited for a range of products. Three age groups were tested. Although there was a good deal of variation in participants' views on green-tinted glass, some patterns emerged.

Consumer perceptions seem to be, at least to some extent, product-dependent. Green-tinted glass was considered more acceptable for some products than others. Beer is viewed as acceptable, even desirable, in green glass, particularly by younger consumers. Similarly, some younger consumers thought that vodka could be preferred in green-tinted glass. Coffee was another product that some participants thought would be acceptable in green-tinted glass. However, many food products, and particularly salad cream, seem to be less acceptable in green-tinted glass. When food products are presented in glass, participants want to be able to see the product. They consider this one of the main reasons for using glass containers. Generally, tinted glass makes this more difficult and was disliked for this reason. However, this response was not uniform, and previously mentioned comments by one of the brand owners about disguising less aesthetically pleasing products are relevant. The negative response to salad cream can be contrasted with the more mixed reaction to tomato ketchup in tinted glass. This may suggest product colour is an important factor. However, associations between colour and food quality may also have much to do with this, Participants were concerned that salad cream in the tinted glass was not fresh, whereas tomato ketchup in the tinted glass was thought by one participant to look spicier. This explanation would also seem consistent with the relatively more positive responses to sweet-corn in tinted glass. Tinted glass also produced some suspicious reactions from participants, with some saying it would make them wonder what manufacturers were trying to hide. Context of use was identified as a possible interacting factor. Participants in the middle aged group indicated that there may be some settings (e.g., restaurants) where purity and clear glass serve a purpose or are expected.

An interesting possibility was identified with respect to the effects of different amounts of green-tint. When products were presented in lighter shade containers there seemed to be an increased tendency for colour differences (as compared to clear flint) to be attributed to the product rather than the glass. Related comments include:

> *"You'd think it had gone off before you got it"*
>
> *"You'd think it was the product instead of the container"*
>
> *"It doesn't look right would think something was wrong with it / take it back if not noticed in shop"*
>
> *"You'd think there was lime in that"*
>
> *"Looks like a different product"*

This occurred for foods but also, to a more limited extent, for beer, with participants suggesting that the beer looked weaker and less appealing when presented in light green bottles. However, when the product was viewed in darker shade bottles participants were aware that the colour they could see resulted from the glass and not the product. One way of explaining these results is that participants weigh the probabilities of whether the glass or the product is more likely to produce the colour. Presumably, perhaps depending on product type, they consider it more likely to be the contents if the shade is lighter and more likely to be the glass if the shade is darker.

Some general, context-free associations with green glass were identified that were not positive. It was regarded by some participants as signifying lower quality, being old fashioned, dirty, and re-used (negative connotation). Clear flint glass was thought to result from more modern and better manufacturing techniques. However, context sometimes seemed to overcome these associations. For example, green beer bottles did not seem to be viewed in this way. The effects of hue and depth of colour may be of importance in this regard and might usefully be explored further. These perceptions were also subject to possible age differences. While some younger participants regard green-tinted glass as 'old fashioned' and the sort of glass you might find "discarded at the bottom of the garden" (when discussed context-free, but see below), some older participants viewed it as being more 'traditional', although there were also some negative associations with hazardous/toxic contents for some in the oldest age group. Spirit bottles were an exception to this pattern. Contrary to the general view of green glass, the younger group were more receptive to a green-tinted bottle in this context. Also, there did seem to be a tendency for consumers from the middle-aged groups to be less likely to notice the colour of the tinted container. Many mistook the glass colour for content colour. It is difficult to explain why this effect should be particular to this group, and it may be an artefact of the sample.

Although, as mentioned above, green glass did have some negative connotations relating to reuse, participants generally seemed positive about the idea of recycling. Younger participants seemed particularly aware of and receptive to the recycling 'message'. Older participants were perhaps more familiar with the concept of recycling bottles, thinking milk bottles, rather than glass content. Participants suggested that bottles manufactured with high levels of recycled glass would need to be promoted and the consumer informed of the reasons for changes in colour in order to improve the acceptability of the bottle.

Finally, it should be noted that, although these focus groups provide useful insight into consumer perceptions of green-tinted glass, they probably over-estimate participants' ability to be able to detect differences and, for this reason, may over estimate negative views. These views are based on 'cued' detection. Participants were specifically asked about glass colour. Sensitivity may be reduced in 'un cued' conditions. Indeed, participants did point this out and indicated that some of the lighter tinted shades of glass might not be easy to detect if no direct comparison was available. Some participants suggested if bottles were seen on a supermarket shelf it might be harder to notice some of the colour alterations.

2.2.3 A 'Cued' Psychophysics Study of Consumer Sensitivity to Container Colour Differences.

Previous psychophysics research indicates that, under controlled and ideal conditions human colour vision is very sensitive, with observers' being able to detect in the region of 7 million colours as defined by differences in hue, intensity and saturation[15]. However, no data are available to indicate colour detection ability in the applied context of variations in green colour in glass containers that are filled with product and available for sale on supermarket shelves. Given the aims of the Colourite project, it seems pertinent to contribute to the process of assessing consumers' sensitivity to differences in such stimuli, so that brand owners and manufacturers have some understanding of the variations in green colour that may go unnoticed by the consumer. In the studies reported here (this section and the following one), beer bottles were selected for investigation due to the high volume of sales in the UK, the potential applicability to other high volume glass packaged products from the UK market (e.g., whisky), and the availability of green tinted samples. As the brief for this work was to focus on the point of sale, for this first study bottles were tested when filled with beer.

For the 'cued' detection task, participants completed a series of trials in which they were presented with two beer bottles that varied in glass colour (see bottle colour measurements section of the Colour Chemistry report in Appendix A). They were required to make a decision as to whether these bottles differed in colour. Findings from the focus groups indicated that, when not informed that a glass colour difference existed, consumers have a tendency to attribute the colour variation to the contents of the container. To give participants the maximum chance to detect the glass colour difference they were informed that a glass colour variation existed between some of the bottles that were to be presented. For the purposes of this study and the following one, two fictitious brand labels were designed, one red and one yellow. To examine effects of adjacent colours, particularly with reference to opponent process theory[16], half of the participants were presented with bottles that had a red label, the other half were presented with bottles that had a yellow label.

[15] Goldstein, E.B. (1989). Sensation and Perception 3rd Edition. Belmont, CA: Wadsworth.
[16] Hurvich, L. & Jameson, D. (1957). An opponent-process theory of colour vision. Psychological Review, 64, 384-404.

2.2.3.1 Method

2.2.3.1.1 Participants

Thirty-six participants (20 male and 16 female) aged 18 - 54 years (mean age=28.6 years) took part in this study. All passed the Ishihara colour blindness test[17] (Ishihara, 1951).

2.2.3.1.2 Materials

Bottles in five colour shades (flint and four levels of green colour depth: Appendix A) were used in this experiment (Figure 9). Each bottle was filled with the same beer. Two different sets of labels (Red - Old Jefferson; and Yellow - Bravel Label) were used.

Figure 9: Two fictitious brands in flint and four shades of green bottles, as used as stimuli.

2.2.3.2 Procedure

On entering the testing room the participant was seated at the end of a desk in front of the presentation area, approximately 1 metre away from the containers. The participant was told 'In the following task you will be presented with two containers at a time and asked to decide whether the glass in the two containers is the same colour or a different colour. Some of the pairs of containers presented to you will be the same colour as one another and some containers will be a different colour to one another'. In each trial, if the participant thought the colour of the two presented containers differed in colour depth, they were asked to decide whether the container on the left or the right was darker and press a correspondingly labelled key on a computer keyboard. If participants considered the containers to be the same then a key labelled 'SAME' was pressed. The participant was told that there would be 64 trials and that they may be presented with the same pair of containers on a number of occasions. They were asked to respond as quickly as possible while maximising accuracy. Participants were told the colour difference was due to the glass bottle not the beer (the same beer was in each bottle). To avoid the participant from gathering other cues as to correct responses, stimuli not in use were kept in a box behind a screen. The participant was also unable to touch any of the stimuli and light levels in the room were maintained within a range of 300 to 500 lux (similar to that in the alcohol section of national supermarkets). The background material that the containers were

[17] Ishihara (1951). Tests for Colour Blindness 10th Edition.

presented in front of was wrapping paper from a Threshers Off Licence, where previous similar research had taken place.

In total 64 trials were completed by each participant (32 blank versus blank and 8 trials of each shade versus blank). The position of the blank container was counterbalanced across participants (for 50% of participants the blank comparison container started on the left) and within trials (in every ninth trial the blank comparison container alternated sides). Eighteen participants viewed all the stimuli with the Old Jefferson label on all the bottles and 18 viewed the Bravel label on all stimuli. The 64 trials took approximately 15 minutes to complete.

2.2.3.3 Results

Figure 10 shows the percentage of correct responses by bottle shade and label viewed (between subjects condition). Performance is plotted against colour differences, as assessed by comparing each green tinted bottle against the blank bottle (Appendix A). Bottle A and B, the darkest bottles, were correctly identified on most occasions. However, the number of correct detections declines for bottle C, and more noticeably for bottle D, which was very close in colour to the blank. The amount of correct responses for trials where two blanks were presented to participants was low. On average, participants correctly identified only 11 of the 32 (33.5%), although this was 58% when the Old Jefferson label was on the bottle and 9% when the Bravel label was on the bottle. Overall bottle shade had a reliable effect on whether the participant responded correctly when the four shades (excluding blank versus blank trials) were included in the analysis. When the means for each shade were tested separately, all differences were reliable apart from bottle A versus bottle B.

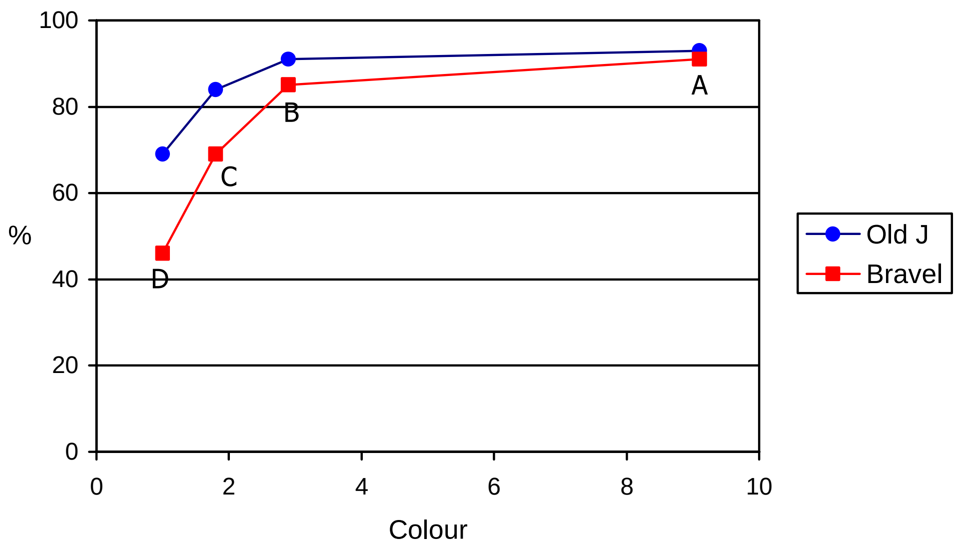


Figure 10: Percentage of correct responses by glass shade and label.

Participants who viewed the red Old Jefferson label made a higher percentage of correct responses than those who viewed the yellow Bravel label. The difference in performance was most apparent for the lightest shades of green bottle (C and D).

2.2.3.3.1 Age differences

To consider the effect of age differences on performance the sample was divided, post hoc, about the median (26 years) to create a younger and an older group. Comparisons were then made of the performance of these groups. As can be seen from Table 3, there was a tendency for the older participants to perform better when detecting a green bottle. However, they performed worse when presented with two blanks. This may indicate between group differences in response criterion, with the older group being more prepared to say 'yes there is a difference'. When statistically tested, effects of age group for overall percentage of correct detections and for correct detections for individual bottle pairings were not found to be reliable.

	A	B	C	D	BLANK
Younger (26 yrs and under)	88.1	86.9	76.9	54.4	42.0
Older (27 yrs plus)	96.9	89.1	75.8	60.9	22.5

Table 4: The percentage of correct responses by age group. NB: Based on 21 participants in the younger group and 15 in the older group.

There were combined effects of glass shade, label viewed, and age group on detection rates (Figure 11). However, this may be due to an anomalous data point for the older participant group when rating the Old Jefferson bottle. This age group were apparently very sensitive to the lightest green glass colour when viewing bottles with a red, as opposed to yellow, label.

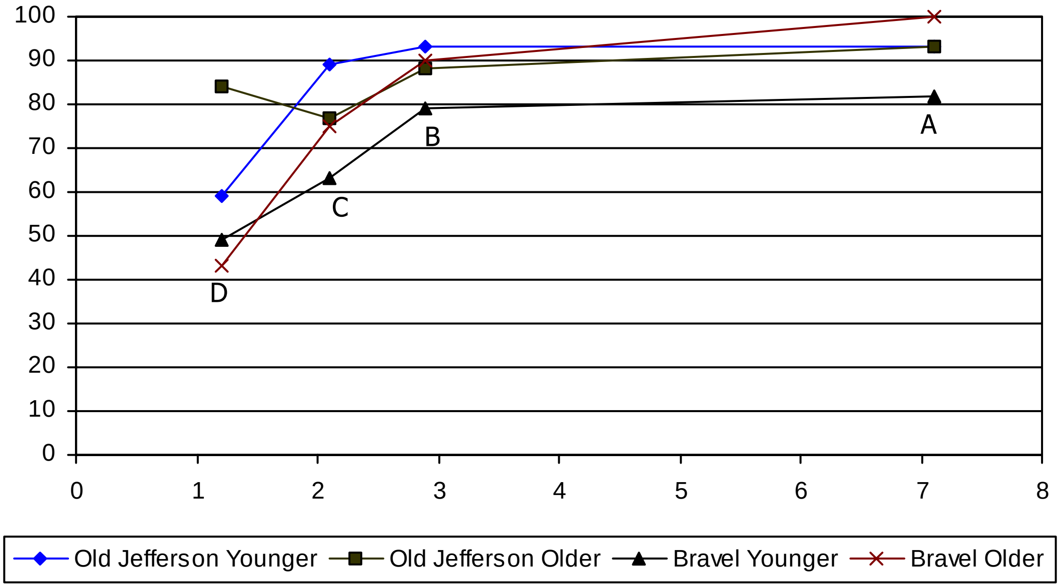


Figure 11: Percentage of correct responses by glass shade (D-A), age group, and label.

2.2.3.4 Summary

Participants' ability to detect a green tint in glass was relatively poor for bottle D, but improved progressively with added colour to the point of Bottle B, where asymptote seemed to have been reached, and additional 'strengthening' of colour had little effect on performance (Appendix A).

Label colour had an effect on the percentage of correct responses that participants made. Participants performed better when a red label was on the bottle than a yellow label. This was most pronounced for the lightest shades of green glass (bottles C & D), and may be influenced by participant age. It may be that this reflects a perceptual bias (see below), with participants being more prone to perceive green tint whether it is there or not, when a red label is applied to the bottle. However, data for trials when both bottles were flint suggest this may not be the case and that sensitivity may have been influenced. Older participants were particularly sensitive to the lightest green bottle when in the red label. However, this data point was somewhat 'out of line' with the remainder of data points for this group and therefore this result requires further investigation and replication.

Anecdotal evidence from participants, when performing the task, indicates that the top of the bottle, and the air space would be the most important for consumers when assessing colour variation in an on shelf comparison situation. This neck area is often covered by paper/card collars on a number of products.

2.2.4 An 'Un-Cued' Psychophysics Study of Consumer Sensitivity to Container Colour

The previous study provided an indication of consumers' sensitivity to glass colour differences when they were aware that there could be a difference ('cued' detection). However, in 'real world' contexts this may not be the case and detection would rely on consumers noticing a difference when they were not expecting one ('un-cued' detection). Therefore this study was designed to test detection performance under these conditions. Practical constraints (e.g., it was not possible to manipulate branded products on supermarket shelves) presented some difficulties for study design. It was necessary to devise a task that was plausible for experimental participants, that would require some sort of evaluation of products (akin to making a purchase decision), but that did not highlight colour differences in glass containers. The approach taken was to devise two fictitious brands and to design labels for each of these (as described for the previous study). Participants were presented with two beer bottles that varied in glass colour, each with a different fictitious brand label. Their apparent task was to select their preferred design. Once they had made their selection participants were also asked whether they had noticed the colour difference. By counterbalancing the presented combination of glass colour and fictitious label, inferences were made about the influence of glass colour on participants' ability to detect colour in an 'un-cued' setting, and also their preferences.

2.2.4.1 Method

Each participant (n=128) was presented with one pair of glass containers (beer bottles). One of these was a clear flint bottle (as would be found on the supermarket shelf), the other was one of four 'colour change' samples (four levels of green-tint, varying in level of saturation: see previous section). Two fictitious brands were devised ('Bravel' and 'Old Jefferson') and appropriate labels were stuck onto the bottles. The combination of glass colour and brand was counterbalanced between participants. Sixty-four participants (20 female and 44 male; mean age 36.26 years, SD 12.59) were presented with empty bottles from which to make a preference selection. Sixty-four participants (37 female and 27 male; mean age 26.8 years, SD 11.82) were presented with full bottles from which to make a preference selection (these were filled with the beer that would normally be sold in these bottles).

Participants were asked to select the design/bottle that they preferred. Participants received no prior information about the underlying purpose of the study and no help was given to the context of their decision. Once they had selected a preferred design, participants were then asked to justify their choice. If glass colour was not mentioned at this point they were specifically asked whether they noticed a difference between the two bottles. The study used opportunity sampling, recruiting participants in Thresher off-licences in Leeds, off the street around Leeds city centre and around the Leeds University campus.

2.2.4.2 Results

In the following section, the darkest green bottle is referred to as 'A' and the clear flint bottle as 'Blank'.

2.2.4.2.1 Empty bottles

When viewing empty bottles, 17 participants (27%) noticed the colour difference; 12 when the Old Jefferson (red) label was on the coloured bottle, 5 when the Bravel (yellow) label was on the coloured bottle. This difference was not statistically reliable.

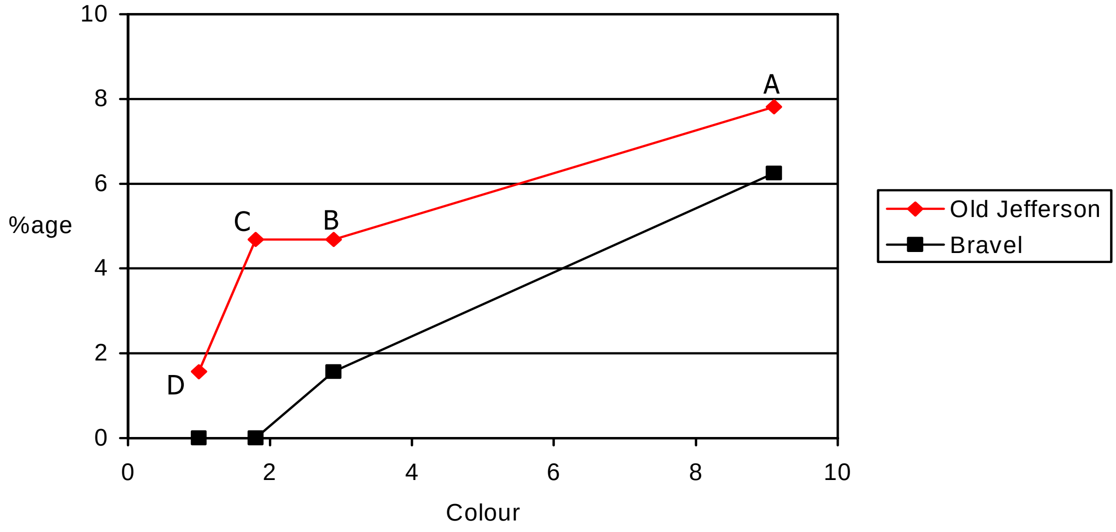


Figure 12: **Breakdown of percentage of participants noticing colour difference (D-A) by label design using empty bottles.**

As would be predicted, the percentage of participants detecting the colour difference increased for the darker shade bottles (Figure 12). Participants were particularly poor at detecting lighter shade colour change bottles when the Bravel label was used (cell frequencies were not sufficient to permit a statistical inferences).

Detected difference?	Bottle preference	
	Flint	Coloured
No	19	28
Yes	10	7
Total	29	35

Table 5: **Breakdown of participants preferring the flint or coloured bottle by whether they detected the colour difference.**

Twenty-nine participants (45 %) preferred the clear flint bottle and 35 participants (55 %) preferred a colour change bottle (Table 5). Whether the participant had detected the colour difference did not have a reliable effect on preference for flint or coloured bottle. However, the Bravel label (n=43) was preferred to the Old Jefferson label (n=21).

2.2.4.2.2 Full bottles

Of the participants who were presented with full bottles, 7 participants (11%) noticed the colour difference; five when the Old Jefferson (red) label was on the coloured bottle, two when the Bravel (yellow) label was on the coloured bottle.

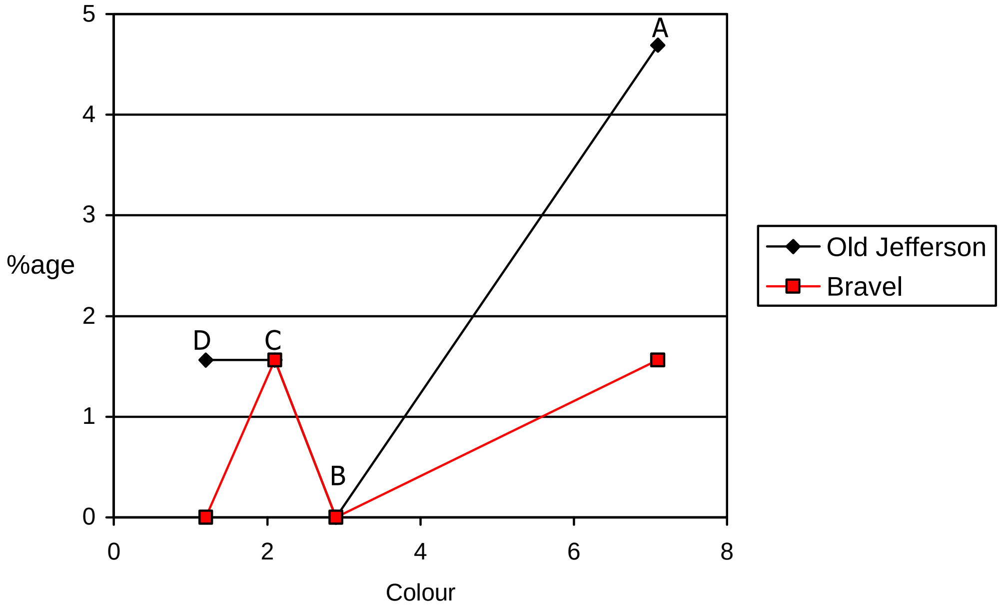


Figure 13: Breakdown of percentage of participants noticing colour difference (D-A) by label design using full bottles.

As can be seen from Figure 13, there was a general trend for the percentage of participants detecting the colour difference to increase with darker shade bottles, with the exception of colour B, which no participant detected. This may be an anomaly in the data. When the Old Jefferson (red) label was on the colour change (green-tinted) bottle the colour change was more likely to be noticed. This appears to be the case for both the lightest and darkest bottle shades, although no statistical inference was possible due to low cell numbers.

Detected difference?	Bottle preference	
	Flint	Coloured
No	28	29
Yes	3	4
Total	31	33

Table 6: Breakdown of participants preferring the flint or coloured bottle by whether they detected the colour difference.

Thirty-one participants (48%) preferred the clear flint bottle and 33 participants (52%) preferred a colour change bottle. Whether the participant had detected the colour difference did not have a reliable effect on preference (Table 6). However, the Bravel label (n=49) was preferred to the Old Jefferson label (n=15).

2.2.4.3 Summary

As expected, there was a trend for participants to detect the difference in bottle colour more frequently when the coloured bottle was relatively darker green. However, even in the darkest shade tested, only a minority of participants detected the difference (14.06% when empty and 6.25% when full). These levels of detection will partly be due to factors such as the viewing conditions and level of misdirection used in this study. Participants indicated a preference for the clear flint bottle and the colour change bottle in fairly equal numbers. This applied to both the empty and the full bottle. No reliable change in this pattern was apparent when the colour of the bottle was manipulated or when considering whether or not participants detected the colour difference. Generally, these results are somewhat encouraging, in that they suggest that un-cued detection rates will be much lower than 'cued' detection rates and that, for bottled beer, colour is not a strong determinant of preference. As identified in the focus groups, beer is often associated with green bottles. For this reason consumer preferences may be much more favourable than would be the case with some other products.

Participants were more sensitive to colour change in empty rather than full bottles. This obviously has implications with regard to the context in which consumer perceptions are being considered and therefore should be evaluated. If the supermarket shelf is the most important context for study then results from full bottles may be regarded as most relevant. If 'in use' perceptions are of concern then results from the participants when presented with empty bottles will also be of interest. Tests of bottles in varying states of emptiness might also be useful. However, it should also be noted that, work of the Department of Colour Chemistry, University of Leeds, has demonstrated that, particularly for clear products (e.g., water and vodka) the effects of green tint are magnified when products are stacked one behind another, as would be found on a supermarket shelf (see Appendix A).

It is interesting to note that, similarly to the previous study, participants appeared to be more sensitive to the colour difference when the green-tinted bottle had a red label ("Old Bravel"). This is consistent with colour contrast theory in that red and green are held to be opposing colours. From this it can be argued that a red label on a clear flint bottle would result a tendency for the bottle to be seen as green. In this study, this might produce a bias, with participants being more likely to perceive the bottle with the red label was green whether or not this was the case. So, for example, participants might believe both bottles were the same colour when the yellow (Bravel) label was on a green-tinted bottle. However, results from the previous study, for trials when two flint bottles were presented, seem to suggest that ability to detect may also be influenced. Further research would be of value.

2.2.5 Consumer Perceptions and Attitudes to Container and Product Type.

This study was designed to examine consumers' perceptions of and attitudes to food and drink containers under manipulations of glass colour (flint versus different shades of green), container type, and product type. Age and gender differences were also examined. Results of the focus groups (see above) indicated the importance of product type as a determinant of consumers' responses to glass of varying green tint. Therefore, this study was a quantitative assessment of this effect.

Participants assessed containers in a setting that approximated supermarket 'on-shelf' display, with regard to type of lighting, level of lighting, and availability of reference products. Products were presented on a shelf, stacked either two or three deep, and flanked by other similar 'reference' containers that were flint in colour. Each participant was presented with three different types of container (a large water/cordial bottle, a spirit bottle, and a small sauce bottle) in each of three colours (flint, lighter green and darker green). The type of product in each container was manipulated, with half of the experimental participants assessing water, whisky, and salad dressing, and the other half assessing orange cordial, vodka, and Italian tomato sauce. Although, in this study, container type and product type were not completely independent (because of a desire to present realistic stimuli), this experimental design permitted some inferences to be drawn as to whether effects of the glass colour manipulation were container-specific or whether they were reliant on the type/colour of product contained within. In addition effects of participant age and sex were also tested.

The CAPDeCO assessment approach (see above) was adopted for this study. Participants were required to provide a series of ratings with respect to the particular stimulus under consideration at that time. So, for example, when assessing the spirit bottle full of whisky, one of the items that participants provided a rating for was "I think the design of this container is high quality". In total 67 items were included, many of which were generated on the basis of the focus group comments. This was the case for a set of items that were concerned with how appetising the contents of the containers appeared. From these items a set of rating scales (combinations of several items) were produced.

2.2.5.1 Methodology

2.2.5.1.1 Participants

Seventy-two participants were recruited through posters placed around the University of Leeds, in a local Age Concern centre, and around the city centre and also through a local newspaper advertisement. Equal numbers of men and women were recruited to one of three age groups (18-34; 35-54; and 55+ years). The age of participants ranged from 19 to 83 years (mean=44.56, sd=18.60). All participants satisfactorily completed the Ishihara Colour blindness Test (Ishihara, 1951).

The economic status of the sample was as follows: 38.9% were employed, 33.3% were retired, 22.2% were students, 2.8% were housewives/husbands and 2.8 were unemployed. The breakdown of the socio-economic status categories for the highest earner in the household was as follows; a (higher managerial/professional) = 6.9%, b (intermediate managerial/professional) =23.6%, c1 (supervisory, clerical, junior professional) = 12.5%, c2 (skilled manual workers) = 5.6%, d (semi and unskilled workers) = 4.2% and e (dependent on the state through sickness, retired, students) = 47.2%.

2.2.5.1.2 Materials

Three different types of container were used as stimuli (for assessment): a spirit bottle (700ml), a water/cordial bottle (1 litre), and a sauce bottle (225ml) (Appendix A Figure 1). To obtain the required shades of green glass, these containers were industrially sprayed to produce lighter and darker green hues. For exact measurements of the colour of these containers see the report from the Department of Colour Chemistry (Appendix A). When presented to participants, these three container types were filled with either: i) water, whisky, and salad dressing; or, ii) orange cordial, vodka, and Italian tomato sauce.

These containers were presented on a shelf, stacked two or three deep, and flanked by two similar containers that were also stacked two or three deep (water/orange cordial bottles were stacked two deep, because of limited availability of containers, all others were stacked three deep). The flanking containers were always made of flint glass or, in the case of one set of water/cordial bottles, clear plastic. The type of lighting (fluorescent tubes 840) was selected to match that typically found in supermarkets and the levels were adjusted appropriately (500-700 lux).

All original labelling was removed from the containers and standardized labels were attached, simply stating what the product was (e.g., "salad dressing"). Labels were printed in black on a light grey background. This label colour was selected to be neutral with respect to the detection of colour in the glass, following the results of the psychophysics studies, regarding label colour, as reported in Sections 2.3.4 and 2.3.5. They were placed around the waist / middle section of the containers. The water/orange cordial bottles also had a label on the bottle shoulder.

2.2.5.1.3 Questionnaire

Participants completed a 67 item computer-presented CAPDeCO Questionnaire[18] for each of the nine sets of products viewed (a total of 594 questionnaire items rated). This questionnaire is a multi-component assessment of product container designs based on the CAPDeCO Model, and focuses on: Cognitive associations and evaluations, Affective Responses, Practicality, Design form, Context, and Outcomes. Items were developed, in part, on the basis of the results of the focus groups. Responses were obtained using a seven point Likert scale, with a negative descriptor at one end (e.g., "not flamboyant") and a positive descriptor at the other end ("flamboyant"). The final scales are as follows: 'Quality' (positive cognitive evaluation), 'Positive affect', 'Negative affect', 'Fun', 'Purity', 'Practicality', 'Everyday', 'Traditional', 'Fragility', 'Logical', 'Decorative', and 'Appetising contents'. In addition participants' responses for the following single items were recorded and tested: "I would like to purchase products in this container", "A would be happy if friends saw this container in my hand/home", "Purchasing products in this container would represent poor value for money".

[18] Westerman, S.J., Tuck, G.C., & Oates, L. (in preparation). Development of a Multi-Factor Psychometric Assessment Method for Glass Food and Drink Containers.

2.2.5.1.4 Procedure

Participants were seated at a table directly in front of the shelves. Initially they responded to a number of items relating to demographics and shopping behaviour. They were then presented with a series of products on shelves. They were asked not to pick up or touch the containers. They were also asked to look away as each shelf combination was set up by the experimenter. The shelf display comprised sets of the product to be rated and the two flanking sets of containers that were placed approximately 20cms away. Containers were presented in a counterbalanced sequence, under the constraint that the same type of container was never presented twice consecutively. This was to encourage participants' sense that they were making different assessments each time (presenting the same container twice in succession, albeit in slightly different colour may have discouraged this).

Participants completed the CAPDeCO questionnaire for each container presented (nine times). Because of the pragmatic difficulties associated with switching the container contents, 36 participants were tested with one set of products (water, whisky, salad dressing) before a further 36 participants were tested with the second set of products (orange cordial, vodka and Italian tomato sauce).

2.2.5.2 Results

Differences in consumer perceptions of particular products that are not influenced by the manipulation of glass colour are beyond the scope of this work, and are not reported here. Moreover, the effects of the between subjects manipulation of container contents are only reported if they interact with the variable 'container type'. The manipulation of 'container contents' concerns the simultaneous change of three products and therefore cannot be interpreted meaningfully in isolation.

There were no reliable effects of container colour on ratings for the 'Quality' (positive cognitive evaluations of design) or 'Positive affect' (positive emotional response) scales. Ratings for the 'negative affect' scale indicated combined effects of container colour and container type. This seems to result from participants reporting relatively increased negative affect (a negative emotional response) when sauces were placed in the darker green containers.

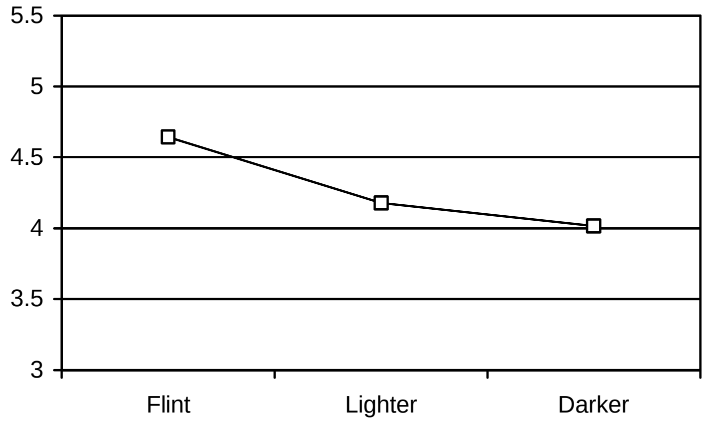


Figure 14: Effects of glass colour on ratings of the 'Appetising Contents' scale.

For the 'appetising contents' scale the effects of glass colour were highly significant. Contents were rated as progressively less appetising as the green tint increased. This effect was stronger for some products. For example, it was particularly strong for orange cordial (Figure 14).

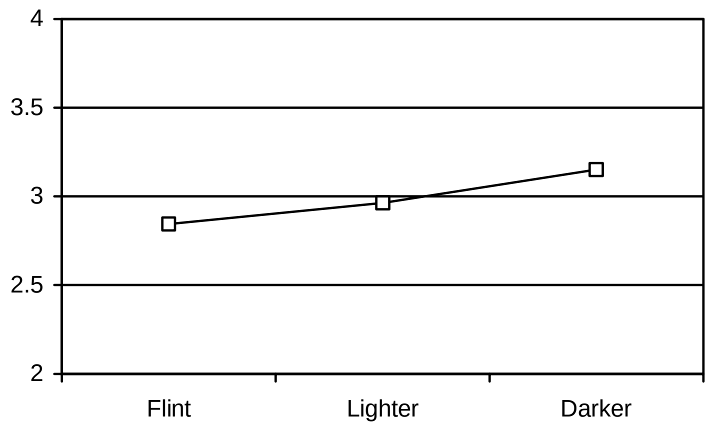


Figure 15: Effects of glass colour on ratings of the 'Decorative' scale.

Ratings on the 'Decorative' scale varied with container colour. Containers were rated as relatively more decorative as the level of green tint increased (Figure 15). This is not altogether surprising, as 'colourful' is one of the scale items. However, this effect varied depending on the type of container, with ratings for the 'decorative' scale increasing in line with colour for the water/cordial bottle and the spirit bottle, but there being little effect of colour for the sauce container.

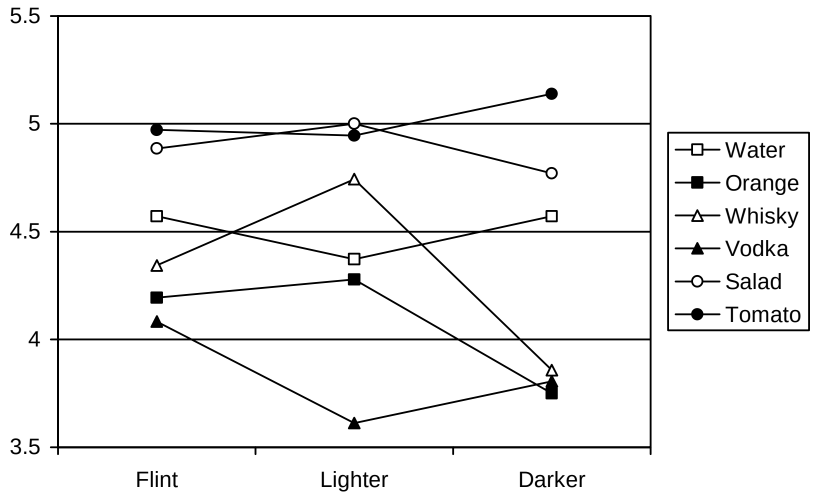


Figure 16: Effects of container type, container contents, and glass colour for the 'I would like to purchase ….' Item.

For the single 'I would like to purchase ….' questionnaire item, relative differences were apparent when considering the combined effects of container type, container contents, and glass colour. Ratings were lower for orange cordial in the darker green colour, although there was little effect of colour on the same bottle when it contained water (Figure 16). Ratings were greatest for whisky in the light green coloured bottle, whereas for vodka it was greater when in the flint bottle and lowest in the lighter green bottle. There was a (small) tendency for the darker green container to increase 'liking to purchase' of red sauce, but decrease 'liking to purchase' of salad cream.

2.2.5.2.1 Effects of age group and gender

The analyses described above were repeated with either age group (younger, middle, and older) or gender as an additional between subjects variable.

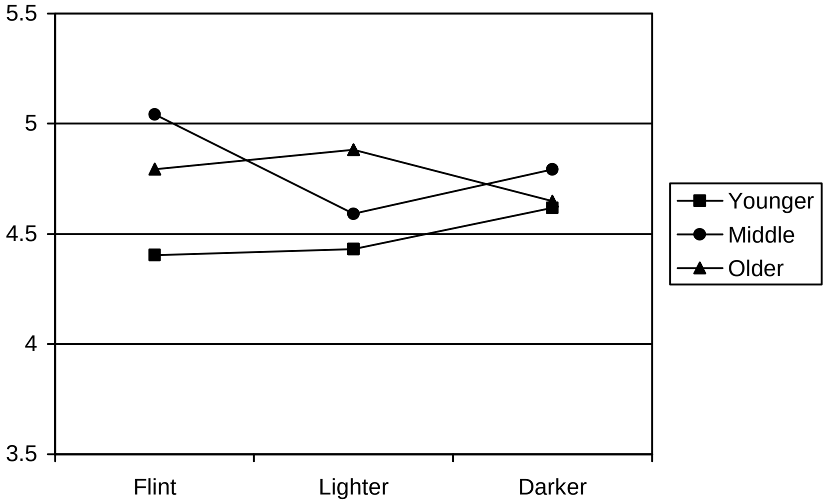


Figure 17: Effects of age group and container colour for the 'Traditional' scale.

The effects of age group combined with those of container colour to produce differences in ratings on the 'Traditional' scale (Figure 17). Broadly, this can be characterised as the older and middle age groups rating flint containers as more traditional while the younger age group rated the darker green container as more traditional.

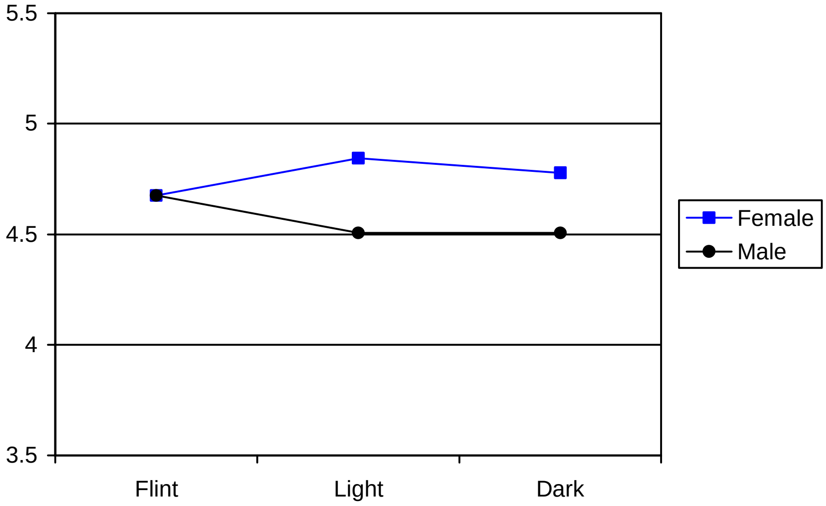


Figure 18: Effects of gender and container colour for the 'Practicality' scale.

There were combined effects of gender and container colour for the 'practicality' scale. As can be seen in Figure 18, female participants tended to regard the green tinted containers as more practical, whereas the reverse was true for male participants.

There were also less easily interpretable patterns that included group differences for the combined effects of:

- age group, container type, and container colour for the 'positive affect' scale
- age group, container type, and container colour for the 'Fragile' scale.
- gender, container type, and container colour for the 'Fragile' scale
- gender, container type, and container colour for the item 'Happy if friends saw..'.
- gender, container contents, container type and container colour for the 'Negative affect' scale.

2.2.5.3 Summary

This section of the report provides details of an experimental study of the effects of manipulating glass colour (flint versus lighter green versus darker green) on consumers' perceptions and attitudes. Effects of container type, container contents, and consumer age and sex were also considered. Containers were presented in conditions that simulated features of supermarket shelf presentation.

From the results of this experimental study it would seem that effects of glass colour are not reliably related to consumers' perception of container quality. However, results suggest that consumers' perception of the contents of the container is a major concern when considering variations in the colour of food/drink container glass. Participants' ratings for a scale assessing how appetising the contents appeared indicated that they thought that the content would be less appetising as levels of green tint to the glass increased. Although interactive effects suggest that this will vary, to some degree, depending on the nature of the product. This is consistent with the results of the focus groups. Nevertheless, for all products tested, the consistent trend was for products presented in green tinted glass to be rated as less appetising than the same product when presented in flint container that was identical in all other respects.

Effects of glass colour, when considered in isolation, were not reliable for participants ratings of the item 'I would like to purchase products in this container', although there were complex combined effects that included effects of container/product type. Given the effects of glass colour on the extent to which the contents were regarded as appetising this may seem surprising. It may be that consumers are able to dissociate the effects of appetising appearance of contents – although this can be questioned on the basis of the results of the focus groups. Alternatively, it would be possible that purchase decisions are a complex amalgam of many factors; with assessments of attributes such as 'decorativeness' and feelings of 'negative affect' influencing decisions.

There were a number of effects of individual differences (age and sex). Caution should be exercised when considering these. Many tests were conducted and this increases the risk that some will reach statistical significance purely by chance variation in scores. Certainly some of these effects are difficult to explain. It would be appropriate to look for consistencies in the results of the two studies before reaching any conclusions with respect to individual differences.

2.2.6 Consumer perceptions and attitudes towards coloured containers: Wine and Jams study

This study was designed to extend the work of the previous study and to consider consumers' responses to glass colour manipulations for two products that had been identified at Colourite project meetings as being of particular interest to involved partners. The first of these was wine (both red and white), and the second was mint jelly. With regard to this latter product, it had been hypothesised that the colour of the jelly would mean that there would be little effect of a green tinted container. To provide a contrast, and to enable confirmation/replication and extension of some of the findings of the previous study, two similar products of different colours, orange marmalade and raspberry jam, were also included for testing and comparison. Based on results for orange cordial, in the previous study, it was hypothesised that orange marmalade would be rated poorly when in darker green containers. The darker colours of the mint jelly and, to a lesser extent, the raspberry jam, might result in little effect for either of these products.

With regard to the wine, there was a particular interest in whether there were any detrimental effects of bottling white wine in green glass. An optimistic experimental scenario was adopted. In an initial survey of wine fill levels, it became apparent that there was no common practice. For this study all bottles were given a plastic cap and filled to this level (i.e., there was no exposed glass at the neck). In this way results might present a 'best case scenario' for brand owners or bottlers, with respect to any detrimental effects of glass colour. Red wine was included to provide a contrast, both in the colour of the product, the likely visibility of the glass colour, and also for the fact that red wine is typically bottled in green glass already.

2.2.6.1 Methodology

2.2.6.1.1 Participants

Thirty-six participants, 15 men and 21 women, aged between 19 and 71 years (mean=43.69) took part in this study. They were recruited via the University of Leeds website, in a local health and fitness centre and from the Leeds area via newspaper advertisements in the local gazette. As a requirement for taking part, participants had to be red or white wine drinkers and/or jam/marmalade/jelly consumers. In terms of employment status, 33.3% were retired, 27.8% were employed, 30.6% were students, 5.6% were housewives and 2.8% were unemployed.

2.2.6.1.2 Materials

Containers

Two container types, a wine bottle or a preserve jar, were used as experimental stimuli. These were available in three glass colours (flint, lighter green, and darker green). The wine bottles were selected from a 'colour change' sample provided by one of the project partners. The jars were industrially sprayed (as per the previous study). The colour of the containers was assessed by the Department of Colour Chemistry (see Appendix A for details). Each colour of wine bottle was filled with both white and red wine. Each colour of preserve jar was filled with orange marmalade, raspberry jam, and mint jelly.

Labels were purpose designed for the preserve jars (rather than use familiar brands) to be appropriate to the product. Colours were based on current leading brands. Label height was approximately 6cm. For the wine bottles, sets of (unbranded) red and white wine labels were purchased from a Home Brewing shop. Wines were filled to the same levels, corked and sealed with a gold cap / sleeve around the neck of the bottle. The fill level reached the cap, making it more difficult for participants to determine glass colour.

Questionnaire

The questionnaire used for this study comprised 15 items. Ten of these were combined, based on the CAPDeCO assessment approach, to form three scales: 'appealing contents', 'quality'; and 'traditional'. The remaining five items were individually tested. Four of these were:

"I would like to purchase products in this container"

"I would be happy if friends saw this container in my hand/home"

"I think the design of this container is elegant"

"Purchasing products in this container would give poor value for money"

The final item differed when testing wines versus testing preserves. For wines participants were asked to rate whether the contents looked very alcoholic, for preserves they were asked to rate whether the contents looked strong tasting.

2.2.6.1.3 Procedure

All participants completed the assessment of the wine bottles first. Three bottles, in each glass colour, of red or white wine were placed in front of participants. Order of presentation (red versus white) and spatial order (left, centre, and right) was counterbalanced. Participants assessed the three bottles starting with the bottle positioned on the left, progressing to the centre bottle and finishing with the bottle positioned on the right. Once the first set had been assessed (15 rating scales for each bottle) the second set (the other wine colour) was presented and rated in the same fashion. Participants were then presented with the preserve jars following the same procedure. Participants were told not to touch or pick up the containers.

The containers were displayed upon two pieces of large white card. Products were placed on one sheet of card whilst, a second sheet of card was placed as a backdrop behind them. Products were always placed equal distances apart (6cm) and in the same position on the card, with the product labelling facing to the front (as they would appear on a supermarket shelf). Lighting levels were set to approximate those found in supermarkets (500-700 lux).

2.2.6.2 Results

Effects of bottle colour (flint versus lighter green versus darker green) and bottle contents (red versus white wine) were tested in combined analyses.

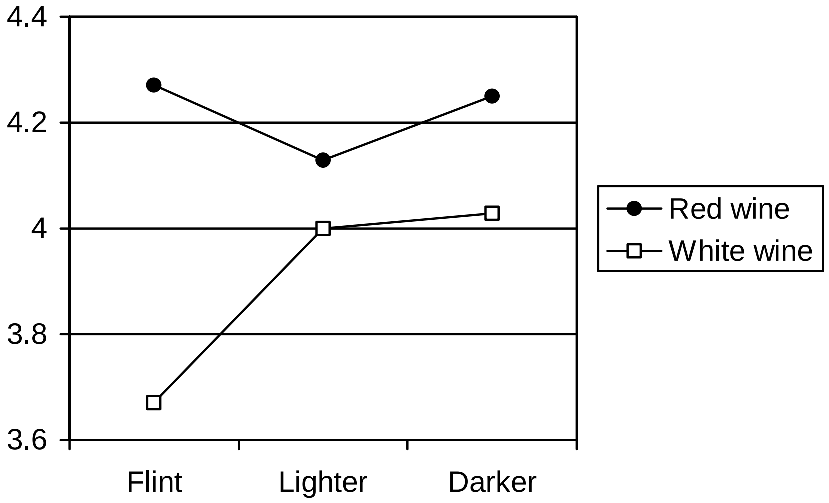


Figure 19: Effects of wine colour and bottle colour on ratings of 'Quality' scale.

Participants rated bottles that contained red wine as being of higher quality than those containing white wine. However, there were also combined effects of bottle colour and wine colour, with bottles containing white wine receiving relatively low ratings of 'quality' when in flint, but the bottle colour having relatively less effect on participants' ratings when the bottle contained red wine (Figure 19). When these effects were tested separately for bottles containing red wine and white wine they were not found to be reliable.

Contrary to the previous study, there were no reliable differences for the 'Appetising contents' scale. There were also no reliable differences for the individual questionnaire items 'happy if friends saw', 'give poor value', or 'likely to purchase'.

Testing the effects of consumer age and gender for wines

Further analyses were conducted to examine the effects of age and gender. For the purposes of analysis participants were allocated, post hoc to one of two age groups (19 to 36 years and 37 to 71 years). There were no reliable effects of gender that related to glass colour.

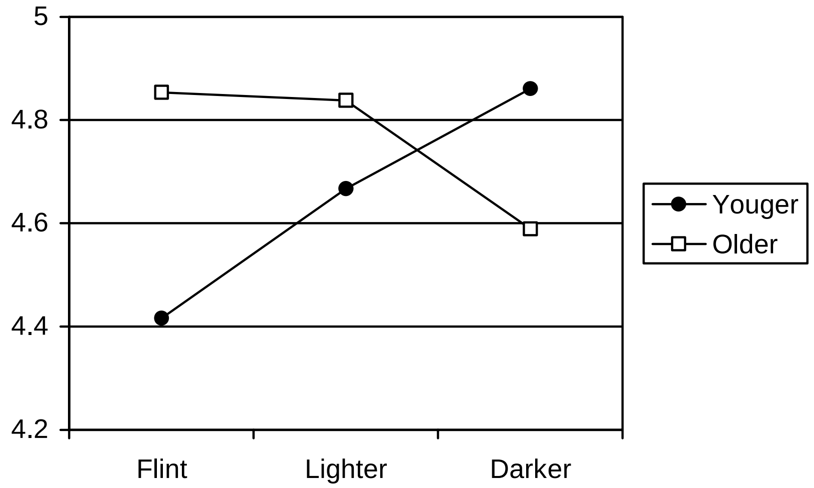


Figure 20: **Effects of age group and bottle colour for ratings on the 'Traditional' scale.**

However, the combined effects of age group and bottle colour produced differences with respect to ratings on the 'traditional' scale. As can be seen from Figure 20, the younger group of participants tended to regard darker green glass as more traditional, whereas the reverse was true for the group of older participants.

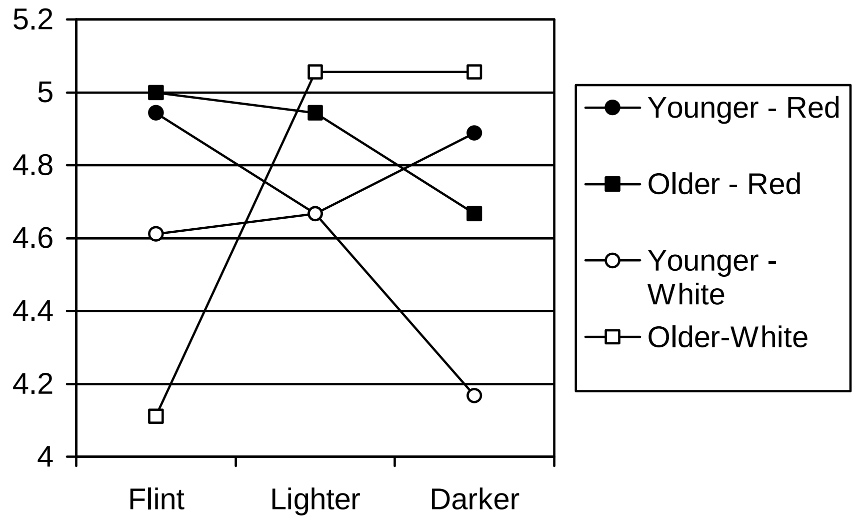


Figure 21: **Effects of age group, wine colour and bottle colour for ratings on the 'happy if friends saw' item.**

Effects of age group, wine colour, and glass colour also combined to produce differences for the questionnaire item 'Happy if friends saw…..'. In large measure this seemed to be due to age differences in ratings for white wine (Figure 21). Younger participants said they would be happier if their friends saw them with white wine that was in a flint or lighter green glass bottle, whereas older participants' ratings indicated that they would be happier if their friends saw them with the lighter green or darker green bottle. This pattern of differences was 'mirrored' to some extent by ratings for the 'poor value' item, with participants' ratings indicating that they generally prefer to be seen with wine bottles that reflect better value.

2.2.6.2.1 Preserve jars

Analyses conducted on ratings of the Jam/Jelly/Marmalade products followed a similar pattern to those for the wines.

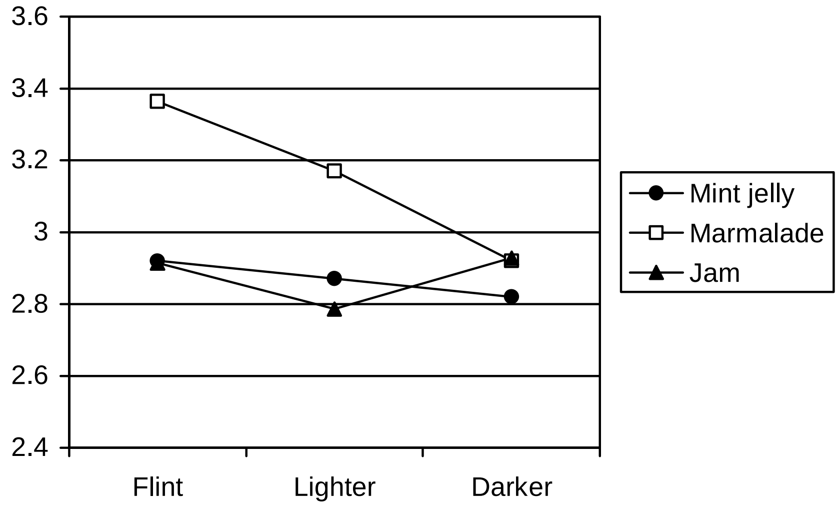


Figure 22: Effects of product type and container colour for ratings of 'Quality' scale.

Combined effects of glass colour and product type produced reliable differences for the 'quality' scale, with orange marmalade being rated as being of relatively high quality when in a flint jar, but as being of progressively lower quality with increasing green hue (Figure 22). In contrast, glass colour did not appear to exert much effect on quality ratings for raspberry jam or mint jelly. Ratings for both the 'Appetising contents' scale and the 'Happy if friends saw….' item followed similar patterns.

Testing the effects of consumer age and gender for jelly, marmalade, and jam

When tested, effects of gender that related to glass colour were not reliable.

When considering age differences, there were combined effects of age group, container colour, and container contents for ratings on the 'elegant' and 'Happy if friends saw…' questionnaire items. These seemed to result predominantly from the darker green container getting lower ratings from the younger group when containing orange marmalade.

2.2.6.3 Summary

This section of the report describes an experimental study of consumers' perceptions of, and attitudes to, two types of product: wines and preserves. Participants were presented with different types of wine (red and white) and preserves (mint jelly, orange marmalade, and raspberry jam) in containers that varied in glass colour (flint, lighter green, darker green). They were asked to rate each container and its contents on a number of scales, designed to obtain a broad understanding of consumer responses.

2.2.6.3.1 Wine

Contrary to results of the previous study, for wine the glass colour manipulation did not have a reliable effect on participants ratings of the 'appetising contents' scale. Given that the bottles used in this experiment were 'colour change' samples (produced when a glass manufacturer changes from flint to green production, or vice versa) and the bottles used in the previous study were sprayed samples, effects of differences in hue could be a possible explanation (see Appendix A, Table 6, for colour measurements of both sets of samples). Alternatively, it is possible that this difference between studies relates to the type of product.

There were combined effects of bottle colour and wine colour for a scale designed to assess consumers' evaluations of container design 'quality'. Participants regarded white wine bottles to be of higher quality when made from the darker green glass. Although, it should be noted that this effect was not found to be reliable when tested in isolation. Moreover, results from other rating scales suggest that preference may be somewhat age-dependent. When assessing white wine, older participants' ratings for the item "I would be happy if my friends saw this container in my hand/home" were higher if the bottle was darker green. However, for younger participants this glass colour received the lowest ratings for this item. Ratings for the item "Purchasing products in this container would give poor value for money" followed a similar pattern with participants reporting that they would prefer to be seen with containers that represented good value. The age-related effects tended to be reversed for red wine, with older participants indicating that, for them, the darker green container was associated with poorer value and that they would be less happy if friends saw them with it. Based on patterns of means, effects for red wine seem somewhat weaker than for white wine. This may be attributable to the bottle colour difference being more difficult to detect when the contents are red wine. This would be consistent with results of the preserves component of this study (see below). However, effects of traditional bottle colour may be particularly strong for wine [19].

When overall data are considered, these results do not suggest that there would be detrimental effects of bottling white wine in green glass. However, patterns of ratings for ratings of the items 'Happy to be seen with…" and 'Poor value" trigger a note of caution, and indicate that this may be somewhat age-dependent, with a less favourable outcome for younger consumers.

2.2.6.3.2 Preserves

For mint jelly and raspberry jam the effect of colour manipulation was relatively small. Presumably for mint jelly, the green contents disguise the green tint of the glass, or participants are happy to see a green product in a green glass container. For raspberry jam, again, the dark shade of the product may make it more difficult for the participants to identify differences in glass colour.

However, for orange marmalade the pattern of ratings indicated a relatively consistent preference for this product in flint glass, with the least preferred glass colour being the darker green. This was apparent in ratings for the 'Appetising contents' and 'Quality' scales and the item 'Like to purchase …'. These effects were also reliable when data for orange marmalade were tested in isolation.

2.2.7 Conclusions

In this section of the report a programme of research is described that was designed to examine consumers' perceptions of and attitudes to green tinted and flint glass. Information was gathered from a market survey of products (Section 2.2.1), focus groups (Section 2.2.2), two detection studies (Sections 2.2.3 & 2.2.4), and two studies in which consumers perceptions of and attitudes towards glass containers that varied in colour (varying strength of green tint), type, and content were tested (Sections 2.2.5 & 2.2.6). From this work, it has been demonstrated that effects of glass colour are dependent on the type of container, the type of product under consideration, the colour of the label applied to the container, and the characteristics of the individual. A broad overview of results is presented here.

2.2.7.1 Perceptions and Attitudes

An important point that was originally noted in the focus group component of this work is that, when glass colour is not strong, there is a tendency for consumers to attribute glass colour differences (as compared to flint glass) to the contents of the container. The detection studies provide an indication as to where important boundaries lie in this respect; i.e., the minimum threshold at which consumers are able to detect some colour variation, and the point at which they become relatively certain that glass colour differences exist. However, whether this is also the point at which attributions change remains to be determined. In two studies in which a variety of ratings were obtained from participants to ascertain their perception of and attitudes towards a range of containers. Scores on a scale (a combination of rated items) assessing the extent to which participants felt the contents of containers looked appetising were frequently (but not

[19] Moody, (1963). Packaging in Glass. London: Hutchinson.

always) strongly influenced by manipulations of glass colour. One of the recognised advantages of glass containers is their transparency and the opportunity this affords the consumer to see the product inside (see Griffin et al., 1985). It would seem that this advantage may be seriously compromised by the use of green tinted glass for some product types.

From these studies we can begin to determine which products these might be. For example, products that are clearly orange in colour tended to be viewed more negatively (assessed as less appetising) when presented in green tinted glass. This was the case for orange cordial (by way of contrast, the same effect was not apparent for water when presented in the same container) and also for orange marmalade (again, by way of contrast, the same effect was not present for mint jelly or raspberry jam when presented in the same container). Salad cream was identified by some participants in the focus groups as having a less appetising appearance when contained in tinted green glass. Consistent with this, in one of the experimental studies, the effects of increased strength of green glass colour were found to be more pronounced for salad cream than for tomato sauce when presented in the same type of container.

Results for vodka and water (both clear liquids) followed a similar pattern with respect to ratings of appetising appearance. Although means were highest when presented in a flint container, they were lowest when presented in a lighter green (as opposed to darker green) container. It is possible that this represents an inverted-U association with colour depth (that might become more apparent if colour depth was increased further), and that presentation in darker greens would be accepted by consumers. In the case of water, this would be consistent with current marketed products, although would run counter to much current marketing for vodka that emphasises clarity.

Although, in many cases, products appeared less appetising when presented in containers with tinted green glass, this did not translate directly into reduced desire to purchase. It is suggested that this may be because other aspects of the container (as assessed, e.g., by ratings for the scale 'Decorative' – which may relate to aesthetic appreciation of the container) combine to produce a more complex pattern of influence.

Consumer perceptions of wine did not follow the patterns of several of the other products tested. There was no effect of bottle colour on how appetising the contents seemed. It may be that the traditional use of green glass is an important feature in this. This would be consistent with the finding of no effect of colour on preference for beer bottles; and forms an interesting comparison with results for the 'appetising' scale for the jams, with glass colour having little apparent effect for raspberry jam or mint jelly. In these instances (but presumably not for white wine), the lack of effect may be because the dark colour of the product masked the manipulated differences in glass colour. However, it should be noted that in the filling and capping of products, for these rating studies, little if any glass in the neck area of the container was exposed without product or cap (an optimistic scenario from the point of view of using green tinted glass containers). Filling to a lower level or not including a cap could make colour judgments easier.

Glass colour-related differences in consumers' ratings of a scale thought primarily to reflect assessments of container design quality (positive cognitive evaluations) were very limited. Within the industry, quality is often held to be most strongly associated with flint glass, and this is a driver for glass clarity. However, results from these studies suggest that consumers' assessments of container design quality may be dependent (when comparing flint with green tinted glass) on the combined effects of container/product. For most products tested no reliable effects of colour were found.

2.2.7.2 Detection

It is useful to know how much colour needs to be present before consumers begin to detect it; but also how much colour leads to consistent detection. Moreover, in applied consumer settings, often colour detection will be of an 'un-cued' nature. In other words, the consumer will not be consciously looking for colour comparisons. Two studies were conducted to address these issues using beer bottles of varying colour as stimuli. Under 'cued' conditions it was possible to identify boundaries at which participants' ability to detect green tint in a glass container was close to chance and, at the other extreme, at which it had reached asymptote. Comparison between 'cued and 'un-cued' performance is complicated by differences in the methodological approach that was required. However, un-cued performance appears substantially worse. When participants were asked about detection of colour differences, using the same materials as for the 'cued study', threshold was not reached and, when the bottle was full, only 6.5% of participants correctly identified the difference. Although it may be that the misdirection that was required in this study was too strong, and that this accounts for this low figure, it would appear that sensitivity to colour differences in an applied setting may be much poorer than cued detection would suggest. However, it should be noted, when considering applied settings, that the perception of green tint is magnified, particularly when the contents of a container are clear (e.g., water or vodka), when containers are stacked one behind another, as would typically be found on supermarket shelves (see report from Department of Colour Chemistry in Appendix A).

A potentially important finding, in both of these studies, was that detection performance appeared to benefit from a red label on the bottle. It seems probable that this relates to 'opponent process theory'[16] and that simultaneous colour contrast effects are in operation. This would lead to a bias to see green, whether or not it was actually present, when a red label was used. However, in the 'cued' study, ability to identify two blanks as being identical was also improved when a red label was used, suggesting that increased sensitivity to green may also be induced. Further work would be useful in this area. More detailed analysis of these data is also possible, taking response criterion into account when assessing performance (sensitivity to differences).

2.2.7.3 Individual Differences

Individual differences in age and sex were examined as predictors of consumers' attitudes towards green tinted glass and age differences were considered with regard to ability to detect colour differences. Effects of gender, although noted in some of the work did not appear strong, easily interpreted, or consistent, and further replication would be required to provide confidence in the reliability of these results.

With regard to age differences, some interesting results were obtained (although, again, further extension and replication would be advisable). In both of the studies that gathered rating scale assessments of participants' perceptions of and attitudes to container designs, older participants were found to view flint glass as relatively more traditional that green glass, and for the reverse to be the case for younger participants. (This only applies to wine in the second study). It is possible that this reflects changing attitudes towards flint glass; although this is obviously speculative. With regard to wine, combined effects of wine colour and bottle colour suggested that older participants take view aspects ("Happy if friends saw…" item) of white wine when in a green bottle more favourably than when it is in a flint bottle. For older participants, there was an opposing trend when red wine was the contents. For younger participants effects were a little less consistent, but ratings (for this item) were relatively higher for white wine in flint or lighter green. This may point to age differences in the acceptability of white wine in green bottles.

Finally, it is worth noting that there is a possibility that older participants are more susceptible to simultaneous colour contrast effects. Data supporting this may include something of an outlier, but replication and extension would be a worthwhile area for research.

2.2.7.4 Limitations and Implications for Future Research

As with any programme of research, particularly applied research, there are limitations to the work that has been done and the inferences that can be drawn. It is important that these are recognised and that the work is set in appropriate context.

First, it should be noted that hue (for the green tinted bottles) was not systematically manipulated. It is possible that different results would be obtained with different hues. Preferences may easily depend on the extent to which a colour is, e.g., green/blue as opposed to green/yellow. As mentioned earlier, measurements of the stimuli use in these experiments are available in Appendix A.

Second, assessing consumer perceptions and attitudes may provide an indication of purchase intentions but will not mirror actual purchase behaviour. Other elements, e.g., value, brand loyalty, and unconscious biases[12], will come into play. In our view, taking a multidimensional approach to the assessment of consumer perceptions, attitudes, and associations helps to identify such effects, but nevertheless, these are topics that should be high on the agenda for future research. Particularly relevant to this is the fact that this research has been conducted in a 'brand neutral' fashion. There may be further associations between brand and colour that will be of important when determining effects of container colour.

Third, it should be recognised that if the question being asked is "will changing from flint containers to green containers have a detrimental effect on sales?", no definitive answer can be given. It is not possible to prove a negative. The best that can be achieved is to provide indications that can be used by industry as contributions to the product design and marketing decision making process.

The final point that we raise here, although doubtless the interested reader will be able to add to this list, concerns consumer awareness of recycling and the potential associated benefits. Views solicited as part of these studies were typically obtained without specific reference to this. When this topic was raised, e.g., at the end of focus groups and in post-experiment debriefing, participants almost always responded positively. Consideration of promotional strategies in this area would be worthwhile, as would study of longer term familiarity effects. Obviously, the studies reported here reflect a 'snapshot in time'. There is reason to believe that consumer opinion may change with exposure to different packaging designs.

2.3 Prediction of Future Colour Demand

This task involved the collation of current, reliable data from which predictions of future container production for the UK and export market were made. The analysis covered the three main glass colours, flint, green and amber. This data was also used for the forecasting of the waste arisings reported in section 2.4.

2.3.1 Methodology

The UK glass waste stream should comprise domestic production plus the net balance between exports and imports. Domestic production can be determined with a high degree of accuracy but no rigorous system exists to collect data on packaging material as customs data invariably relates to the contents of the package. Undeclared cross-channel trade further adds to the uncertainty of such data. Nonetheless due to the obligation to recover packaging material the industry collates all relevant material in an attempt to provide a working estimate for regulatory and other purposes. The data presented here is that compiled for use by the PackFlow team of industry experts.

For the purposes of estimating the colour:

UK glass Production + Filled Imports + Empty Imports – Filled Exports – Empty Exports

Various data sources were compiled in order to quantify these sources over the period 2001-2004 and predict changes in the market through to 2008.

Essentially the methodology employed entailed classifying glass containers into a number of defined sub-groups which are known to account for the vast bulk of glass packaging products. Historic data on domestic production and import/export was then obtained on these sub-groups. The data was then used as the basis for forward predictions (to 2008) but, where appropriate, was modified in the light of the specialist knowledge of the PackFlow members.

The following sub-groups formed the basis of the analysis:

- Spirits
- Wines
- Beer/Alc. Beverages
- Soft Drinks
- Foods
- Cosmetics

Sources of data and calculations used can be found in Appendix B.

2.3.2 Home Trade Market Trends

Accurate data is available from UK manufacturers on their glass production and the proportion of that production which is used domestically. Beers, alcoholic beverages and wine are predicted to see sustained growth to 2008 whilst soft drinks are predicted to lose market share to other forms of packaging.

2.3.3 Imports and Exports

The UK is a net importer of glass, importing a large volume of green glass annually in the form of continental wines and beers. The UK exports around 600,000 tonnes and imports over 1 million tonnes. While the UK imports and exports similar amounts of clear glass the amount of green is much higher than exports and production. Imports and filled exports are based on less reliable data compared with Home Trade and empty exports. This is due to limited sources of data and the calculations used to quantify the glass packaging from hectolitres of contents imported.

Based on the best data available it is predicted that by 2008, relative to 2004, imports of glass packaging would increase by just over 160,000 tonnes whist exports would remain relatively static.

2.3.4 Predicted UK Glass Waste Stream (2008)

Details of the current (2004) and predicted (2008) UK glass waste stream by type and by colour are given in Table 7.

Tonnages	2004				2008			
	Clear	**Amber**	**Green**	**Total**	**Clear**	**Amber**	**Green**	**Total**
Spirits	74959	40638	73847	189444	83917	47247	85820	216984
Wines	221508	1087	481698	704293	253801	0	559981	813782
Beer/Alc. Beverages	204575	169401	341475	715451	222281	187355	362002	771639
Soft Drinks	290260	21607	19724	331592	271882	19409	19540	310831
Foods	466692	6360	11521	484573	496176	6010	15574	517761
TCP	44416	16714	16657	77786	45706	21093	14585	81385
Total	**1,302,409**	**255,807**	**944,922**	**2,503,138**	**1,373,764**	**281,115**	**1,057,503**	**2,712,382**

Table 7: UK waste stream predictions (Intermediate years given in Appendix C).

2.3.5 Conclusions

A very significant imbalance exists between the colour profile of the glass produced by the UK's container manufacturers and that found in the waste stream. The principal cause being the large imports of wine and beers packaged mainly in green glass. The export from the UK of large volumes of spirits packaged predominantly in clear glass is also a major contributory factor. This colour profile of glass recovered from the waste stream will thus contain significant proportions of green glass. Unfortunately as glass is increasingly collected in a mixed form the presence of large quantities of green glass will greatly inhibit the ability of the UK container manufacturers to obtain good quality clear glass for use in their melting furnaces.

2.4 Prediction of Future Collections

The UK's container glass industry has long recognised the importance of recycled glass as a feedstock to its furnaces. The industry pioneered the bottle bank collection scheme with the introduction of the first facility in Barnsley in 1977. The coverage of the scheme was gradually increased and the 1000th bottle bank was commissioned in 1982. In 1986 the Glass Industry made a firm commitment to the UK government that it would double the number of existing sites and reach a total of 5,000 by the year 1991; a target that was actually achieved in 1990. The bottle bank scheme was then expanded rapidly until by the year 1997 a total of 22,074 sites were in operation. Since that time the expansion has ceased and the latest returns show an actual fall in the number of established sites.

At the beginning of 2002, some 20796 bottle bank ("bring") sites were established throughout England, Scotland, and Wales and glass collection from these banks exceeded 500,000 tonnes.

In recent years environmental issues have become a major political concern and governmental bodies have increasingly resorted to legislative means as a method of increasing the recycling rate of many materials including glass. Current UK legislation that has a potential influence on the recycling effort includes:

- Landfill Allowance Trading Scheme (LATS)
- Household Waste and Recycling Act
- Packaging Waste Regulations
- Integrated Pollution Prevention and Control Directive (IPPC)
- Environment Protection Acts 1990 and 1995
- Aggregates Tax
- Climate Control Levy
- End-of-Life Vehicles
- Waste Electrical & Electronic Equipment (WEEE)
- Removal of Hazardous Substances (RoHS)
- Heavy Metals – Essential Requirements

Many of these pieces of legislation seek to achieve their aims by a combination of target setting and penalties for under achievement. Unfortunately, whilst all these regulations have the same laudable intention of minimising waste and increasing the recycling rates, in practice their different emphasis can lead to incompatible and even conflicting targets for the obligate parties. Typically the cash starved local authorities will be seeking compliance with regulation at the least cost rather than the best environmental outcome. In relation to glass recycling, the collection of colour sorted material promotes the more environmentally sound route of remelting the glass. However, municipal authorities do not have material specific targets but are driven by simple overall collection rates so many do not bother to collect glass and, of those that do, a significant number collected glass in mixed form as this is perceived to be the cheapest option.

Thus in recent years the UK has seen a large increase in the level of mixed colour glass collection across the country linked to the growth in kerbside collection. The trend to mixed collection can also be seen at Materials Recycling Facilities (MRF's), the driving force in this instance being the lack of space the hosts are willing to provide for the facility.

British Glass regularly analyses data collected from Local Authorities on the amount of municipal kerbside and "bring" glass collected and is able to determine the relative proportions of colour sorted and colour-mixed glass. British Glass data for the 2002/03 indicated that 48% glass collected via kerbside schemes was of mixed colour; the corresponding value for the bring system was 15%. Overall mixed glass collection was equivalent to 23% of all municipal glass collected (equivalent to 13% of total glass). A more recent (2004/5) survey by Valpak determined that the relative proportions of glass collected by bring, kerbside and commercial schemes were 56, 40 and 4% respectively. The more recent Valpak data recorded a marked increase in the amount of glass collected in a mixed form, with 23% of the glass collected by the bring systems now in a mixed form; the corresponding figures for the kerbside and commercial streams being 56 and 66%. The overall mixed glass collection rate is thus calculated at 40%. Details of the 2004/5 surveys are given in Figure 23.

The bring system thus remains the primary route for glass collection accounting for 56% of all glass collected. However, few new sites are being commissioned whilst kerbside collection is growing apace; in some cases at the expense of the local bring facility. Kerbside collection is being driven by the Household Waste and Recycling Act which stipulates that local authorities must collect at least 2 materials from all households and is also encouraged by the targets laid out in the Waste Strategy 2000. The volume of glass collected from kerbside schemes grew by over 80% in the 2 year period 2001-3 and its growth rate continues to accelerate. It is anticipated that in the near future Kerbside will supersede the bring system as the principal mode of glass collection. Kerbside schemes tend to favour the collection of mixed glass as the premium paid for collecting colour sorted glass is generally not considered sufficient to cover the additional costs. The number of kerbside collections is forecast to continue to rise in the medium term and the majority of these will collect only mixed glass. By contrast the volume of glass collected from the bring system will stagnate and increasingly be converted to mixed glass collection. By 2008 it is predicted that the combined effects of these trends will result in around 60% of all municipal glass being collected in a colour-mixed form. A relatively small amount of glass is currently collected from commercial sources (pubs and clubs); this volume is also predicted to rise and again the favoured mode will be mixed collection due principally to the lack of storage space.

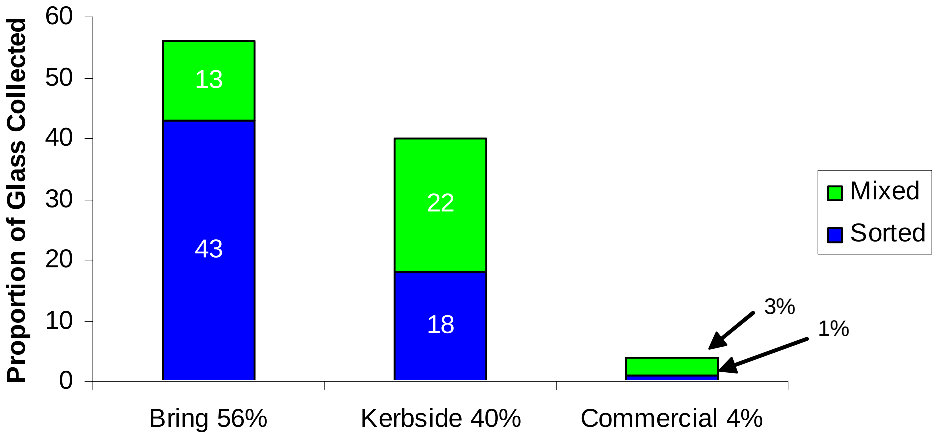


Figure 23: Glass collection modes with the resultant effect on colour separated glass arisings.

2.4.1 UK Container Glass Production and Remelting Capacity

Currently the UK produces in excess of 2 million tonnes of packed glass; the colour split of the glass manufactured and the amounts of recycled, colour sorted glass that were remelted in 2005 are given in Table 8. Glass manufacture inevitably incurs some production losses and the process has a typical yield of 85%. Fortunately all the factory losses can and are recycled back into the furnace. Thus glass has a basic 15% internally recycled level prior to the inclusion of any externally sourced glass (foreign cullet). For the purposes of this report the term "recycled glass content" will relate only to external cullet and will be expressed as a fraction of the factories' packed ware production.

Table 8 demonstrates the predominance of flint glass manufacture in the UK. However, much of this flint glass leaves the UK form of spirit bottles, whilst imported glass tends to arrive in the form of predominantly green wine and beer bottles. This colour imbalance is reflected in the UK's waste stream and ultimately in the relative levels of recycling that are achieved by the glass container industry.

	Flint	Green	Amber
Production (tonnes packed)	1,297,000	419,000	375,000
Production (%)	62	20	18
Recycled glass content (tonnes)	315,000	345,000	82,000
Recycled glass content (%)	24	82	22

Table 8: UK container glass production and recycled content[20].

Supplied with pristine quality cullet no technical reason exists to prevent container furnaces operating at recycled glass (cullet) levels of 90% irrespective of the colour of the glass. In reality waste glass collected on an industrial scale will inevitable suffer some degree of colour cross-contamination. Colour contamination significantly reduces the practical cullet levels that can be achieved in the manufacture of flint and amber glasses but has little impact on the levels that can be accommodated in green glasses. Thus the degree of colour contamination, allied to customer specifications, determines the upper levels of cullet that can be accommodated in glass manufacture. Based on operational experience the practical upper levels of cullet that can be melted are given below in Table 9.

	Flint	Green	Amber
Production (tonnes packed)	1,297,000	419,000	375,000
Maximum recycled glass content (%)	50	90	50
Maximum recycled glass content (tonnes)	649,000	377,000	188,000
Colour sorted recycled glass (tonnes)	277,000	310,000	71,000
2004 shortfall (tonnes)	372,000	67,000	117,000

Table 9: Maximum cullet levels practicably achievable in container furnaces.

Based on current forecasts from the glass container manufacturers total glass production is predicted to rise to 2.54 million tonnes by 2008. The predicted rise in flint production for 2006 is due to both the commissioning of a new glass manufacturing facility in Cheshire, of which the first phase of production will be flint container glass, and the predicted increase in sales due to the football World Cup finals in summer 2006. At the time of writing an estimation of production from the proposed green container glass furnace, part of the second phase of the new glass manufacturing facility in Cheshire was not available and therefore data are not included. Details of these predictions are given in Table 10.

Year	Flint (tonnes)	Green (tonnes)	Amber (tonnes)	Total (tonnes)
2004 [a]	1,315,000	423,000	332,000	2,070,000
2005 [a]	1,297,000	419,000	375,000	2,091,000
2006	1,683,000	455,000	343,000	2,483,000
2007	1,688,000	486,000	341,000	2,517,000
2008	1,706,000	503,000	332,000	2,541,000

Table 10: Predicted container glass production 2004 to 2008 ([a] – actual).

The forecast rise in the production of container glass will not however be matched by a similar rise in the availability of good quality colour-sorted cullet from bring sources. The trend to mixed glass collection will actually reduce the availability of this material. Table 11 details the anticipated arisings of colour segregated

[20] UK Container Glass Manufacturers production data collated by British Glass.

glass. In addition, there will be further colour separated glass from kerbside. However, the fraction of colour separated glass is not reliably monitored and it is known to be relatively small, the majority being collected as mixed colour.

Year	Flint (tonnes)	Green (tonnes)	Amber (tonnes)	Total (tonnes)
2004	264,000	200,000	60,000	526,000
2005	266,000	196,000	57,000	519,000
2006	257,000	192,000	58,000	507,000
2007	237,000	181,000	55,000	473,000
2008	231,000	178,000	48,000	457,000

Table 11: Predicted recovery of bring colour-sorted container glass 2004 to 2008.

2.4.2 The UK Waste Glass Stream

DEFRA calculates the current total amount of glass in the waste stream in 2005 at 2.5 million tonnes, of which some 39 % or 945,000 tonnes are estimated to be green. Table 12 provides details of the container glass in circulation in the UK waste stream and the current levels of that glass which is recovered for return to melting furnaces within the UK.

	Glass in Circulation (tonnes)	Glass Remelted (tonnes)	Recovery Rate (%)
Clear	1,302,000	315,000	24
Green	945,000	345,000	36
Amber	256,000	82,000	32

Table 12: Colour profile of waste glass stream.

Waste glass is collected by a number of systems. Returning the glass to the melting furnaces is considered to be a good environmental option and the glass manufacturers offer a relatively high price for good quality colour sorted glass; this being especially true for flint glass. As the demand for flint glass substantially exceeds the supply from the colour sorted sources techniques have been developed to extract flint glass from mixed sources. The colour sorting technology is able to add significant quantities to the flint glass that is available to the glass manufacturers but the product contains a higher level of colour contamination than that delivered by the dedicated bring sites. Demand for recovered glass also arises from the many “alternative uses” that have been developed, and an increasing amount of processed cullet is now exported. The glassmaker thus no longer has automatic first call on glass collected

2.4.3 Predicted levels of Glass Recovery and Reuse

As many of the regulations which seek to encourage materials recovery and recycling are target driven there is a requirement to collect data in order to check compliance and for the purposes for future target setting. PackFlow[21] is the UK’s most authoritative study of the waste stream in relation to packaging waste which includes container glass. PackFlow 2008 was initiated by Valpak in May 2004 to provide a strategic overview of the measures that would be needed to achieve compliance with targets set by the European Packaging and Packaging Waste directive. The PackFlow analysis and forecasts drew on data collected from several sources including DEFRA, glass industry sources (British Glass) and information from compliance schemes.

According to DEFRA’s published figures the total quantity of glass packaging in the UK’s waste stream in 2005 amounted to 2.5 million tonnes. Consumption of glass packaging is predicted to grow to a value of 2.7

[21] Packflow data https://www.valpak.co.uk/nav/page1189.aspx

million tonnes by 2008. The Packaging Waste Regulations has set a recovery target for 2008 of 60% or approximately 1.63 million tonnes (based on the 2.7 million tonnes forecast).

Table 8 indicates that the container industry currently has the capacity to absorb approximately 1.2 million tonnes of glass and the industry would undoubtedly be a willing recipient of the material. If the growth in production indicated in Table 4 proves to be a reality then the industry would be able to utilise 1.47 million tonnes of recovered glass by 2008. Unfortunately the industry's ability to utilise cullet is not simply a matter of available tonnage but rather is critically dependant upon the colour split available; in particular the amount of flint glass of an acceptable quality. This constraint will prevent the industry realising its full recycling potential and the PackFlow analysis anticipated that the industry would only have access to approximately 800,000 tonnes of glass of an acceptable quality. In order to meet the 2008 target the balance must be directed to alternative uses, principally aggregates or export. The PackFlow analysis suggests that, based on current trends, the recovery effort will miss this recovery target by approximately 185,000 tonnes.

The latest 2005 returns show that the industry was able to out perform the PackFlow estimate for that year and recycled 742,000 tonnes. Based on this performance there would appear grounds to revisit the 2008 estimate of 800,000 tonnes. In consultation with the industry a revised 2008 figure of 900,000 tonnes is suggested. The ability to achieve this figure lies with the supply side of the industry and critically their ability to produce sufficient flint cullet of an acceptable quality; an increasing amount of which will need to be extracted from the mixed glass collection sources.

Table 9 predicts that in 2008 green glass manufacture will amount to 503,000 tonnes and will thus be able to assimilate approximately 450,000 tonnes (90% recycling rate) of the recovered glass. Initially this demand will be satisfied by the colour-sorted sources which by 2008 should amount to 178,000 tonnes, the balance of 272,000 tonnes will be met by colour sorting the by now plentiful mixed fraction. The mixed fraction is predominantly green and, as green glass manufacture can tolerate much higher levels of colour contamination than its flint counterpart, the sorting process is programmed to divert indeterminate material into green steam rather than risk contaminating the flint. The result is that the typical green, flint and amber outputs from the sorting process are nominally 75, 20 and 5% respectively. The actual colour profile of the mixed fraction contains less than 75% green but the sorting process has the effect of skewing the output in favour of the green fraction. Thus in order to fully satisfy the green manufacturing demand for cullet some 272,000 must be provided from mixed sources. In order to provide 272,000 tonnes of green glass some 360,000 tonnes of mixed glass must be sorted. Colour sorting 360,000 tonnes of mixed glass would also produce 72,000 tonnes of flint glass (20%) and 18,000 tonnes of amber (5%) which would be available to add to the respective colour-sorted resource. Thus processing the mixed stream to the maximum green domestic demand would direct approximately 800,000 tonnes to remelting application (457,000 tonnes bring plus 360,000 tonnes colour sorted).

Unfortunately providing an additional 100,000 tonnes of cullet to the UK melters to meet a target of 900,000 tonnes does not simply entail reprocessing a further 100,000 of mixed glass as the market for green is now saturated. The demand for the 100,000 tonnes of "additional" glass now exists only in flint and amber manufacture, and in order to provide this quantity some 380,000 tonnes of mixed glass must be processed and in so doing will generate a surplus of 280,000 tonnes of green glass. Thus the economics of sorting in excess of 360,000 tonnes of mixed glass, sufficient to meet a re-melt target of 800,000 tonnes, are dependant on finding a market for the surplus green glass (exports?). Figure 24 illustrates the influence of the limited demand for green cullet.

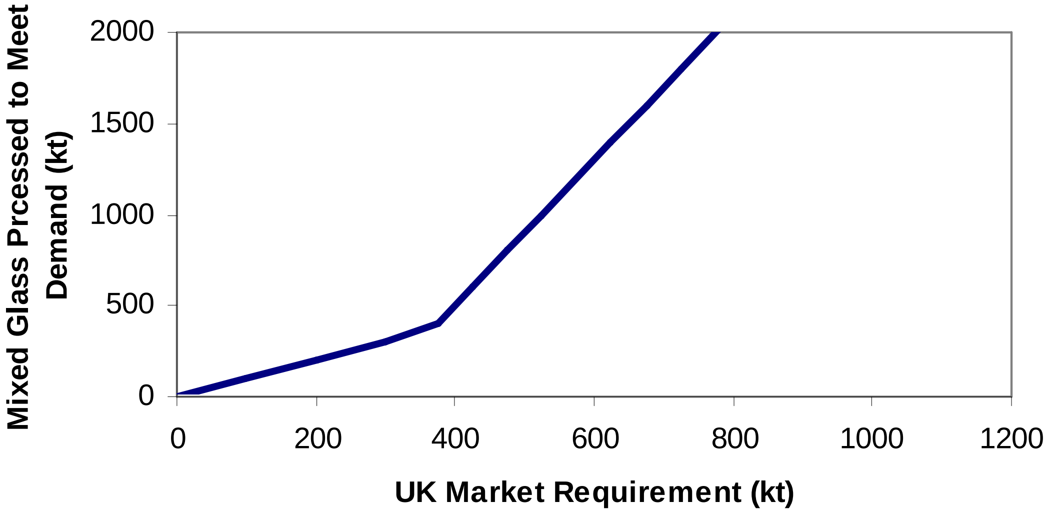


Figure 24: Mixed glass processing and domestic demand

Meeting a target to re-melt 900,000 tonnes is thus contingent on the supply industry's ability to colour sort 740,000 tonnes of mixed glass. Predicted arisings of colour-sorted flint and amber glasses in 2008 are estimated at 231,000 and 48,000 tonnes respectively (Table 11). Assuming that the supply side has the capacity to process 740,000 tonnes of mixed glass and that the generation of a large green surplus does not make the process uneconomic then Table 13 would represent the recycling levels in operation in 2008. Additional colour sorting would be greatly encouraged by either an increase in domestic production of green glass, which would increase demand for green cullet, or by exports.

Predicted Cullet Arisings 2008	Flint (tonnes)	Green (tonnes)	Amber (tonnes)	Total (tonnes)
Glass Production	1,706,000	503,000	332,000	2,541,000
Maximum recycled glass content	853,000	453,000	166,000	1,472,000
Colour-sorted recycled glass	231,000	178,000	48,000	457,000
Process 740 mixed	148,000	555,000	37,000	740,000
Total recycled glass	379,000	733,000	85,000	1,197,000
Total to re-melt	379,000	453,000	85,000	917,000
Surplus	-	280,000	-	280,000
Recycled glass content (%)	22	90	26	36

Table 13: Predicted availability of cullet by colour (2008).

2.4.4 Increasing the levels of Glass Recovery and Recycling

The cullet utilisation predicted in Table 8 is based on the colour demands as foreseen by the PackFlow team. A recent study, commissioned by WRAP, has highlighted the influence of the imports of green wine bottles on the UK's glass recycling efforts. As a result of this study WRAP will be seeking to improve the availability of cullet in the UK by encouraging changes to the wine trade. Essentially WRAP will be adopting a two-pronged approach of encouraging the bulk importation of wine to be bottled in the UK and, where this is not an option, persuading overseas wine exporters to bottle their UK product in flint glass. The first option would increase domestic demand for green glass production whilst the second would help address the colour imbalance between UK production and the glass found in the waste stream. The benefits of these two approaches are considered below.

2.4.4.1 Increasing Domestic Demand for Green Glass

If the domestic demand for green glass could be increased by the bulk importation of wine for UK filling, or by any other route including exports of green cullet, benefits would accrue as more mixed glass could economically be sorted. Green glass is the largest product stream from the sorting process and once the demand for this material is met sorting for the minor constituents rapidly becomes uneconomic. Increasing the green glass production would automatically increase the demand for green cullet. This increased demand could only be met from mixed sources but, assuming that the additional green glass had no adverse effect on the sorting capabilities, the sorting would also "liberate" additional flint and amber glass that would otherwise have been uneconomic to extract. Assuming the current colour profile for green, flint and amber outputs from the sorting process are unchanged at 75, 20 and 5% respectively then, for every 1000 tonnes of green glass produced, some 270 and 65 tonnes of flint and amber glass respectively would be extracted from the mix. In effect the level of green glass production would determine the recycling ratios achieved by both the flint and amber furnaces.
Figure **25** illustrates the potential influence of increased green production on the flint recycling ratio.

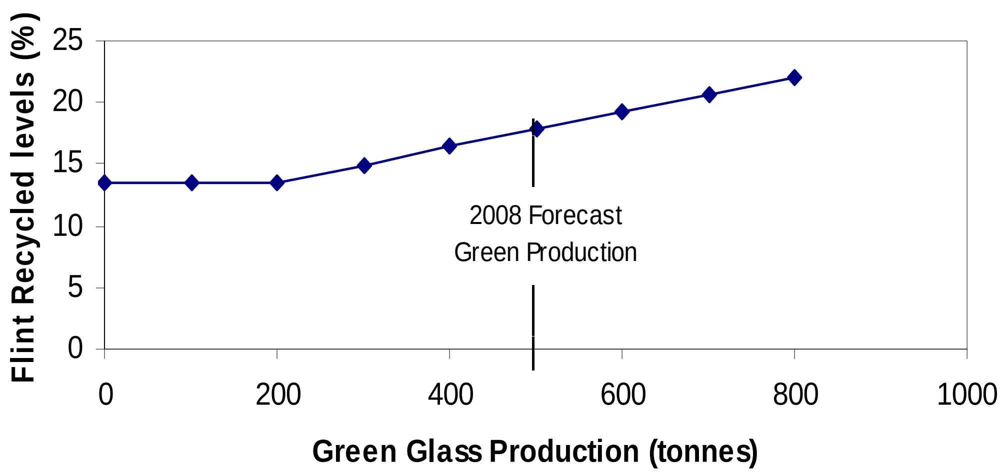


Figure 25: Influence of increased green production on the flint recycling ratio.

2.4.4.2 Increasing imports of Flint Glass

The UK is currently and will continue to experience a severe shortage of flint cullet. As the amount of pre-sorted flint glass from the bring sites declines the industry will be increasingly reliant on extracting flint glass from the mixed stream. Unfortunately green glass is the principal constituent of the mixed glass fraction. The amount of green wine bottles in this waste stream is the major contributory factor to this outcome. Should efforts to persuade overseas wine producers to bottle their UK-bound products in flint glass be successful then this would again benefit the recycling effort.

Ideally the mixed glass would be fully sorted into its constituent colours to provide feedstock for the melting furnaces. However, the colour sorting technology is not 100% efficient and in practice current sorting technology "loses" between 6 to 8% within the flint and amber fractions, the losses being retained within the green fraction. Thus colour sorting of the current profile of mixed colour glass yields approximately 20% flint, 5% amber and 75 % residual nominally green glass. The apparent change in the colour profile of mixed glass that has been colour sorted is given below in Table 14. The green component is seen to grow as it is able to accept limited colour contamination from the flint and amber streams.

Colour Component	Flint	Green	Amber
Glass in Mix (%)	28	60	12
Glass Recovered (%)	20	75	5
Recovery Efficiency (%)	71	125 [a]	42

Table 14: Colour profile of mixed glass ([a] – green recovery includes process losses from other streams)

If a substantial shift from green to flint were to be effected then as with the preceding scenario more of the mixed fraction could be economically sorted before the green demand is sated and further sorting becomes unviable. Figure 26 illustrates the effect of increasing the proportion of flint glass in the mixed stream at the expense of the green component (the amber fraction is assumed unchanged at 5%).

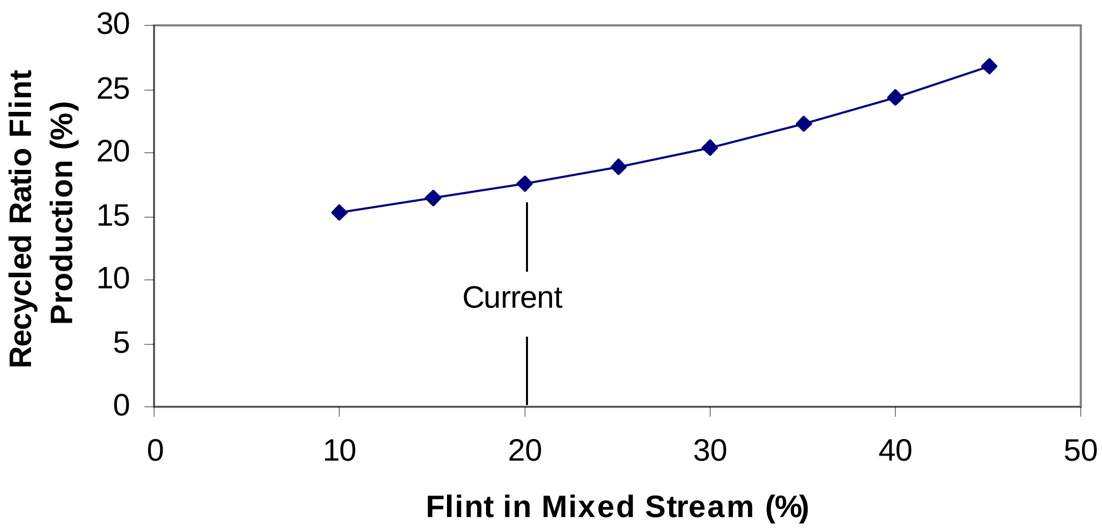


Figure 26: Influence of increasing the proportion of flint glass in the mixed stream.

2.4.5 Conclusions

Under ideal circumstances the glass container manufacturing process could operate at recycling levels of around 90%, however in practice many factors frustrate this ideal outcome. The UK glass industry produces predominantly flint glass so has a need for flint cullet. Unfortunately the colour imbalance between the import and export trade tends to flood the UK market with green glass. The traditional "bottle bank" systems yield good quality colour sorted glass and are a relatively cost effective method of collection. Increasingly glass is collected by kerbside collection schemes which tend to collect the glass in a mixed form. Regulatory limits are now imposed on packaging manufacturers and users as to the level of recovery and recycling that must be achieved. Re-melting glass is a good environmental option and the glass manufacturers are keen to use recycled material. Unfortunately the combination of the colour profile in the waste stream and the mode of collection inhibit the amount of glass that is directed towards the glass manufacturers.

The glass manufacturers were able to utilise a total of 742,000 tonnes of recovered glass in 2005, equivalent to a recycling rate of 35%. This total comprised the colour segregated glass that arises from the bring system "topped up" with colour-sorted glass extracted from mixed sources. At this level of recycling the preponderance of green glass delivered by the collection system begins to pose a problem as the demand for green glass in nearing its saturation point. In simple terms all the glass from the colour–sorted mixed stream can be used up to a recycling rate of 800,000 tonnes. Past this landmark the green demand is met and the useful extraction rate from the mixed falls to 25%. Thus in order to push recycling up to a further 100,000 tonnes to 900,000 tonnes almost 400,000 tonnes of mixed glass must be sorted. This obviously entails having the necessary installed sorting capacity and having a viable market for the surplus 300,000 tonnes of green glass.

The analysis underlines the importance of the bring system in providing large quantities of good quality colour sorted glass to the glass melters. Flint glass will remain the principal product of the UK's container glass furnaces for the foreseeable future and the bring system is best able to provide large quantities of good quality flint cullet at an economic price. The trend to mixed collection will inevitably lead to severe shortages in flint and amber glass for the UK melters and inevitably lead to recovered glass being directed into less environmentally beneficial options e.g. aggregates.

3 Industrial Implementation

This section relates to the work that was carried out under industrial conditions in working glass manufacturing plants and cullet processing facilities. The section reports on the current industrial practice, explores different decolouriser systems, the predictive glass colour model, development of a cullet specification and the effect of recycling on the heavy metal content of commercial cullet.

3.1 Benchmarking of Current Practice

The initial phase of this task involved a survey of current UK container manufacturers practice with regard to cullet level, quality and decolouriser use. This information was gathered by site visits and completion of a questionnaire (see Appendix D). Compositions and glass formulations were collected but is confidential information, so it is not possible to report exact levels of addition; however Table 15 illustrates the decolouriser levels found within the UK industry in the initial portion of the trials. The quantities of decolourisers have been normalised to a basis of 2000 kg of sand addition for each batch. In addition, samples of the batch materials, cullet and items of production were taken for colour and chemical analysis; results of which are reported where appropriate. This information is critical in the understanding of what decolourisers have been used and what comprises current practice and was the starting point for the decolouring investigation.

Decolouriser	**Decolouriser use (kg) relative to 2000 kg of sand**						
	a	*b*	*c*	*d*	*e*	*f*	*g*
Selenium Metal	0.05	0.07	0.03	0.13	0.08	0.19	
Cobalt Oxide	0.001	0.005					
Ceria			0.50				0.54
Zinc Selenide							0.02

Table 15: Typical level of decolourisers used by project partners, based on 2000 kg of sand.

At the time of the survey (January 2005) most of the UK container glass manufacturers were using selenium as the main decolouriser for flint production with some small additions of cobalt and/or cerium oxide in some cases. Predominantly the selenium is added as elementary selenium (Se) and introduces a pink colour that partially masks the green from the Fe^{3+}. Cobalt oxide shifts the colour towards a blue colour and is a relatively strong colorant. Cobalt oxide in combination with selenium will shift the perceived colour towards neutral (white). Elementary selenium is volatile at temperatures above 400°C and it is estimated that 80% could possibly be lost to evaporation. Some project partners have trialled zinc selenide as a replacement for selenium; it is thermally stable up to 850°C and therefore suffers lower evaporation losses. Some manufacturers have experience of using a zinc selenide system, but the cost effectiveness of its use makes the change over barely favourable. Selenium is a relatively expensive batch material and is classified as a toxic material and there is a drive towards seeking alternative decolourisers.

The levels of Se and CoO addition made are similar in most cases, as is the level of iron in the glasses which tends to be the controlling factor in any decolouriser addition. The Se is weighed in as part of a premix batch material to ensure the accurate dosing of a minor ingredient. It was found that the furnace operators tended not to adjust the decolouriser mixture for glass pull, cullet loading etc, reflecting the opinion that the dynamic nature of the furnace is best controlled by constant decolouriser mixtures. Maintaining a constant level of decolouriser can, on occasions, result in the production of pink glass when the cullet levels fall low and there is too much decolouriser in the glass shifting the colour towards the red (pink). Generally colour control for customers for whom the colour is critical is done by establishing visual standards for high and low extreme then working within those shades. Where glasses may have high levels of cullet, resulting in increased chrome and iron contents, the level of Se should be adjusted accordingly. However, this was generally found not to be the case and reflects a (mistaken?) belief that technologists have a good empirical understanding of the decolourising action of selenium. In reality beyond a certain level of iron and chrome the Se decolouriser is ineffective, and represents unnecessary expense.

The price of Se has increased from $90/kilo on 24/12/04 to $120/kilo by 25/02/05 which is equivalent to a change from £50/kilo to £66/kilo. Transferring this to a typical batch this has increased costs by £0.50 per tonne of batch, which equates to over £50,000 per annum increase for a typical sized furnace. This rise in Se metal prices continued, reaching a high of around £160 per kilo for the metal (December 2005), principally due to demand in the Far East and China in particular. Due to the instability in the Se metal market container glass manufacturers are now more willing to investigate other decolourisers.

This continuing price increase has led a supplier to begin promoting cerium oxide (CeO_2) to the industry and GTS has been closely working with the CeO_2 supplier by undertaking some experimental investigations as part of this project to review the level of addition and the effectiveness of CeO_2 as a decolouriser. At least three companies have trialled CeO_2 as a decolouriser to replace Se over relatively long production runs and others are also considering trialling this system. The current situation is such that only very small amounts of selenium are being added into container glass, and this project work has demonstrated that CeO_2 decolouriser system is cost effective.

During the project at least two companies trialled CeO_2 as a decolouriser to replace Se and now others are also considering trialling this system. While significantly larger amounts of CeO_2 are required, the reduced cost does make the economics favourable, especially when the availability of the Se is becoming a concern. From these industrial trials GTS has established a practical understanding of CeO_2 decolouriser system and will continue to offer technical assistance to glass container manufacturers. The melting trials were run in order to further understand the ability of CeO_2 to decolourise and whether other complementing colouring oxides are required.

3.2 Specification for Furnace Ready Cullet

GTS and SGT in conjunction have worked on the development of a specification for furnace ready cullet with input from UK container glass manufacturers and glass processors. The specification is based on previous cullet specifications used between customer/suppliers. The specification has gone through numerous reiterations to develop a widely accepted specification. The specification is based on cullet quality assessment data collected by SGT and GTS before and during the project by undertaking an extensive cullet sampling regime to assess current and past cullet quality on numerous samples.

Based on the cullet assessment data, the cullet specification has been developed and refined to suit the requirements of both glass manufacturers and glass processors. It was agreed that the colour specification was the overruling concern when maximising cullet additions, therefore, the specification is primarily intended to address the issues of colour contamination. Table 16 shows the agreed colour specification for the cullet used in container glass manufacture.

Glass Production – Colour	Coloured contaminants			
	Flint	Green	Amber	Other
Flint	Min 97%	Max 1.5%	Max 2.5%	Max 1.0%
Green	Max 10%	Min 70%	Max 20%	Max 1.5%
Amber	Max 10%	Max 20%	Min 80%	Max 1.0%

Table 16: Cullet colour specification.

Contaminant	Maximum permissible leve
Moisture	2 wt%
Organic	0.3 wt%
Inorganic including refractory material	0.001 wt%
Ferrous metals	0.002 wt%
Non-ferrous metals	0.001 wt%
Other glass types (Pyrex, crystal, ovenware, cooker top, plate, lighting, mirror, art, auto windscreen, opal, medical etc)	0.001 wt%

Table 17: Contamination specification (information only).

Table 17 shows the typical maximum contamination levels for cullet used in container glass manufacture; however, it has been agreed with the project partners that due to the sample size specifying the contamination level would not be appropriate. Therefore, these limits have been included for information only and should only be used in conjunction with a large sample size. There has been much debate during the project about the minimum sample size for determining the level of contaminants and no agreement could be reached without further work. However, it was agreed that the sample size would have to be in excess of 1 tonne.

The full detailed specification is enclosed in appendix E. In addition, a 'materials safety data sheet' accompanies the specification which is attached in appendix F. Both the cullet specification and cullet materials safety data sheet will also be available as standalone documents.

3.2.1 Cullet Sampling - GTS

In order to aid the development of the colour specification of furnace ready cullet, GTS carried out a cullet sampling survey. The aim of the sampling regime was to gain an understanding of the availability and the quality of the cullet currently available on the market for container glass manufacturers and to develop a cullet sampling procedure. Samples were taken from both cullet processors and container glass manufacturers between February and December 2005, with sampling taking place every three weeks. If testing is to be restricted to colour determination then a representative sample can be obtained with many fewer increments.

3.2.2 Method

A representative sample of a cullet pile was obtained by taking scoops of approximately 500 g from around the pile (Figure 27), from the base to the top. 10 to 12 scoops give approximately 5 to 6 kg of cullet, which was then mixed and reduced in size by the 'cone and quarter' method. The cullet was piled up, split into four and opposite quarters were removed. The process was then repeated to obtain a sample size of approximately 2 kg. A general observation of the cullet was made during this process to look for any major contamination (such as tamper rings, caps or plastic inserts such as in olive oil caps). This contamination will probably not end up in the final sample, but is worth noting as an indicator of the quality of the cullet. Figure 28 shows the flow chart of the cullet sampling and analysis procedure.

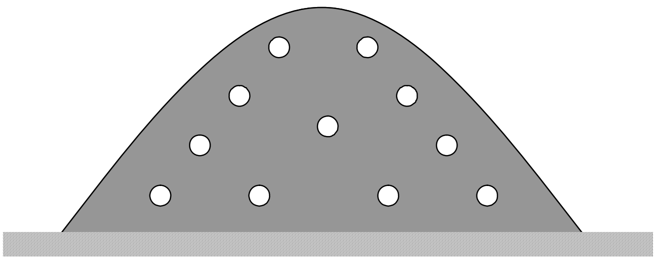


Figure 27: Multiple sampling model from the cullet pile and an operative taking a sample from a cullet pile.

The cullet was weighed into trays of a known weight (with a 2kg sample being split into three trays) and dried in an oven at 110°C for at least 1 hour. This ensured the cullet was dry, and it was then weighed again. The cullet was heated to 550°C and held at that temperature for at least an hour - burning off any organic substances that may have been present. The cullet was then weighed again.

Percentage weight losses on drying and ignition were then calculated, where:

$$weight\ loss\ (\%) \quad = \quad \frac{initial\ weight - final\ weight}{initial\ weight} \quad \times 100$$

Once the cullet had cooled, it was analysed for size distribution. This was done by using large stackable sieves, with apertures of:

- 31.5 mm
- 16 mm
- 8 mm
- 4 mm

Using a suitable sieve shaker, the cullet was shaken for at least 2 minutes to ensure size separation. The individual size fractions were then weighed, and recorded. The ferrous contamination was removed by passing the cullet close to a large magnet. The remaining cullet was then spread on a light coloured flat surface and separated by hand into:

- Flint
- Green
- Amber
- Miscellaneous
- Ceramic & stone
- Non ferrous contamination

3.2.3 Sample Size

Some debate exists over the size of the sample taken for analysis. Large samples of cullet will obviously give the fairest representation of the quality of cullet being analysed, but as analysing cullet is a labour intensive process it is not always economically viable to analyse large samples. The sampling method outlined above aims to be a quick technique that container glass manufacturers can easily adopt that gives reliable representative results. The cullet sampling technique used by GTS was tested against a project partner's sampling technique to test whether smaller samples give the same results as larger samples. Green cullet was sampled, with GTS collecting 5 kg from around the pile, and the project partner sampling 50 kg from around the pile. The results in Table 18 show that within the boundaries of experimental error, a 5 kg sample gives the same colour contamination results as a 50 kg sample. However, it has been accepted that a sample size of 5 kg is not appropriate for determining the level of other contaminants and this is an area of further work outside the scope of this project.

Sample Size	Flint %	Green %	Amber %	Misc %
5 kg	13.02	78.46	8.07	0.42
50 kg	12.26	79.23	7.93	0.59

Table 18: Comparison of a 5 kg versus a 50 kg sample size.

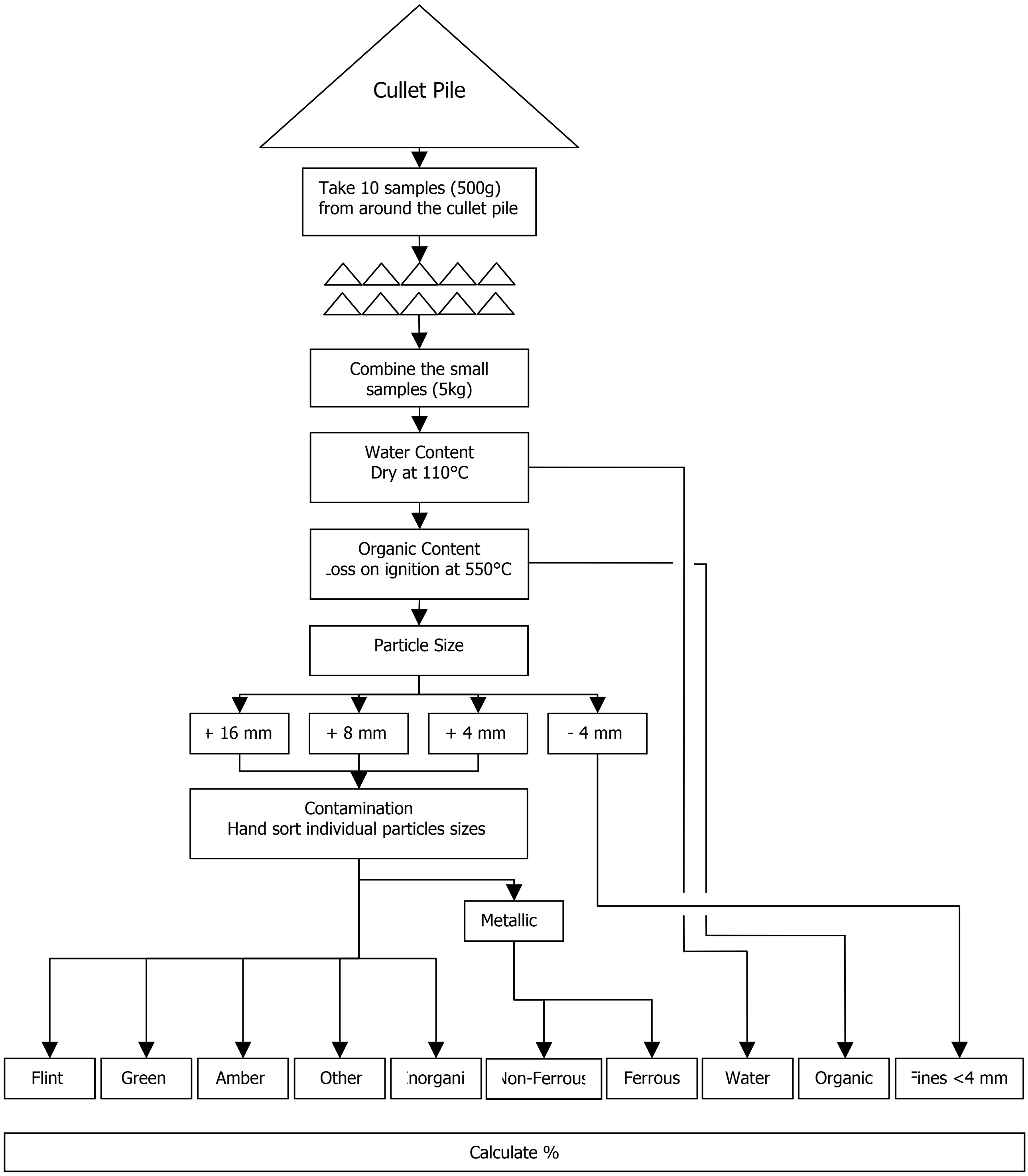


Figure 28: Flow diagram of the sampling method and quality assessment used in the collection and analysis of cullet samples.

3.2.4 Results

3.2.4.1 Availability

The availability of both flint and amber cullet was an issue and at times during the cullet sampling it was not possible to sample flint or amber cullet from some container glass manufacturers and cullet suppliers, as there was no available cullet. Larger companies appeared to have a sufficient supply of flint cullet to meet their requirements, but smaller companies find it more difficult to purchase adequate flint cullet, especially flint cullet of a high quality. During the project there appeared to be no issue with the supply of green cullet.

3.2.4.2 Colour Contamination

Over one hundred samples of cullet were collected and analysed between February and December 2005. Table 19 shows the results of the colour contamination of flint, green and amber cullet. Results presented are the minimum, maximum and average percentages of the different colour contaminants.

Flint Cullet	**Average wt %**	**Minimum wt %**	**Maximum wt %**
Flint	97.02	92.00	99.28
Green	1.64	0.13	4.63
Amber	0.61	0.03	2.07
Misc colour	0.69	0.01	6.76
Green Cullet			
Flint	12.90	5.78	19.65
Green	77.96	60.55	88.45
Amber	9.30	5.24	20.76
Misc colour	0.50	0.25	1.13
Amber Cullet			
Flint	9.56	3.26	46.07
Green	19.30	2.12	30.30
Amber	72.23	23.36	93.41
Misc colour	0.36	0.03	0.85

Table 19: Colour contamination of sampled cullet between February and December 2005.

From Table 19 it can be seen that the average flint cullet available on the market between February and December 2005 contains 97.02% flint glass, 1.64% green glass, 0.61% amber glass and 0.69% miscellaneous glass. The miscellaneous glass was mainly blue glass, but did contain small amounts of flat glass, mirrored glass, wired glass, enamelled glass and TV glass. The figures for the average quality of the flint cullet surprised some project partners, as it is often claimed that flint cullet used by project partners contains at least 99.5% flint glass. The lowest flint glass content of the samples taken was 92.00%. The principal colour contaminant of the flint cullet was green glass, with the highest amount observed being 4.63%. As green glass contains high levels of the strongly colouring chromium and iron ions flint cullet with high levels of green glass could potentially adversely affect the colour of glass produced. Extremely high levels of miscellaneous glass, 6.76 %, was found in a couple of samples, again this could lead to strong colouring agents such as cobalt, iron and chromium being added to the final glass.

The average green cullet collected between February and December 2005 contained 12.90% flint glass, 77.96% green glass, 9.30% amber glass and 0.50% miscellaneous glass, as shown in Table 19. The colour contamination of green cullet is not as critical as it is with flint glass. The colouring agents that are introduced by flint, amber and miscellaneous glass into green cullet tend not to cause colour control issues as green glass already contains high levels of strong colorants. The amount of flint glass found in green cullet is of interest as there is a shortage of flint cullet. An average amount of 12.90% flint glass was found in green cullet, with amounts as high as 19.65% and as low as 5.87% presenting an opportunity to extract this flint glass from the green cullet, assuming favourable economics. This could potentially help address the colour imbalance of cullet that currently exists.

The average amber cullet collected between February and December 2005 contained 9.56% flint cullet, 19.30 % green glass, 72.23% amber glass and 0.36% miscellaneous glass, as shown in Table 19. The colour contamination of amber cullet analysed varied tremendously. The amount of amber glass was as high as 93.41%, but was as low as 23.36%, which is an unacceptable level for amber cullet. The average value of 72.23% of amber glass in amber cullet was low. The variations in the amber content are by necessity matched by those of the flint and green glass contents. The most plausible explanation to this variation being that most amber cullet is the product of the colour sorting facilities which have limited separation efficiencies.

3.2.4.3 Contamination

The contamination of the cullet samples collected between February and December 2005 is shown below in Table 20. As previously noted care should be taken interpreting these results as the sample size was designed for colour assessment and was below the size required to produce a truly representative sample for other tests.

Flint Cullet	Average wt %	Minimum wt %	Maximum wt %
Inorganics	0.045	0.000	0.390
Ferrous	0.004	0.000	0.061
Non-ferrous	0.002	0.000	0.020
Organics	0.30	0.10	0.88
Moisture	0.56	0.03	1.42
Green Cullet			
Inorganics	0.007	0.000	0.030
Ferrous	0.000	0.000	0.005
Non-ferrous	0.002	0.000	0.020
Organics	0.31	0.11	1.26
Moisture	0.76	0.04	1.77
Amber Cullet			
Inorganics	0.022	0.000	0.104
Ferrous	0.001	0.000	0.009
Non-ferrous	0.001	0.000	0.005
Organics	0.26	0.09	0.45
Moisture	0.45	0.07	1.14

Table 20: Contamination level of the sampled cullet between February and December 2005.

3.2.4.4 Inorganic Contamination

The average amount of inorganics, which includes all types of inorganic material such as refractory, pyroceramic, ceramic etc, found in flint, green and amber cullet was 0.045%, 0.007% and 0.022% respectively. All of these averages are relatively high and may cause the container glass manufacturer problems during melting, especially if the inorganic material is a piece of refractory or pyroceramic. One particular sample of flint cullet contained a large piece of ceramic, representing 0.390% of the cullet sample. The levels of inorganic material in green and amber cullet are lower than the levels seen in flint cullet. Considering that most inorganic materials tend to be light in colour it is probable that they are less likely to be detected by operatives or light sensitive sorting equipment.

3.2.4.5 Ferrous Contamination

Less ferrous material than inorganic material was found in the cullet samples. This is due to the ease with which ferrous material can be removed during processing by magnets. Most of the ferrous material found was wired safety glass and most of this was found in the flint cullet. The presence of ferrous material can cause the container glass manufacturer problems during melting as it can form metallic inclusions in the glass, or colour streaking.

3.2.4.6 Non-Ferrous Contamination

The non-ferrous material found in the cullet samples was mainly aluminium anti-pilfer rings and foil. These can cause critical metal inclusions when melted in the glass either as aluminium or silicon due to electrochemical reduction of the silica in the presence of aluminium. The level of non-ferrous contamination was lower than the levels of ferrous contamination, with an average of 0.002, 0.002 and 0.001% being found in flint, green and amber cullet respectively. One sample of flint cullet was found to contain as much as 0.020% non-ferrous contamination.

3.2.4.7 Organic Contamination

The organic content of the cullet samples, measured by loss on ignition at 550 °C, was found to average 0.30% for flint cullet, 0.31% for green cullet and 0.26% for amber cullet. The organics present came from plastic and paper labels, and the remnants of oils, sugars and other foodstuffs in the glass containers. Some cullet samples contained high levels of organics, with a maximum of 0.88% for flint cullet, 1.26% for green cullet and 0.45% for amber cullet. High levels of organics could cause a problem for the container glass manufacturer as it could produce a change in the redox of the glass. Organic material will cause the glass to become more reducing, which could affect the refining and colour of the final glass.

3.2.4.8 Moisture Contamination

The average moisture contamination found was 0.56% in flint cullet, 0.76% in green cullet and 0.45% in amber cullet. The level of moisture found in the samples was not considered high enough to cause a problem to the container glass production.

3.2.4.9 Particle Size

The particle size of the cullet analysed is shown in Table 21. The particle size of cullet depends on the cullet processor and the requirements of different factories. Some cullet processors grind the cullet to a fine particle size so that any contamination that has not been detected and removed will melt into the glass. Other cullet processors prefer to keep the cullet at a coarser size as it allows them to detect contamination more easily.

Flint Cullet	Average wt %	Minimum wt %	Maximum wt %
> 31.5 mm	0.41	0.00	3.79
> 16 mm	23.88	0.00	90.31
> 8 mm	30.65	0.02	45.37
> 4 mm	28.16	2.14	54.56
< 4 mm	16.91	0.41	59.04
Green Cullet			
> 31.5 mm	0.17	0.00	1.76
> 16 mm	22.85	0.00	50.99
> 8 mm	32.30	7.19	51.75
> 4 mm	29.96	9.13	61.77
Amber Cullet			
> 31.5 mm	0.92	0.00	6.83
> 16 mm	27.87	0.00	51.13
> 8 mm	28.87	8.39	43.51
> 4 mm	26.52	12.87	53.87
< 4 mm	17.52	1.17	57.93

Table 21: Particle size of sampled cullet between February and October 2005.

3.2.4.10 Quality Variance

It is interesting to observe how the quality of flint cullet has varied through out the course of the sampling regime. Figure 29 shows how the level of green glass in flint cullet has varied. Figures given are percentages and are average values for the month.

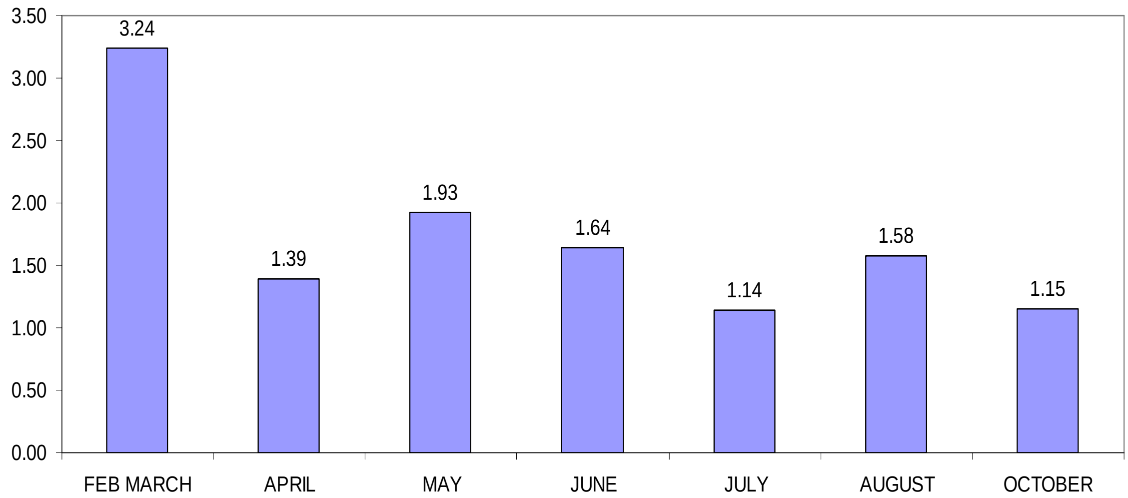


Figure 29: Percentage of green glass in flint cullet.

It can be seen that the level of green glass in flint cullet reduced since sampling began in February. The percentage in February and March was 3.24 %, but the average level since June dropped to half or less than that level, with the figure for October being 1.15 %, a considerable improvement since February. The levels of amber cullet also decreased during the course of the project as seen in Figure 30. The initial level of amber glass in flint cullet in February and March was 0.81 %, but by October this figure had dropped to 0.34 %.

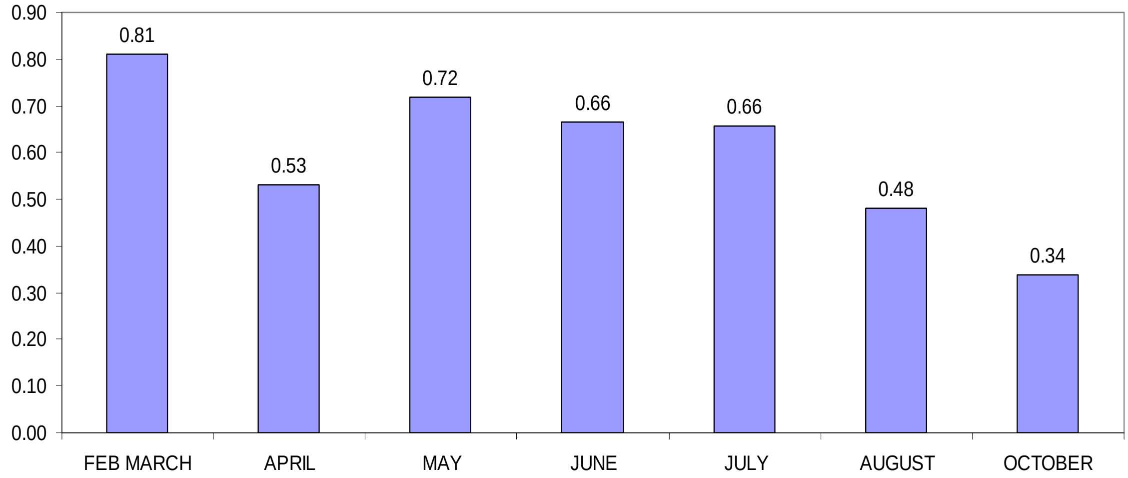


Figure 30: Percentage of amber glass in flint cullet

The colour contamination of flint cullet has decreased throughout the duration of the project. The reason for this is not clear, it may be due to seasonal variation, with more glass being collected early in the year after the Christmas period as mixed cullet, or better sorting technology may have been installed during the year, or it may be that this project has raised the issue of cullet quality and that cullet processors may feel that they are being 'watched', so they improved the quality of their cullet to meet the customer demands. To show the value of the cullet sampling exercise it is helpful to look at an individual factory, for example with 'Factory X' it can be seen that the level of green glass in the flint cullet has changed. The results are shown in Figure 31. Due to commercial sensitivity the values have been normalised to a relative value of 100 for
February, by August and October the level had dropped approximately 80% to a value around 20.

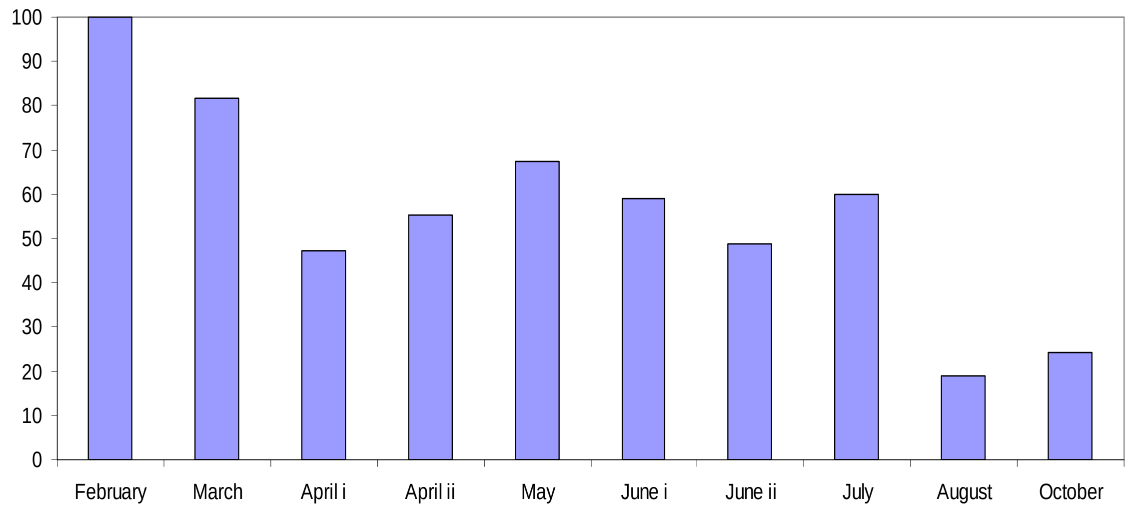


Figure 31: Level of green glass in flint cullet at Factory X

3.2.5 Cullet Sampling - SGT

In addition to the routine cullet sampling and analysis undertaken by GTS, SGT had previously undertaken a similar analysis in 2000 on over 100 cullet samples. Table 22 shows historical cullet analysis undertaken by SGT, which was used as a baseline for observing a shift in cullet quality.

Flint Cullet	Ave	Min	Max
Flint	94.30	79.33	99.90.
Amber	0.48	0.02	1.82
Light Green	4.28	0.02	12.47
Dark Green	0.56	0.02	1.60
Misc (mostly blue)	0.36	0.12	1.39
Green Cullet			
Flint	6.44	4.81	8.20
Amber	11.12	1.14	30.33
Light Green	29.70	21.26	42.82
Dark Green	51.02	28.81	63.77
Misc (mostly blue)	1.70	0.48	6.14
Amber Cullet	**Ave**	**Min**	**Max**
Flint	6.63	1.21	13.37
Amber	80.75	68.84	94.56
Light Green	6.64	1.79	10.78
Dark Green	5.10	2.19	9.75
Misc (mostly blue)	0.86	9.25	2.82

Table 22: The range of colour contamination found in cullet samples undertaken by the SGT in 2000 as part of the cullet specification development.

Comparing the cullet quality data from 2000 (Table 22) with 2005 (Table 19) show that the cullet quality in terms of colour contamination has improved for flint but slightly diminished for green and amber. Table 23 shows a comparison of the two sets of cullet quality data, in addition the flint cullet in terms of green contamination has improved from 5.14wt% in 2000 to 1.64wt% 2005. These improvements in colour contamination for flint cullet have probably been brought about by the investment by cullet processors made over the same period. Also, awareness of the whole supply chain of cullet from glass end-users to collectors has greatly improved which has probably contributed to this increase in colour quality. The decline in the colour quality of the green and amber cullet has probably been brought about by the shift in the glass collection method which has resulted in the increased level of mixed colour glass collected from kerbside and commercial collections which are predominantly mixed colour at the expense of the traditional colour-sorted bring sites

Cullet Colour	2000 (wt%)	2005 (wt%)	Variant (wt%)
Flint	94.30	97.02	2.72.
Green	80.72	77.96	- 2.76
Amber	80.75	72.23	- 8.52

Table 23: Comparison of the three cullet colours from 2000 & 2005

3.2.6 Summary of Cullet Sampling & Cullet Specification

The sampling regime was an essential exercise, in that it has highlighted the availability and quality of container glass cullet in 2005. There was found to be a shortage of acceptable quality flint and amber cullet and an excess of green cullet.

The 5 kg testing method developed by GTS was found to be a reliable technique for gaining a representative sample for colour contamination assessment. However, there is still the question of a suitable sample size for determination of the concentration of other contaminants. It is recommended that further work is conducted into sampling method for other critical contaminants.

The colour integrity of the cullet was found to be lower than the figures often quoted by cullet processors and container glass manufacturers. The colour contamination of flint cullet was found to be relatively high. As flint glass tends to be used for premium products which are easily coloured by contamination a potential problem arises. In particular the average amounts of green and miscellaneous glass, 1.64 % and 0.69 % respectively, could adversely colour the flint glass at high cullet additions. Green cullet was found to contain an average of 12.90 % flint glass. As there is a shortage of flint cullet the flint contamination represents a potential source from which to extract the material and thereby help address UK's colour imbalance problem. The colour contamination of amber cullet was found to vary widely. The amber glass content of amber cullet was found to vary from 23.36 % up to 93.41 %, with an average of 72.23 %.

Other (non-colour) contamination was found, at sometimes high levels, in the cullet. High inorganic levels that could lead to inclusions in the glass were found; flint cullet having an average of 0.045 % inorganic. The organic content was also quite high in some samples with green cullet having an average of 0.76 % organic content, which could lead to changes in redox for container glass manufacturers. However, as stated caution must be exercised in interpreting the results due to the small sample size used.

The quality of flint cullet has improved during the sampling period of February to December 2005. The green and amber glass contents of flint cullet have decreased, with the level of green glass in the later samples seeing a 65 % reduction over the initial samples taken in February and the amber content seeing a 58 % reduction over the same period. The reason for this reduction has not been identified, but the quality of a process often improves whilst it is being monitored. Furthermore, the quality assessment data was often provided to the cullet supplier from the glass manufacturer, which in turn probably increased the cullet processor's awareness and prompted the need to refine the process to deliver improved cullet quality. In addition the cullet quality in terms of colour has improved for flint glass between 2000 and 2005. This is probably attributable to the investment in cullet processing equipment within this period. However, there has been a decline in colour quality of green and amber between 2000 and 2005 probably due to the increase in mixed colour glass collections.

3.3 Investigation of Colour Control

3.3.1 Introduction

This area of work investigated the practical and economic methods of controlling glass colour. Due to the requirement to maximise cullet additions in flint container glass, the investigation was centred on flint container glass. Furthermore, due to the variation in colour of green and amber glass depending on the product and/or brand image it was not practical to investigate the colour control of green or amber glass. Also, it would not be possible, especially with amber, to replicate the melting conditions (redox) on a laboratory scale. The following sections report the laboratory glass melting trials undertaken to develop understanding of glass decolouring for the follow on full scale industrial trials conducted at two project partners' sites.

3.3.2 Green Cullet Additions

A series of melts were carried out to investigate the addition of green cullet to a flint batch. 300g melts were carried out in an electric furnace at 1450°C, cast and annealed. The melts were undertaken using commercial batch materials and recipes to simulate the composition and batch chemistry of commercially produced container glass. The batch materials and basic recipe followed are shown in Table 24.

Raw Material	Weight (g)
Sand	133.60
Soda Ash	41.57
Limestone	27.75
Spanish Dolomite	11.52
Feldspar	5.86
Calumite	3.36
Saltcake	1.34
Flint Cullet	75.00
Green Cullet	0.00
Total	**300.00**

Table 24: The batch recipe for the FG series of glass melts, with 28 wt% cullet addition.

Throughout the series of melts the overall cullet content was kept constant. However, the % green cullet introduced into the batch was gradually increased whilst the % of flint cullet was reduced to maintain 28 wt% cullet additions. To ensure that representative and consistent cullet additions were made to the individual melts, a sample of pure flint cullet and pure green cullet were crushed, ground and sieved to a consistent composition and size fraction. The samples of cullet were provided by a number of project members. The melts carried out along with the corresponding % of green cullet present in the final glass are shown in Table 25. Based on 0.2 wt% Cr_2O_3 content of the green glass used in the flint cullet, the level of green glass in the flint cullet and associated Cr_2O_3 level can also be estimated (Table 25).

Series code	Green cullet in final glass (wt%)	Green glass in the flint cullet (wt%)	Estimate of the Cr_2O_3 in final glass (ppm)
FG 0	0.00	0.0	0
FG 2	0.25	0.9	5
FG4	0.50	1.8	10
FG 5	1.00	3.6	20
FG 6	2.00	7.2	40
FG 7	3.00	10.8	60
FG 8	4.00	14.4	80
FG 9	5.00	18.0	100

Table 25: The green cullet content in the final glass of the FG series.

Ultraviolet visible spectroscopy (UV-Vis) measurements were undertaken to obtain colour coordinates. The colour coordinate system used was the CIE L*a*b as previously described (Section 2.1.2). The colour coordinates a and b that depict colour are shown in Figure 32.

The series showed good correlation between the amount of green cullet (also Cr_2O_3 content) present in the final glass and the colour coordinates; as the amount of cullet was increased the glass colour became steadily greener.

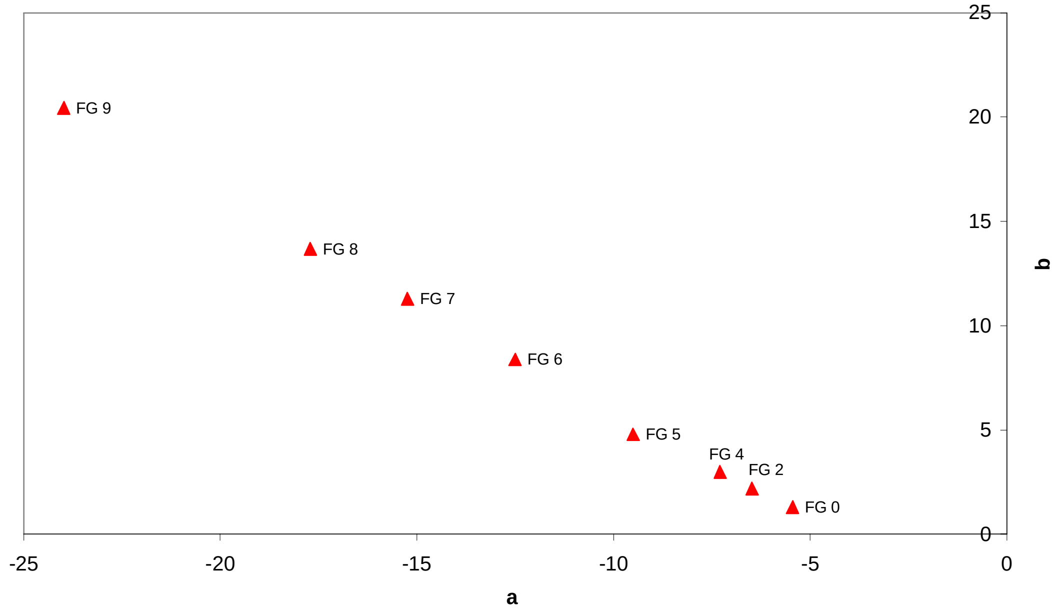


Figure 32: The colour coordinates a and b for the FG series of melts (Normalised to 40 mm glass thickness.)

These colour coordinate measurements were used at a later date to compare them to measurements carried out on a similar series of melts but with the presence of a decolouriser. This would allow for maximum additions of green cullet to a flint batch, however, before such comparisons could be made a number of decolouriser systems were investigated to ensure that the most suitable decolouriser was selected.

3.3.3 Selenium (Se)

As reported, selenium is the most commonly used decolouriser for commercial container glass and as such a series of experiments were designed and undertaken to further investigate Se decolouriser. A series of melts were carried out using selenium as a decolouriser to act as a benchmark for this study. However, it was important that selenium was present in the correct oxidation state. Therefore a number of initial melts were carried out that were overdosed with selenium to ensure that the appropriate pink colour was introduced. The melts were based on the composition of FG 0 with 28 wt% cullet addition, as shown in Table 26, with additions of selenium premix. The initial level of premix added was an approximation of the current practise in industry. The melts were then repeated with double and triple the amounts of decolouriser. The levels of decolouriser added as a premix are shown in Table 27.

Analyte	Wt (%)
SiO_2	71.90
Na_2O	13.7
K_2O	0.35
MgO	1.49
CaO	10.97
Al_2O_3	1.37
Fe_2O_3	0.04
SO_3	0.21

Table 26: The chemical composition of the base glass FG 0 (28 wt% cullet addition), determined using X-Ray Fluorescence (XRF) Spectrometry.

Selenium premix	Selenium (wt%)
80 g: 2000 Kg (Current Practice x 1)	0.0029
160 g: 2000 Kg (x2)	0.0058
240 g: 2000 Kg (x3)	0.0087

Table 27: The selenium premix additions that were made to the melts based on the composition of FG 0.

The selenium melts introduced a faint brown colour to the glass which was due to the production of intermediate polyselenides under a reducing atmosphere. The melts were repeated with an increased level of saltcake to oxidise the glass and hence to improve the colour of the glasses. Unfortunately, with laboratory melts of this scale it is difficult to replicate the redox conditions of an industrial furnace and with some series of melts it was not possible to fully investigate this phenomenon.

3.3.4 Cerium Oxide (CeO_2)

A similar series of melts were carried out to investigate the effects of cerium on the base glass FG 0. The melts were based on the composition of FG 0 with increasing additions of cerium oxide (CeO_2) premix at a fixed cullet addition of 28 wt%. The initial level of premix added was an approximation of the current practise in industry, followed by double and triple the amount of decolouriser, as shown in Table 28.

Cerium oxide premix	CeO_2 (wt%)
600 g: 2000 Kg (Current Practice x 1)	0.0216
1200 g: 2000 Kg (x2)	0.0432
1800 g: 2000 Kg (x3)	0.0648

Table 28: The CeO_2 premix additions that were made to the melts based on the composition of FG 0.

To confirm the effects of the addition of CeO_2 to the base glass FG 0, an additional number of melts were carried out based on the composition of a typical flint container glass, as shown in Table 24.

Analyte	Wt (%)
SiO_2	71.51
Na_2O	13.47
K_2O	0.39
MgO	0.98
CaO	11.80
Al_2O_3	1.27
Fe_2O_3	0.07
SO_3	0.16
Cr_2O_3	0.005

Table 29: The basic composition of a typical flint container glass.

UV-Vis measurements were carried out and the results are shown in Figure 33 with the corresponding level of cerium oxide premix. The spectra show that as the amount of CeO_2 increased the absorption at the longer wavelengths of the spectrum decreased whilst the ultraviolet cut off shifted to a longer wavelength. The absorption at wavelengths of 380 nm and 1050 nm are due to the presence of the ferrous and ferric ion, respectively. The spectra indicate that as the concentration of CeO_2 increased the amount of ferrous decreased whilst the amount of ferric increased due to the oxidation of the glass melt from the presence of CeO_2, confirming the role of CeO_2 as a chemical decolouriser.

The results suggest that a physical decolouriser would be required in combination with CeO_2, to mask the colour of the yellow/green ferric ion and the green trivalent chromium ion.

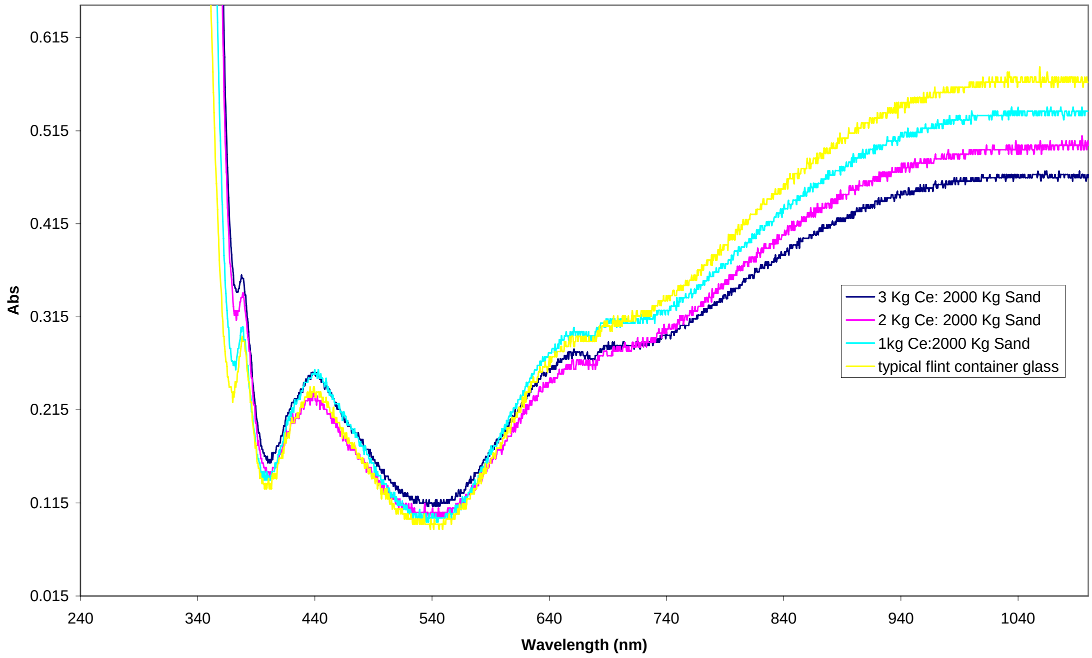


Figure 33: The absorption spectra of a typical flint container glass with increasing additions of cerium premix.

3.3.5 Neodymium Oxide (Nd_2O_3)

Neodymium oxide (Nd_2O_3) coloured glasses exhibit dichrosim due to the absorption of a narrow but intense absorption band at approximately 590 nm, which divides the transmitted spectrum into blue and red. Therefore, the glass may appear red or blue depending on the type of lighting, wall thickness of the glass and the concentration of Nd_2O_3. The absorption spectrum of a flint glass containing 7.5 wt % Nd_2O_3 is shown in Figure 34.

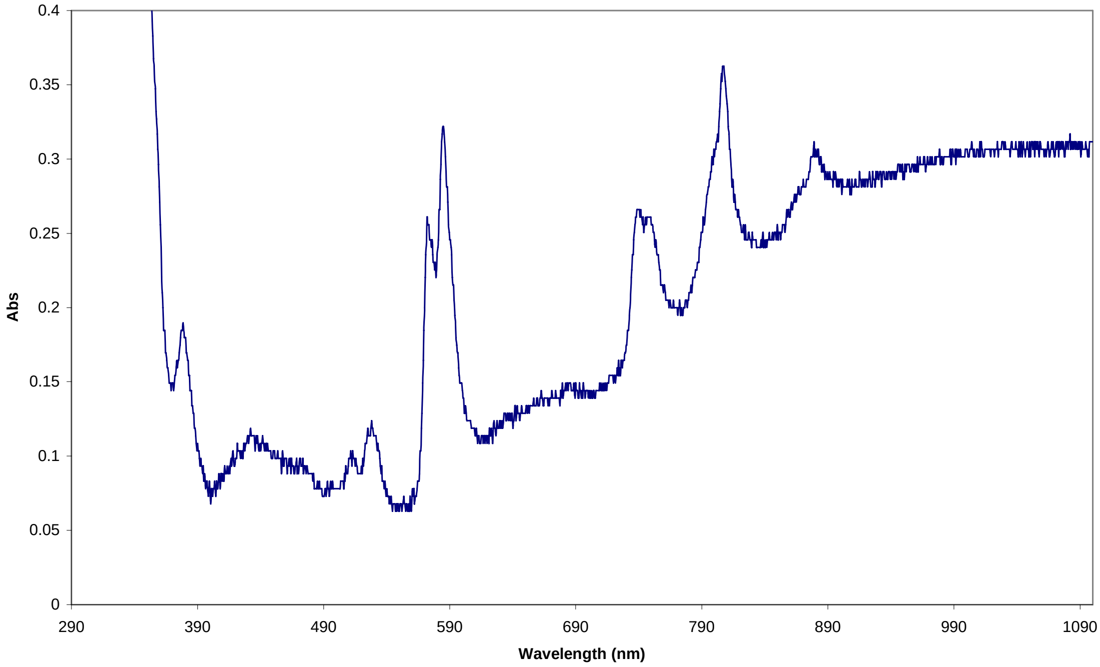


Figure 34: The absorption spectrum of a flint glass based on the composition of FG 0 with an addition of 7.5 wt % Nd_2O_3.

Using the basic recipe of FG 0 a small number of melts were carried out with increasing additions of Nd_2O_3 premix. UV-VIS measurements were undertaken and were normalised to 2.5 mm which is the approximate thickness of a container glass. The colour coordinates of these samples are shown in Figure 35.

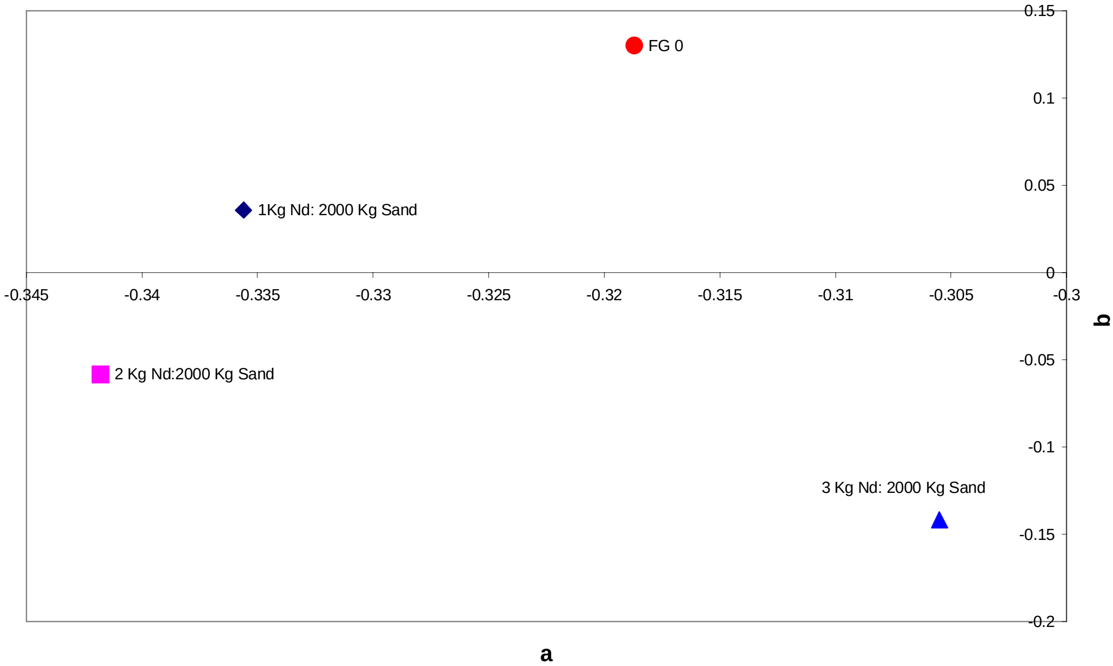


Figure 35: The colour coordinates for FG 0 with increasing additions of Nd_2O_3. (Normalised to 2.5 mm glass thickness)

The results show that for a glass such as FG 0 with a 0.04 wt % Fe_2O_3 content (no added Cr_2O_3 either via the batch or green cullet), the addition of a premix containing 3 kg of Nd_2O_3 per 2000 kg of sand would not be sufficient to introduce the desired blue/red colour. A simple model was used to predict the effects of different additions of Nd_2O_3 on the colour coordinates of a typical flint container glass, which contained 0.07 wt % Fe_2O_3 and 0.005 wt % Cr_2O_3. The predicted colour coordinates are shown in Figure 36 and indicate that a typical flint container glass would require more than 5 wt % Nd_2O_3 in the final glass.

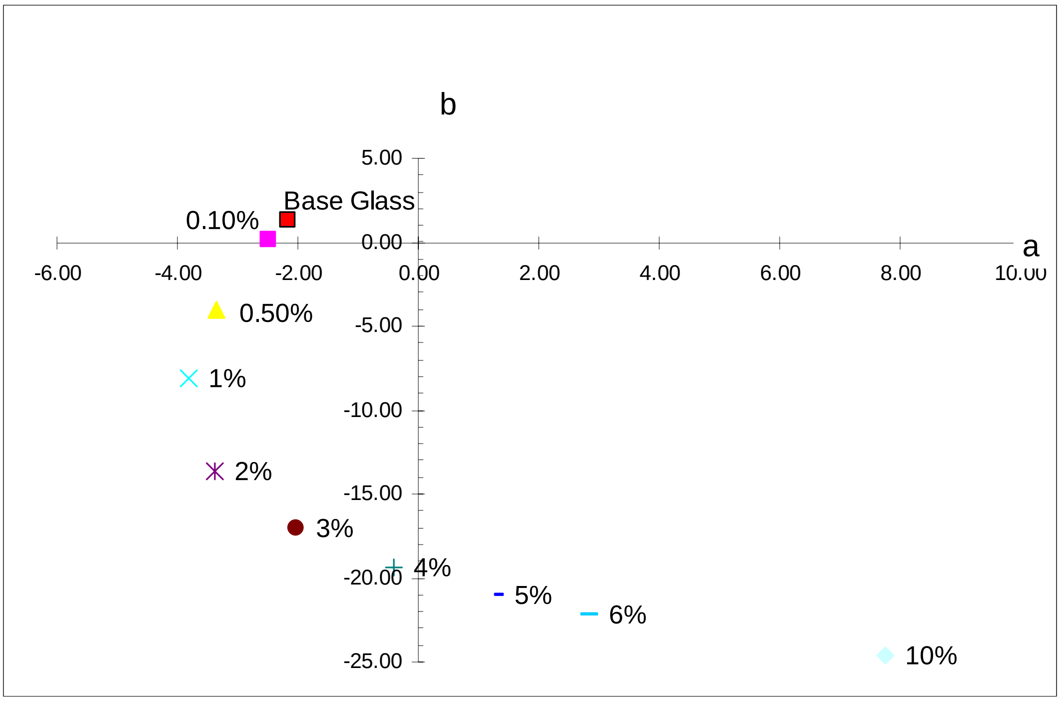


Figure 36: **The predicted colour coordinates of a typical flint container glass containing 0.07 wt% Fe_2O_3, 0.005 wt% Cr_2O_3. The corresponding additions of Nd_2O_3 are expressed as a wt% of Nd_2O_3 in the final glass.**

The results indicated that it would not be economically feasible to use solely Nd_2O_3 as a decolouriser due to the large additions that would be required. Although if Nd_2O_3 in combination with cerium was used it may be possible to use a smaller quantity to mask the presence of the paler ferric ion. However, due to the economic implications and that the colour of the glass is affected by not only the quantity of Nd_2O_3 added but by other factors such as wall thickness and lighting, the use of Nd_2O_3 as a physical decolouriser was not investigated further due to the economic and technical constraints.

3.3.6 Small Scale Melts verses Industrial Melts

Prior to the investigation of further melts it was essential that a comparison could be made between the laboratory melts and typical industrial concentrations of the dominant colorant Cr_2O_3. The colour split data for good, average and poor quality cullet, taken from the cullet study are shown in Table 30.

The colour split data along with the typical analysis of a flint, amber and green cullet were used to calculate the levels of Cr_2O_3 that would be present in a flint container glass for cullet additions of both 40 % and 60 %. The levels of Cr_2O_3 are shown in Table 31.

Quality of Cullet	Glass Colour wt%		
	Flint	Green	Amber
Good	99.28	0.13	0.03
Average	97.38	1.61	0.64
Poor	93.88	4.63	2.07

Table 30: **The percentage colour split of good, average and poor quality flint cullet, taken from the cullet analysis results in Table 19.**

Quality of flint cullet	Cr_2O_3 (ppm) (40 wt% cullet)	Cr_2O_3 (ppm) (60 wt% cullet)
Good	4	6
Average	15	23
Poor	40	60

Table 31: The calculated concentrations of Cr_2O_3 present in flint container glass for maximum, average and minimum quality cullet for additions of 40 wt% and 60 wt%.

The melts that were carried out based on the composition of a typical flint container glass, as shown in Table 31, contained approximately 50 ppm Cr_2O_3 which correlated to the addition of poor quality cullet. An additional number of melts were carried out with a 50 % reduction in the concentration of Cr_2O_3 which correlated to the addition of average quality cullet. The melts were based on the composition shown in Table 32.

Analyte	wt (%)
SiO_2	71.51
Na_2O	13.47
K_2O	0.39
MgO	0.98
CaO	11.80
Al_2O_3	1.27
Fe_2O_3	0.07
SO_3	0.16
Cr_2O_3	0.0025

Table 32: The composition of a base glass with addition of Cr_2O_3 to simulate an addition of average quality cullet.

3.3.6.1 Erbium Oxide (Er_2O_3)

A number of melts were carried out with increasing additions of erbium oxide (Er_2O_3). The melts were based on the composition shown in Table 32 and corresponded to the addition of poor quality cullet. UV-Vis measurements were undertaken and the colour coordinate results are shown in Figure 37.

The results show that the coordinates move closer to the origin as the amount of Er_2O_3 increased indicating that Er_2O_3 would be an effective decolouriser. However, based on an average batch cost of approximately £50 per tonne the cost of producing a tonne of glass containing 0.1 Wt % Er_2O_3 would increase by approximately 14 %. Likewise to produce a glass containing 0.2 Wt % and 0.3 Wt % Er_2O_3 the batch cost would increase by 28 % and 42 %, respectively. Therefore, at such levels of addition it would not be an economical proposition although if Er_2O_3 was used in conjunction with another decolouriser it may become viable.

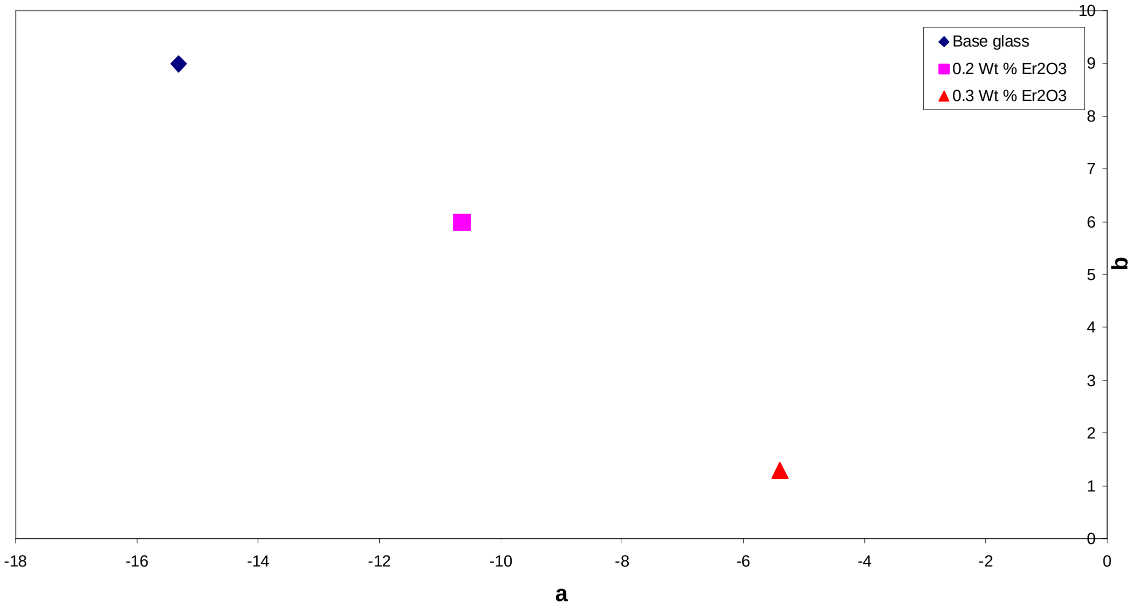


Figure 37: The colour coordinates of a typical flint container glass with increasing additions of Er_2O_3.

The absorption spectrum of Er_2O_3 showed three characteristic peaks at 360 nm, 380 nm and 520 nm, as shown in Figure 38. The spectrum indicated that Er_2O_3 may be more effective if used in conjunction with CeO_2 to aid in the masking of Cr^{3+} and Fe^{3+} or in conjunction with CoO. Therefore, a number of melts were carried out containing Er_2O_3 + CoO and Er_2O_3 + CoO + CeO_2 to investigate these combinations further.

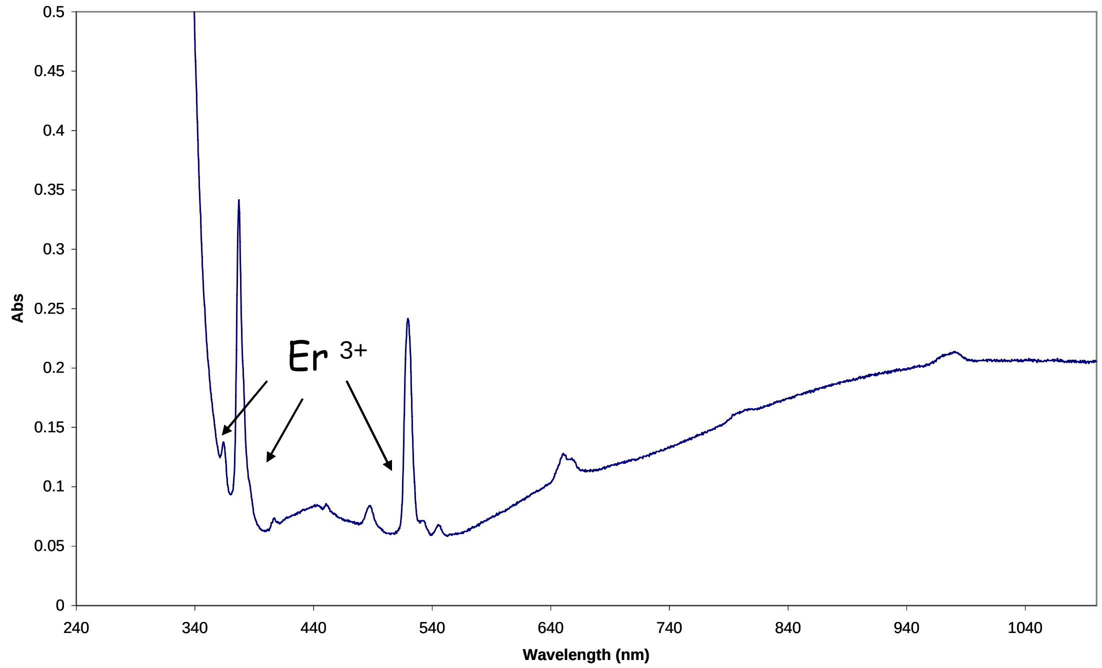


Figure 38: The absorption spectrum of a typical flint container glass doped with Er_2O_3.

The colour coordinate results for the melts containing Er_2O_3 and CoO are shown in Figure 39. The additions of erbium were 0.1 – 0.3 Wt % with the concentration of cobalt ranging from 1.6 to 3.2 ppm. The colour coordinates for the melts containing Er_2O_3, CoO and CeO_2 are shown in Figure 40.

A comparison of the absorption spectra for the melts containing 0.2 Wt % Er_2O_3 and CoO and 0.2 Wt % Er_2O_3, CoO and CeO_2 is shown in Figure 41. The absorption spectra suggested that the melts containing CeO_2 showed a reduced ferrous content. However, as the absorption of the ferric ion was masked by that of Er_2O_3 the role of CeO_2 could not be verified. A comparison of the colour coordinates for the two series of melts is shown in Figure 42. The results indicated that although CeO_2 may have acted as a chemical decolouriser, at such levels of addition in the presence Er_2O_3 and/or CoO it did not appear to aid in the overall decolourisation of the glass.

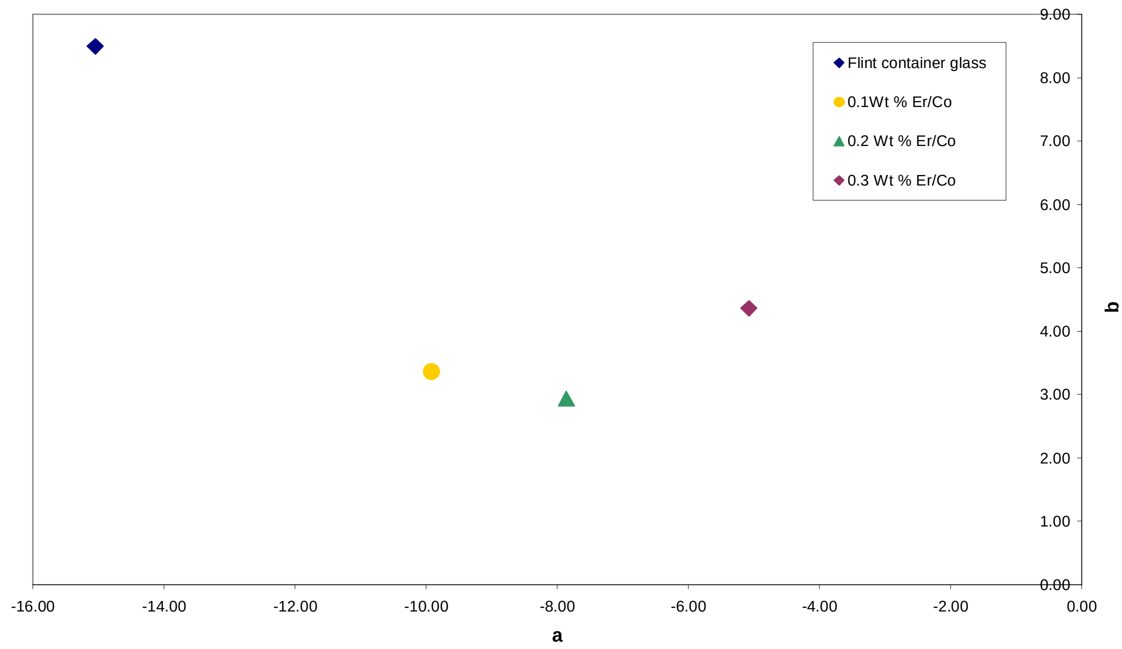


Figure 39: **The colour coordinates of a typical flint container glass as the level of Er_2O_3 was increased from 0.1 wt % to 0.3 wt %, whilst the concentration of CoO ranged from 1.6 – 3.2 ppm.**

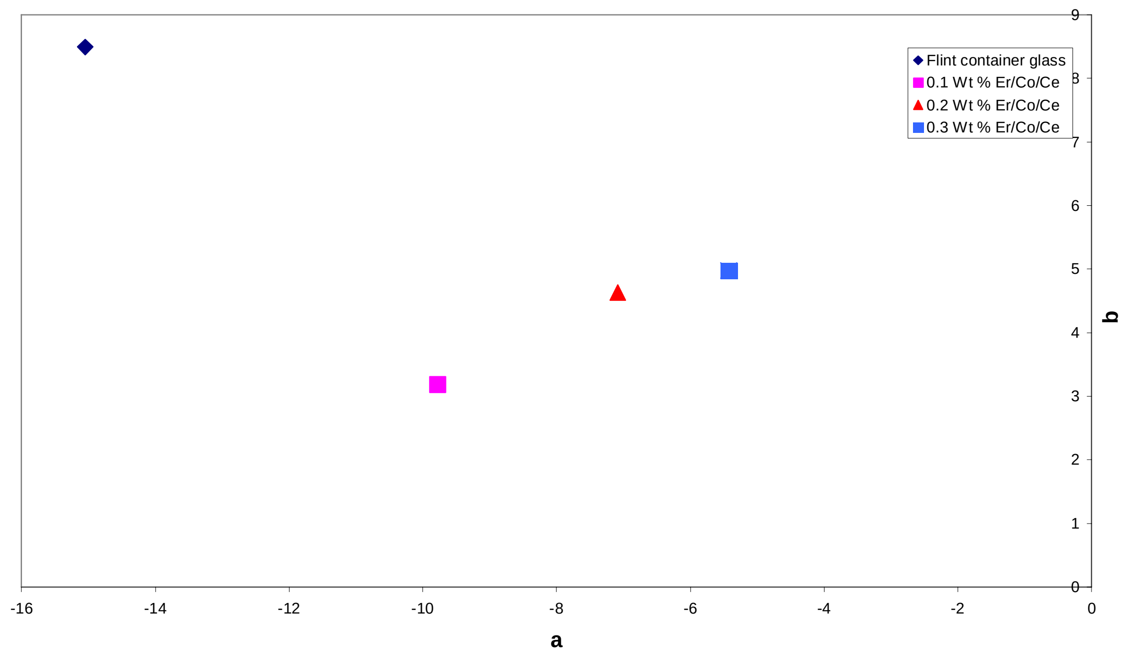


Figure 40: **The colour coordinates of a typical flint container glass. The levels Er_2O_3 and CoO ranged from 0.1 wt % to 0.3 wt % and 1.6 ppm to 3.2 ppm, respectively, whilst the addition of CeO_2 remained constant at 0.07 wt%.**

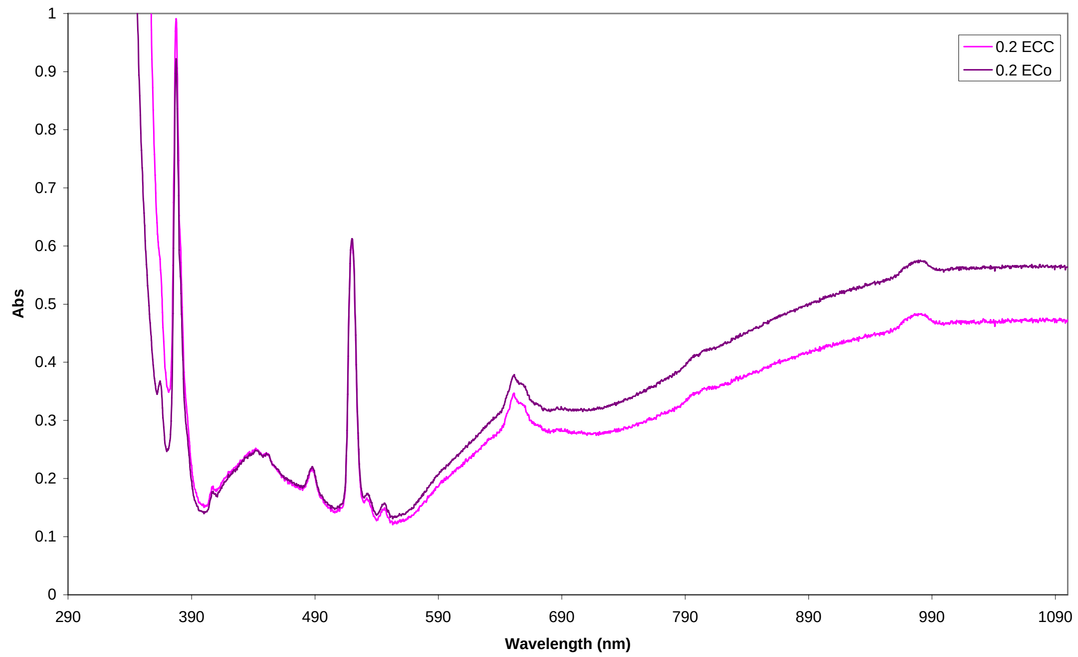


Figure 41: **A comparison of the absorption spectra of 0.2 Wt % Er_2O_3 with CoO (ECo) and 0.2 wt % Er_2O_3 with CoO & CeO_2 (ECC) melts.**

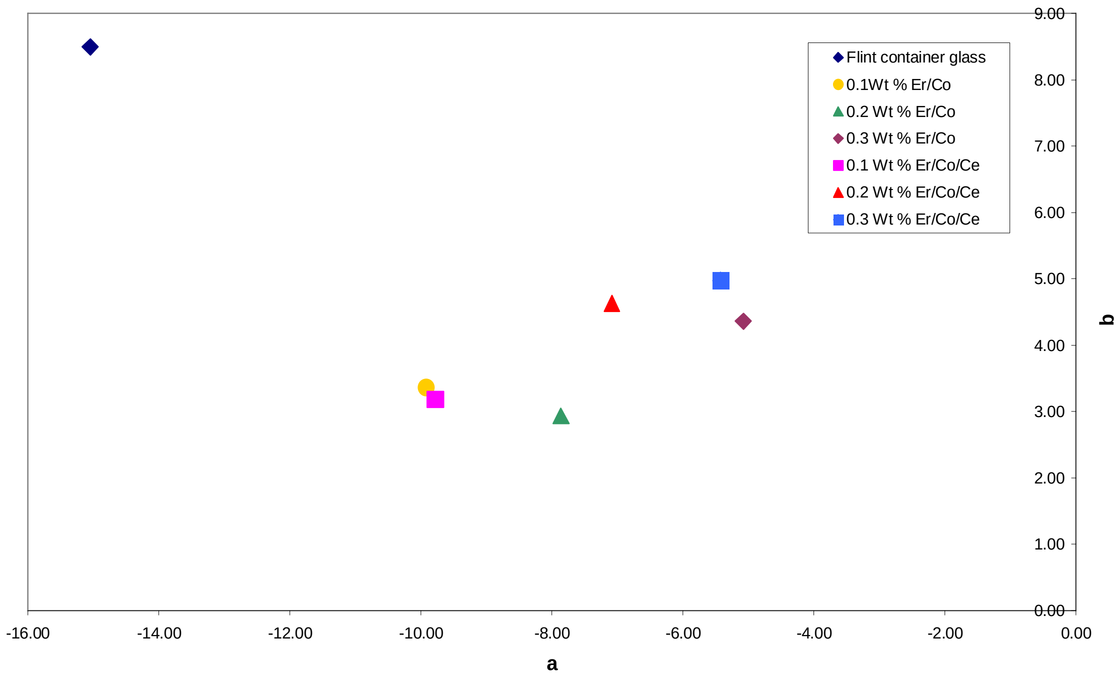


Figure 42: **A comparison of the colour coordinates results of Er_2O_3 + CoO melts and Er_2O_3 + CoO & CeO_2 melts.**

A comparison of the results for the melts containing Er_2O_3 and Er_2O_3 + CoO suggested that Er_2O_3 would not be an economically feasible option even in conjunction with CoO. However, before any conclusions could be drawn it was necessary to carry out a number of additional melts.

A further series of Er_2O_3 melts were carried out based on the base glass composition shown in Table 32. The melts contained approximately 25 ppm Cr_2O_3, which corresponded to the addition of average quality cullet. UV-Vis measurements were carried out and the colour coordinate results are shown in Figure 43. The results indicate that the colour coordinates move closer to the origin as the amount of Er_2O_3 was increased.

A comparison of the colour coordinate results of the Er_2O_3 melts containing 50 ppm and 25 ppm of Cr_2O_3 is shown in Figure 44. The results indicate that a 25 ppm reduction of Cr_2O_3 in the base glass has resulted in similar coordinate results to those previously achieved with an addition of 0.1 Wt % Er_2O_3. Likewise an addition of 0.2 Wt % Er_2O_3 has resulted in similar coordinates to those which were achieved with 0.3 Wt % Er_2O_3. The results suggest that for a 50 % reduction in the concentration of Cr_2O_3, a third less Er_2O_3 is required to achieve the same degree of decolourisation.

The melts indicate that although Er_2O_3 is an effective physical decolouriser, it may not be an economically viable route. However, the trials have highlighted the importance of the quality of cullet. The results suggest that a third less Er_2O_3 could be used by switching from poor to average quality cullet, which in turn would reduce the erbium decolourising expenses by 14%

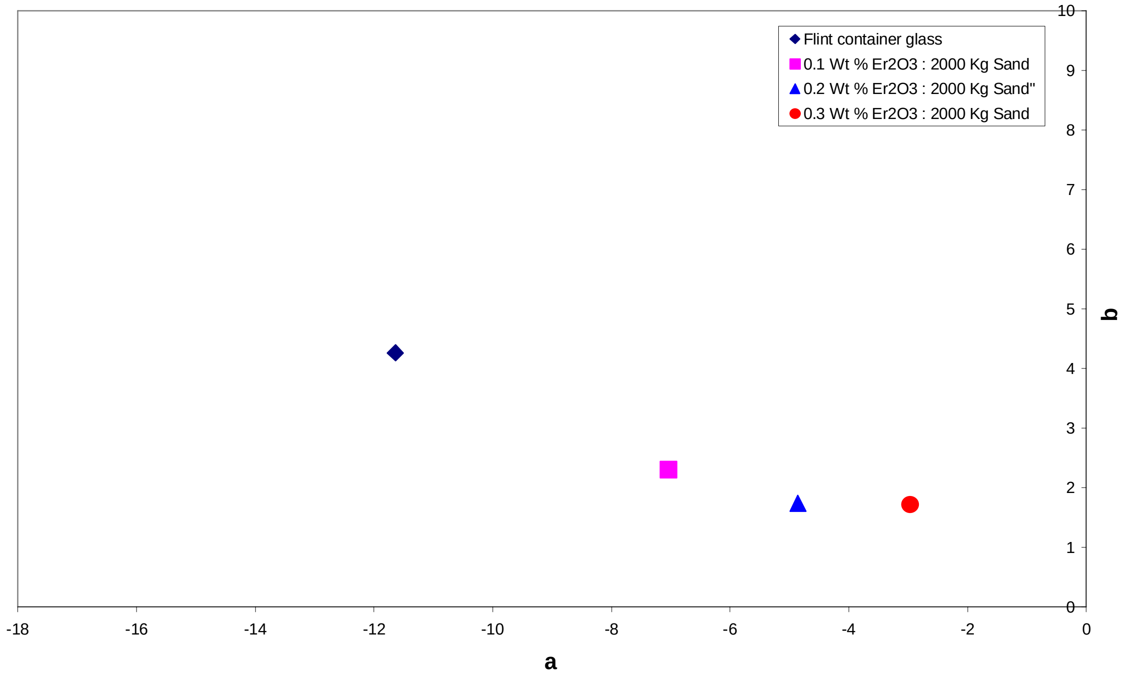


Figure 43: The colour coordinate results for a flint container glass with increasing additions of Er_2O_3 premix.

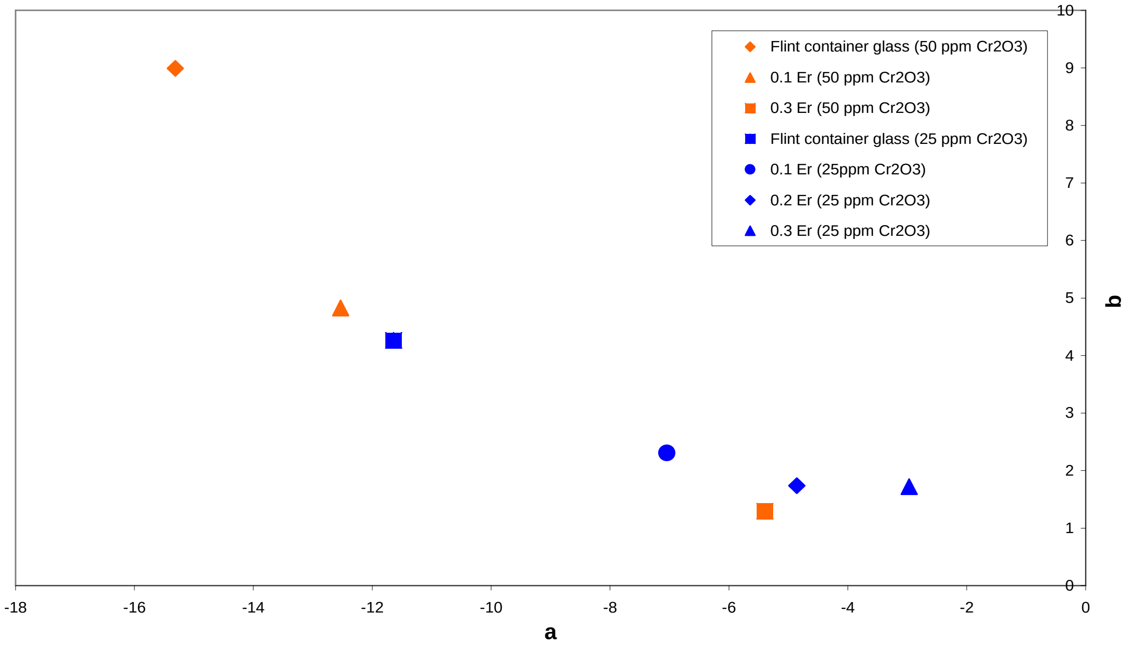


Figure 44: **A comparison of the colour coordinate results for the Er_2O_3 melts containing 50 ppm and 25 ppm Cr_2O_3 based on the addition of poor and average quality cullet, respectively.**

3.3.6.2 Further CeO_2 Glass Melts

The previous CeO_2 melts confirmed the role of CeO_2 as a chemical decolouriser. However, in industry it is known that much lower levels of CeO_2 are used. Therefore a number of melts were carried out to try to optimise this level with 50 ppm Cr_2O_3 and 0.07 wt% Fe_2O_2 additions. Using the previous glass composition, shown in Table 32, the level of CeO_2 was varied between 0.6 Kg to 1 Kg per 2000 Kg sand. UV-Vis measurements were carried out and the colour coordinate results are shown in Figure 45.

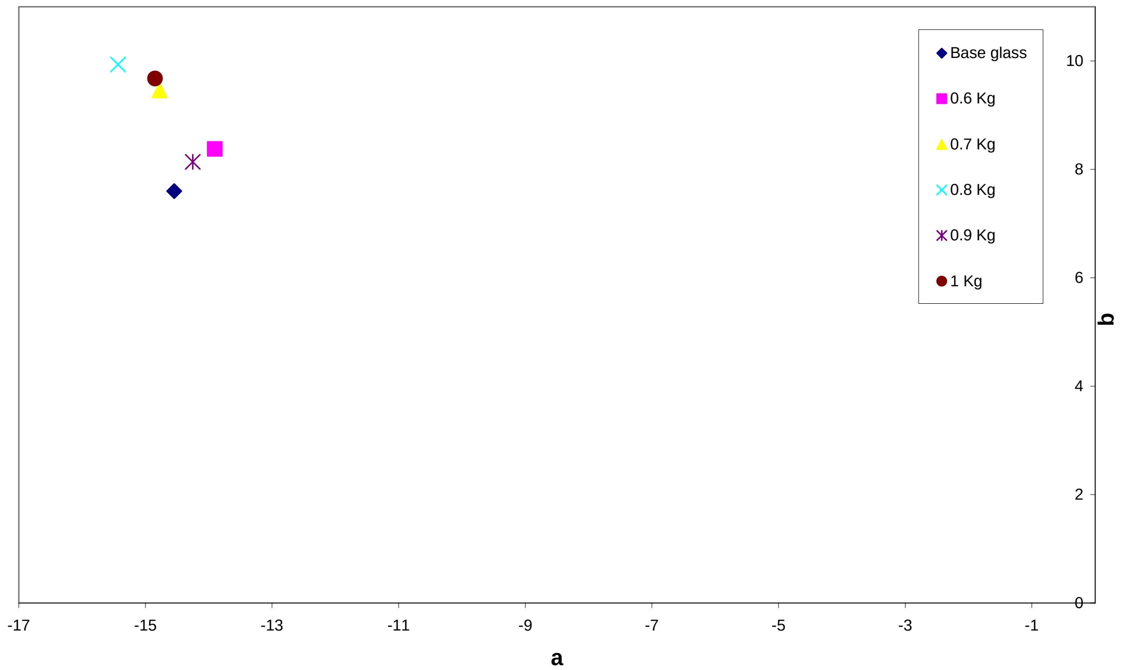


Figure 45: **The colour coordinates of a typical flint container glass as the level of CeO_2 was increased from 0.6 Kg to 1Kg in 2000 Kg sand.**

The colour coordinates of all the CeO_2 melts appeared to be more yellow/green compared to the base glass. This was due to a reduction in the amount of the blue ferrous ion and an increase in the amount of the yellow/green ferric ion, verifying the role of CeO_2 as a chemical decolouriser. However, the results appeared to be very scattered and no obvious relationship could be determined between the amount of CeO_2 present and the colour coordinates obtained.

To determine whether it was possible to measure the effect brought about by making small additions of CeO_2, it was vital that the errors which were associated with this decolourising system were evaluated. To assess these errors four identical batches were melted that each contained 0.6 Kg CeO_2 per 2000 kg sand. UV-Vis measurements were undertaken on these samples and the colour coordinate results, along with the previous results are shown in Figure 46. The errors associated with each repeat melt were expressed as error bars and are shown in Figure 47.

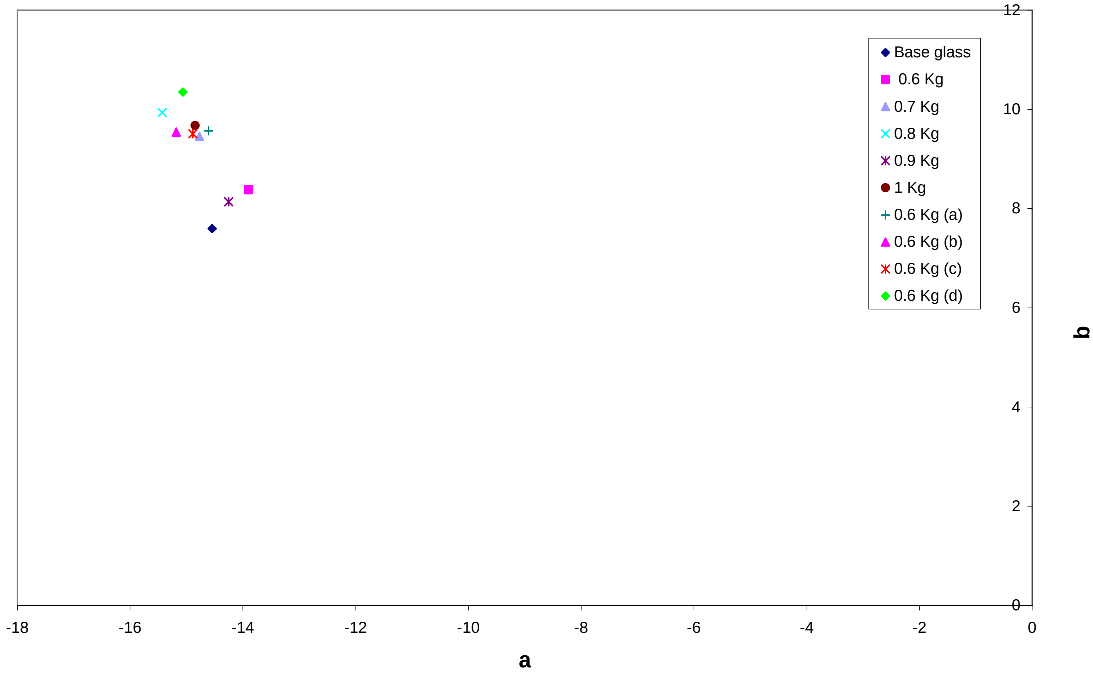


Figure 46: The colour coordinates of a typical flint container glass as the level of CeO_2 was varied.

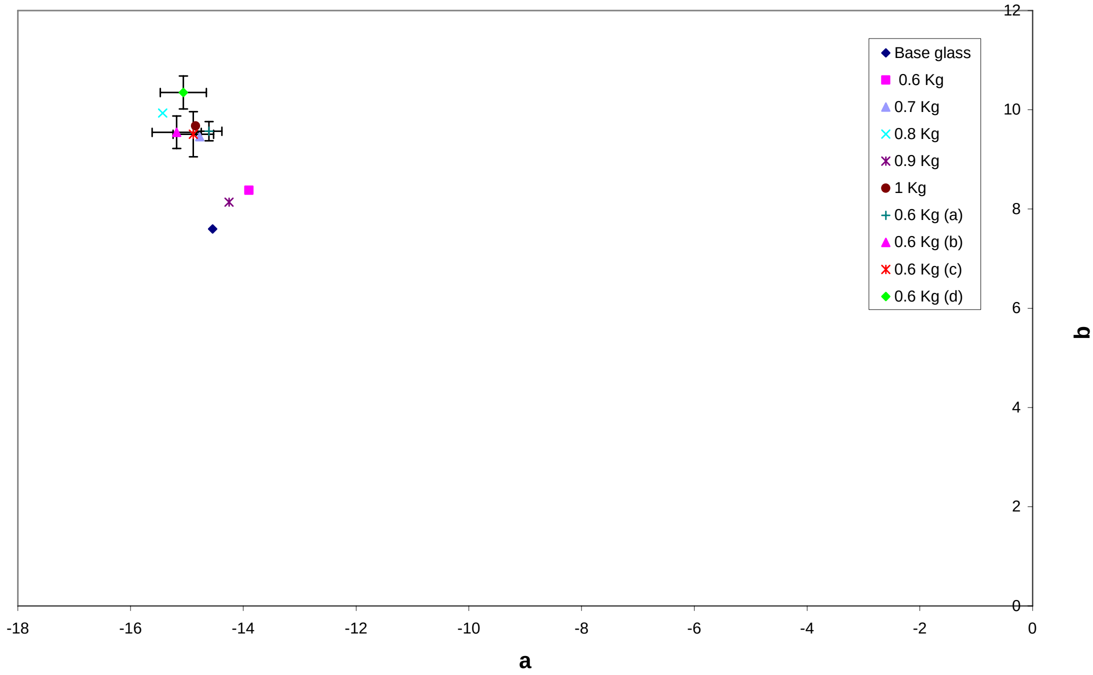


Figure 47: The colour coordinates of a typical flint container glass as the level of CeO_2 was varied. The errors associated with each repeat melt are expressed as error bars.

The results show that it would be difficult to optimise the level of CeO_2 used as the error associated with each measurement was quite significant compared to the change in the colour coordinates brought about by making such small alterations in the level of CeO_2.

The colour coordinate results for all the CeO_2 melts are shown in Figure 48. The results show that as the level of CeO_2 was varied between 0.6 to 3 Kg per 2000 Kg sand the colour coordinates remained about a central location. The results confirmed that although CeO_2 does behave as a chemical decolouriser it would be required to be used in conjunction with a physical decolouriser to mask the green colour introduced by 50 ppm Cr_2O_3.

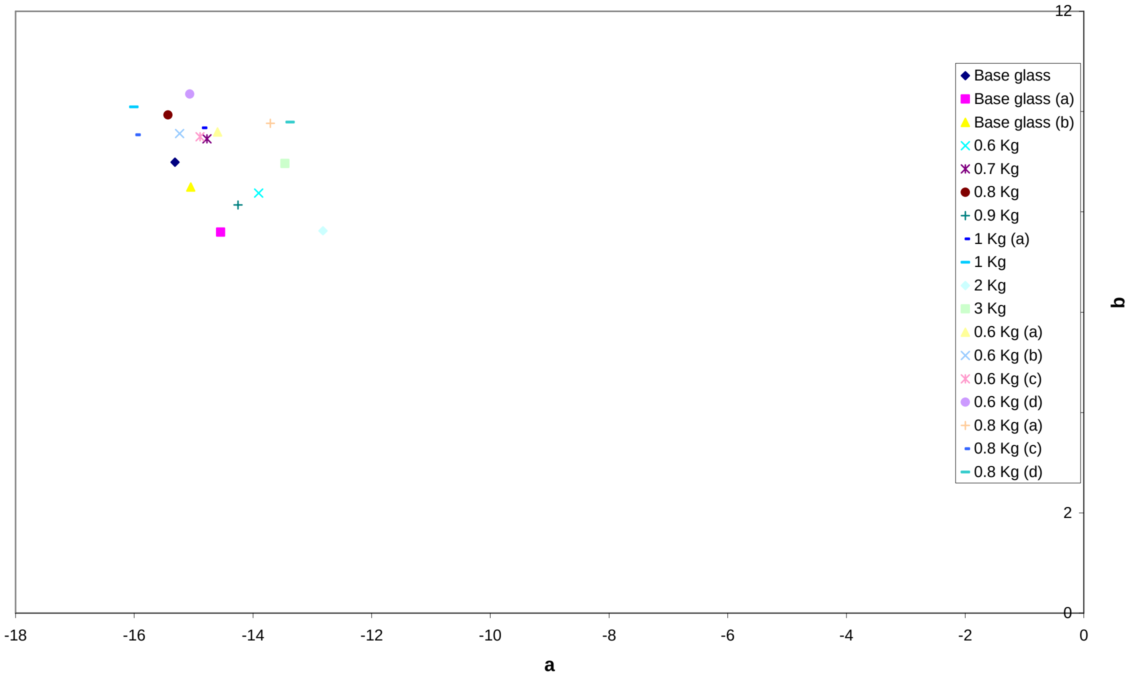


Figure 48: The colour coordinate results for the CeO_2 melts containing 50 ppm Cr_2O_3 corresponding to the addition of poor quality cullet.

A similar series of melts were carried out, based on the composition shown in Table 32. The melts contained approximately 25 ppm Cr_2O_3, which corresponded to the addition of average quality cullet. UV-Vis measurements were undertaken and the absorption spectra and colour coordinate results are shown in Figure 49 and Figure 50, respectively.

As with the previous melts, the results showed that as the amount of CeO_2 was increased the absorption at the longer wavelengths of the spectrum decreased, whilst the ultraviolet cut off shifted to a longer wavelength. The results also confirmed that as the concentration of CeO_2 increased, the amount of ferrous decreased whilst the amount of ferric increased.

The colour coordinate results indicate that all the CeO_2 melts appeared to be less blue/green and more yellow and compared to the base glass, confirming the oxidation of ferrous to ferric. However, overall the results appeared to be scattered and no obvious relationship could be determined between the amount of CeO_2 present and the colour coordinates obtained.

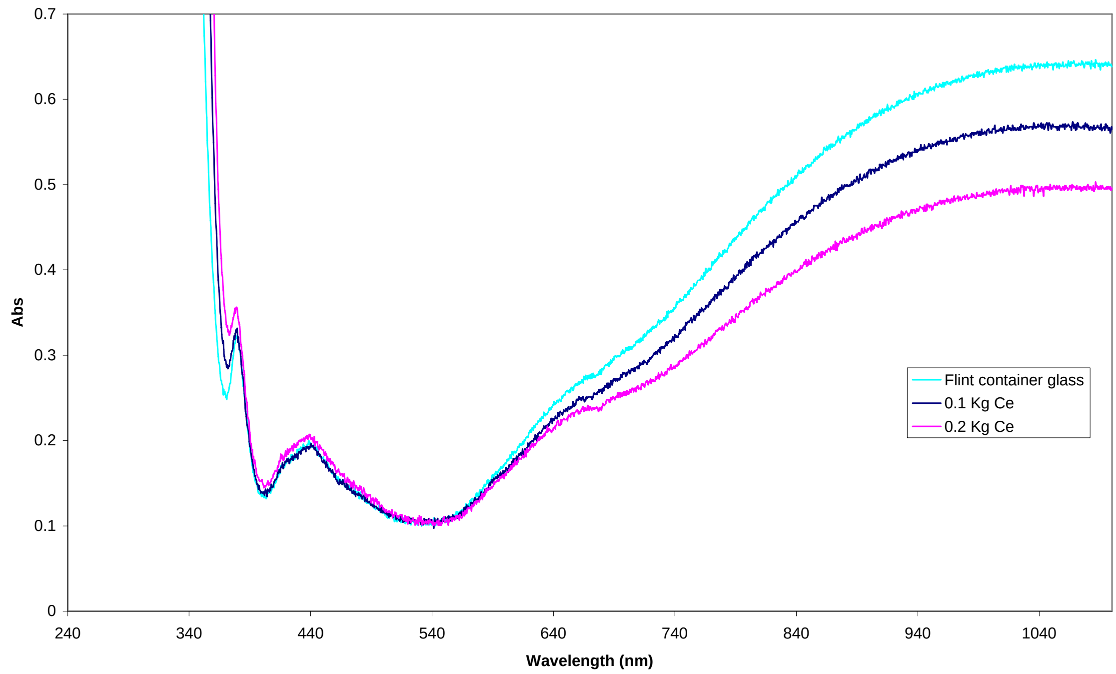


Figure 49: The absorption spectra of a typical flint container glass with increasing additions of CeO_2 premix.

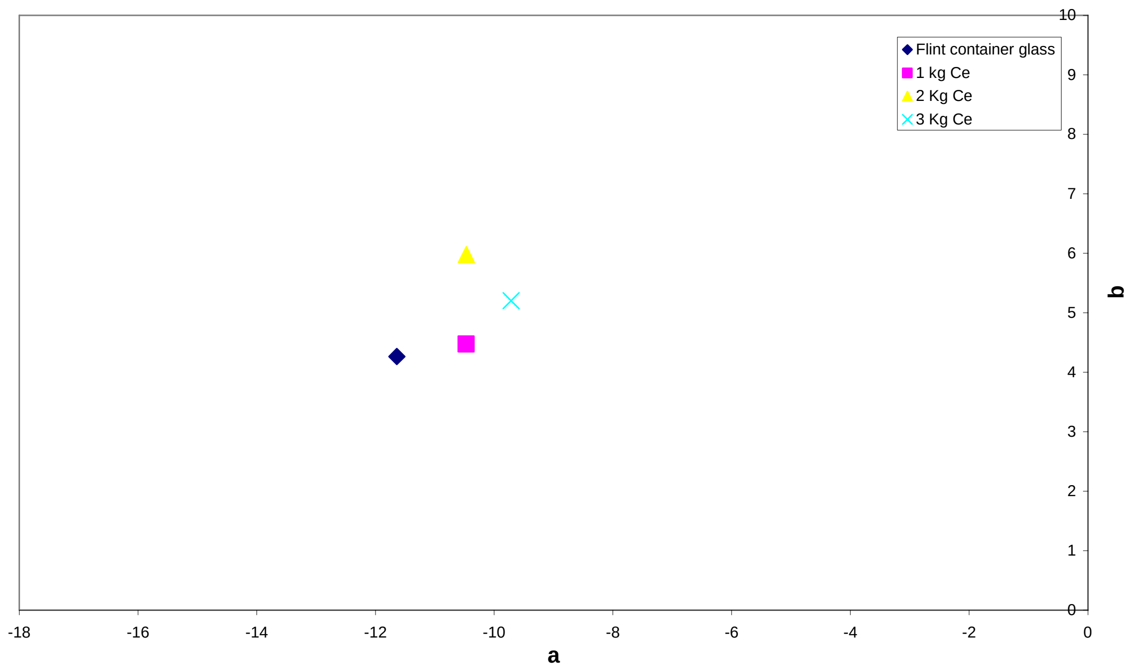


Figure 50: The colour coordinates of a flint container glass with increasing additions of CeO_2 premix.

A comparison of the colour coordinate results of the CeO_2 melts containing 50 ppm Cr_2O_3 and 25 ppm Cr_2O_3 is shown in Figure 51. The results show that the melts containing 25 ppm Cr_2O_3 are closer to the origin due to a 50 % reduction in the quantity of Cr_2O_3. However, as the amount of CeO_2 is varied the colour coordinates still remain about a central location not moving far from the base glass.

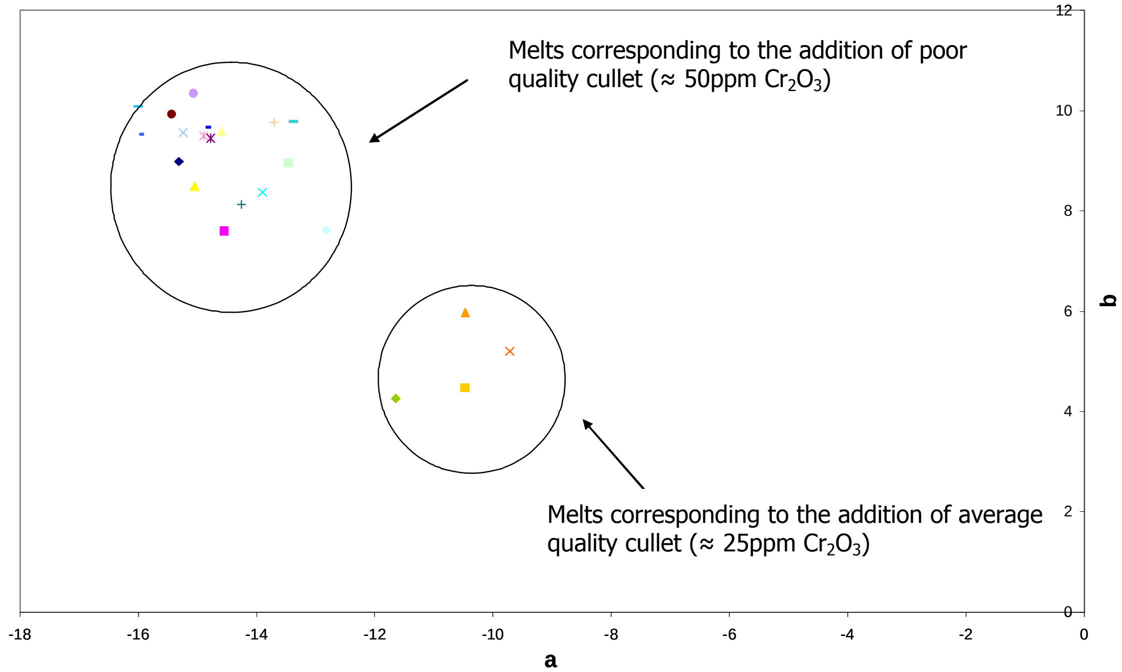


Figure 51: A comparison of the colour coordinate results for the CeO_2 melts containing 50 ppm and 25 ppm Cr_2O_3

Previous research suggested that the minimum and maximum amount of CeO_2 required was three fold and six fold the amount of Fe_2O_3 present in the glass. Therefore a number of melts were carried out based on the composition of a typical flint container glass, as shown in Table 29, with CeO_2 additions ranging from one to six fold the level of Fe_2O_3.

UV-Vis measurements were undertaken and the absorption spectra and colour coordinate results are shown in Figure 52 and Figure 53 respectively.

As was observed with previous melts, the absorption spectra show that as the amount of CeO_2 increased the absorption at the longer wavelengths of the spectrum decreased whilst the absorption at the ultraviolet edge shifted to a longer wavelength. The spectra show that as the amount of CeO_2 increased, the amount of ferrous decreased whilst the amount of ferric increased.

The colour coordinate results indicated that as the amount of CeO_2 increased the coordinates become less green/blue and more yellow, confirming a reduction in the blue ferrous ion and an increase in the yellow/green ferric ion.

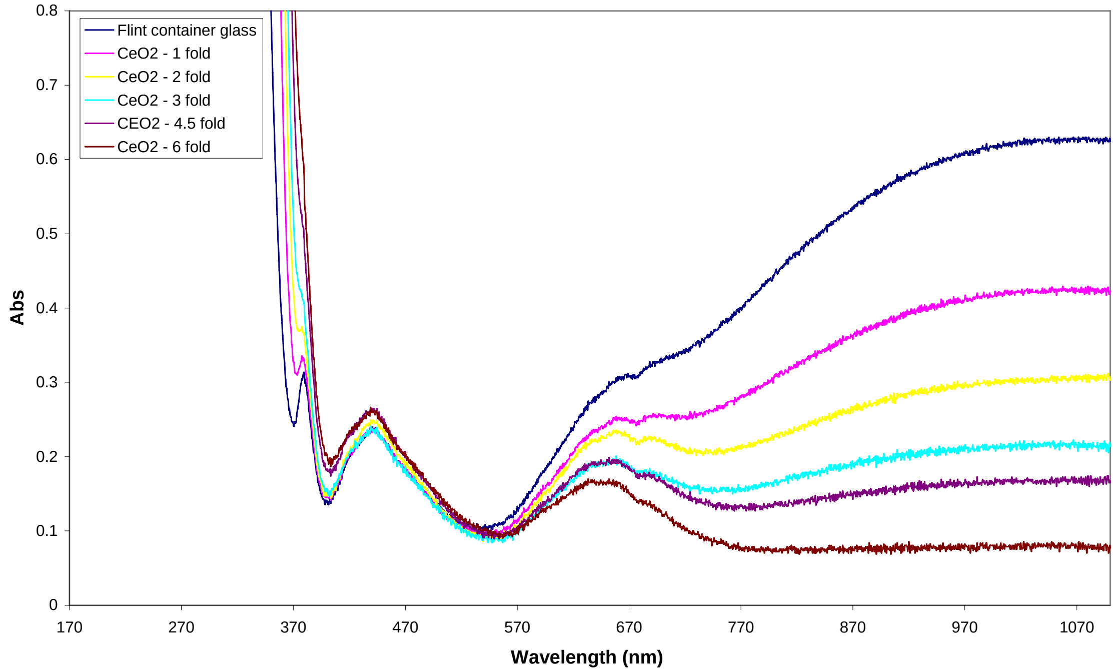
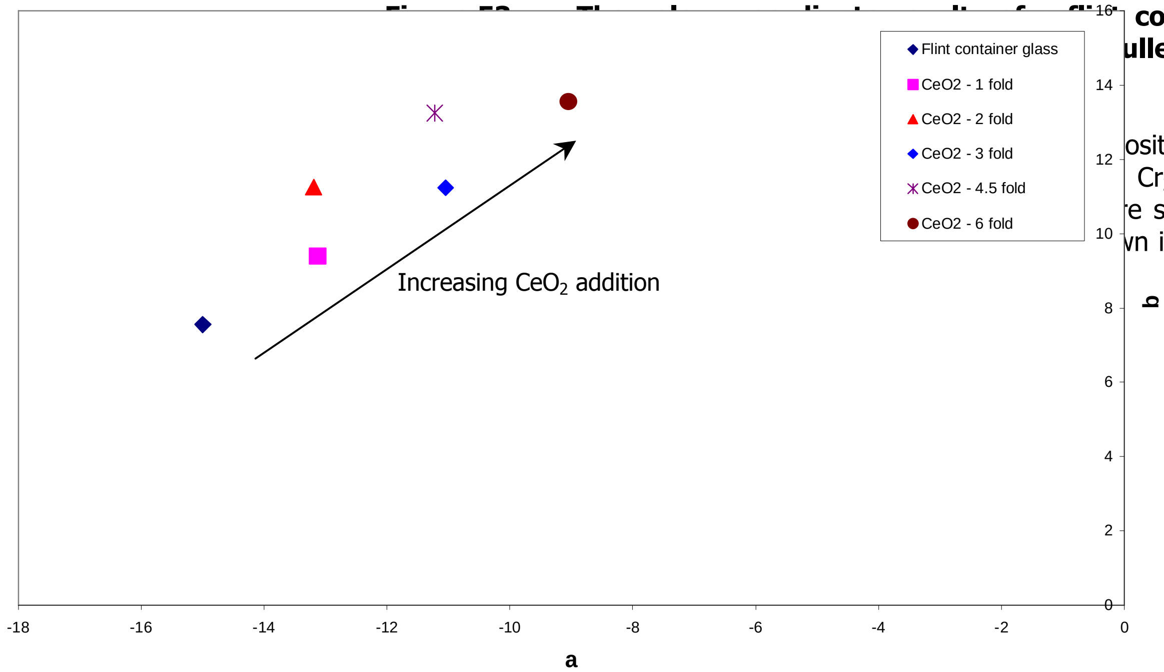


Figure 52: **A comparison of the absorption spectra of a series of melts based on the composition of a typical flint container glass with increasing additions of CeO_2.**



container
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Cr_2O_3 was
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wn in Figure

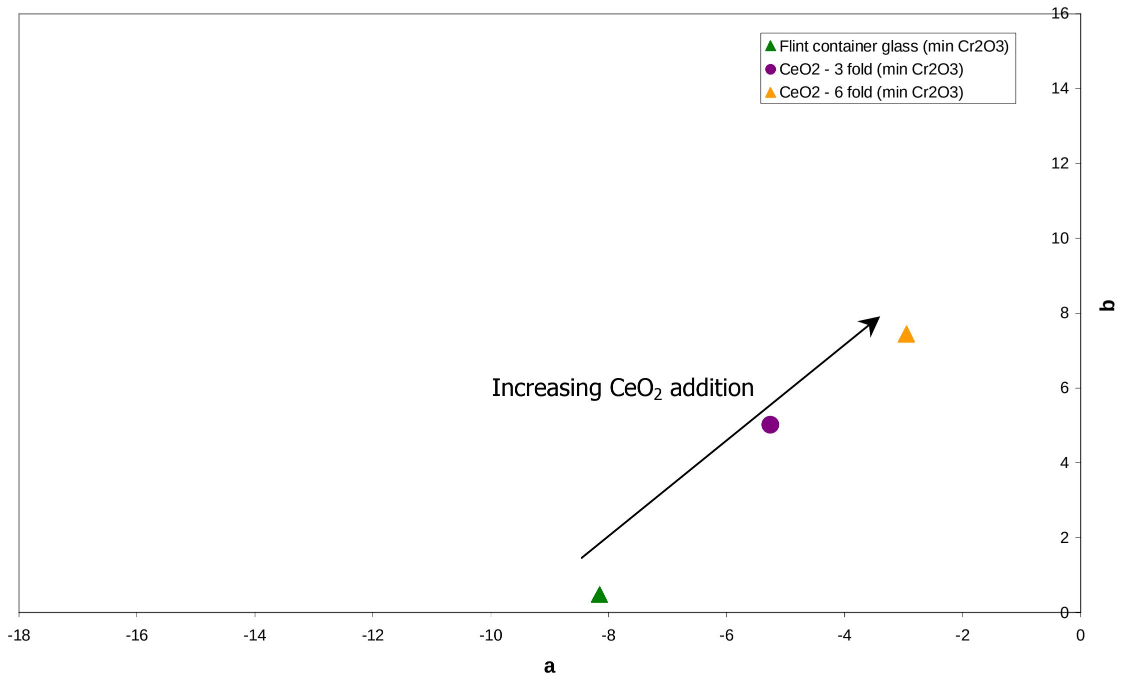

Figure 54: **The colour coordinates of a flint container glass (minimal Cr_2O_3 content) with increasing additions of CeO_2.**

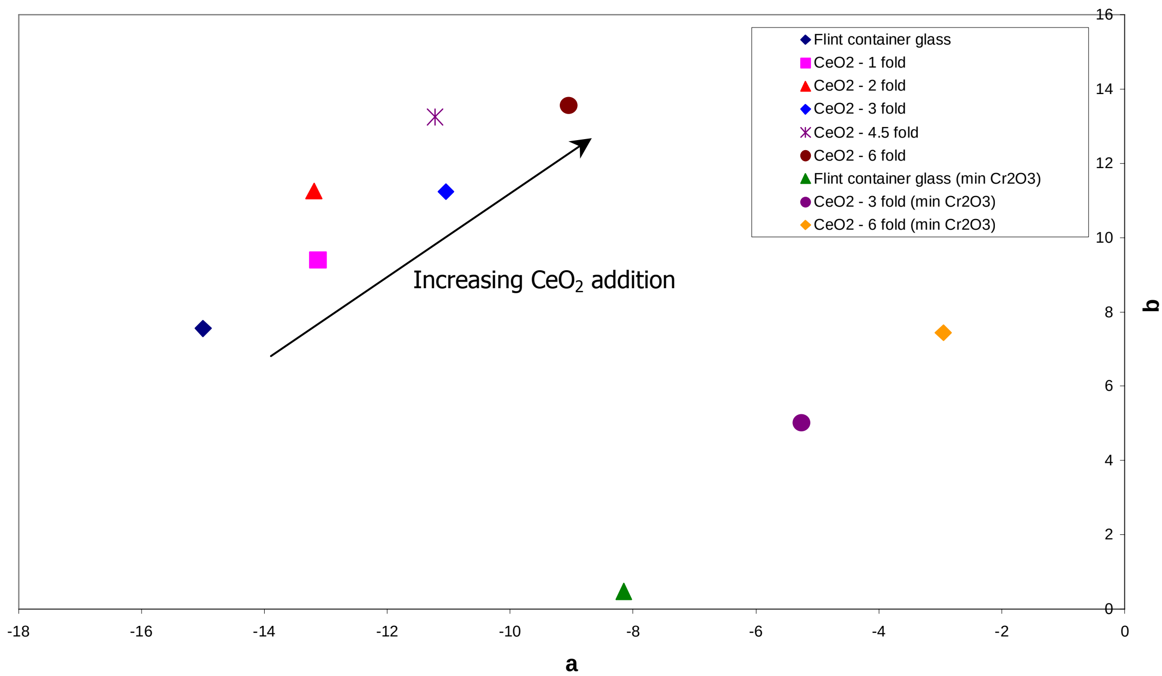

Figure 55: **A comparison of the colour coordinate results of the melts containing 0.07 wt % Fe_2O_3 and 0.005 wt % Cr_2O_3 and the melts containing 0.07 wt % Fe_2O_3 and a minimal level of Cr_2O_3.**

The results suggest that if sufficient quantities of CeO_2 are added, a significant change in the colour coordinate results is observed which indicates an alteration in the redox of the glass as the blue ferrous ion is oxidised to the paler yellow/green ferric ion. For industry to take full advantage of the chemical decolouriser CeO_2, much larger CeO_2 additions are required than those which are currently used in industry. However, for the melts containing 0.07 Wt % Fe_2O_3 a three fold and six fold addition of CeO_2 led to an increase in the batch cost of 18 % and 35 %, when based on an average cost of £ 50/per tonne glass.

The results suggest that although CeO_2 does oxidise ferrous to the paler ferric form it may not be an economically favourable route and it would not be sufficient to use solely CeO_2 to decolourise a flint container glass containing cullet of average quality and below. The presence of a physical decolouriser would also be required to mask the dominant green trivalent chromium ion and the yellow/green ferric ion.

3.3.7 Colour Control Summary

A. The selenium melts did not act as a benchmark for this study. The desired pink oxidation state was not introduced into the glass as the redox conditions of an industrial furnace were difficult to replicate. However, two full scale furnace melts were conducted that provided valuable data on selenium combined with CeO_2.

B. The investigation showed that it would not be economically viable to use Nd_2O_3 as a physical decolouriser and would be complicated due to the dichroic effect of Nd_2O_3.

C. Although Er_2O_3 is an effective physical decolouriser it is not an economically viable route with the addition of 0.1 Wt %, 0.2 Wt % and 0.3 Wt % Er_2O_3 increasing the batch cost by 14 %, 28 % and 42 %, respectively. However, this study did highlight the importance of the quality of cullet. The results showed that Er_2O_3 decolourising expenses could be reduced by a third by switching from poor to average quality cullet.

D. The results showed that the addition of CeO_2 could lead to a significant change in the redox of the glass as the blue ferrous ion is oxidised to the paler yellow / green ferric ion. However, this would require much larger CeO_2 additions than currently used in industry which may not be economically favourable. The presence of a physical decolouriser would also be required when using cullet of average quality and below to mask the green introduced by the trivalent chromium ion and the yellow / green ferric ion.

3.4 Predictive Colour Model

This part of the project focussed on producing a computer programme (Microsoft Excel format) that allows the prediction of the colour of the glass produced with various levels of added cullet. It allowed the calculation of the quantities of decolourants needed to restore the glass to acceptable colour and determined the cost of these changes. A working programme was produced, presented to furnace managers at two tutorial sessions and trialled in various factories. It was the intention that the interaction with industry would continue after completion of the project in order to allow the programme to be tailored to individual needs and circumstances as well as to deepen understanding of the behaviour of different melting operations. The programme serves two key functions:

1) to allow the use of higher levels of recycled glass and;
2) to reduce waste and the cost of expensive raw materials by giving greater control of the melting operation.

3.5.1 Methodology

The programme has been based on Microsoft EXCEL, which has provided a well understood platform for its construction. There were several steps in the design of the programme to facilitate colour prediction, including:

1) Calculation of the glass composition from the batch composition;
2) Determination of the total level of colorant impurities from all the various possible sources in the batch;
3) Prediction of the total optical absorption of the specimen from the known impurity levels;
4) Calculation of the colour coordinates from the predicted optical absorption spectrum;
5) Prediction of the additives required for minimum colour and determination of the corresponding batch cost.

3.5.2 Calculation of Glass Composition and Dopant Levels

This part of the programme uses a batch calculation method developed by GTS. It requires a knowledge of the composition of all the raw materials including both internal and external cullet, with a particular emphasis on key colorant ions present, i.e. Fe and Cr. The overall glass composition is assumed not to affect the final glass colour, and therefore the programme will not be reliable for glasses other than the typical soda-lime-silica composition used for containers but the narrow range of compositions used within the container industry should prevent any significant errors.

As part of the data input and batch calculation, batch redox is calculated to allow prediction of the Fe^{2+}/Fe^{3+} ratio. Similarly operating parameters such as furnace temperature can be included in the calculation of redox. Finally possible added decolourisers (Se, Ce, Er, Nd, Co) can be incorporated into the defined batch composition so that their effect on colour can be calculated. The programme is designed to allow any other suggested decolourisers/colorants to be added at a later date.

3.5.3 Determination of a Predicted Spectrum

The spectra for the individual ions are expressed as the sum of a number of Gaussian shaped peaks, using absorbance units as a function of wavenumber within the visible, near IR and UV part of the spectrum. Obtaining these fits has been a significant part of the effort expended on this project. The overall spectrum is then simply the sum of the individual components weighted according to the predicted concentration of that species. Reflection losses are assumed constant throughout the spectrum; while this is not exactly correct the associated errors are small and will not vary significantly from glass to glass. Data have been collected to allow the programme to be modified for this effect at a later stage.

The calculated spectrum can be compared with spectra measured using factory specimens as a check on the accuracy of the results. The fits are quantitative and allow determination of the concentrations of added colorants such as iron, which exists in two oxidation states. The same approach allows the known contributions to the spectrum to be subtracted and the remaining components due to phases such as Se to be determined by difference. This operational mode, although not the intended approach, has potential value in investigating effects such as the contribution of Ce to the UV absorbing properties of the glass.

An important part of this calculation is the determination of the proportions of iron (and other redox species) present in the ferrous and ferric states. This has been achieved using the experimental fits obtained by Simpson and Myers[22] for the relationship between redox number and Fe^{2+}/Fe^{3+} ratio. The effect of temperature has been included by using reported activation energies. This aspect of the work requires further study in that under strongly reducing conditions iron-sulphur amber formation is possible while under strongly oxidising conditions chromium may be oxidised to the carcinogenic 6+ state. Such potential effects, being normally outside of the operating range used for flint glasses, are not currently included, but deserve further consideration.

As part of the redox calculations the effects of using cerium as a decolouriser have been determined. The initial results model those reported well but two undergraduate projects are currently being undertaken to provide a check on the interactions between cerium and iron at high temperature. Measurements made on samples obtained from industry confirm the current predictions of the programme.

3.5.4 Selenium Behaviour

An important decolouriser used for container glass currently is selenium. This has a high cost and will probably be needed in larger quantities to decolorize glasses with higher levels of impurities. The work undertaken as part of this project to analyse the early results of a study on the effect of adding different levels of decolourisers indicated that the selenium contribution to the absorption does not vary linearly with added selenium levels. This effect was incorporated into the model used but the underlying reasons for the effect deserves further study. Volatilisation losses need to be minimised for environmental reasons and the contributions of retained Se in external cullet need to be fully understood. There are also reported possible interactions between Fe and Se which may contribute to the decolourising effect and, when fully optimised, may help to minimise the cost of this expensive component. The programme in its present form will be a useful tool in this analysis.

3.5.5 Colour Coordinate Calculation

This uses standard colour coordinate data at 2 nm measurement intervals and assumes a D65 light source, the modern equivalent of Illuminant C (average daylight in the Northern Hemisphere). The results were checked against those obtained on measured spectra using software at GTS and showed a close agreement. The numbers calculated refer to a standard specimen thickness of 40mm in accord with the standard approach adopted at GTS, but are easily adjusted to other thicknesses. The results expressed in terms of L*a*b colour coordinates are reported both graphically and in numerical format on the front page of the programme, based on the compositional data input.

3.5.6 Colour Optimisation

Currently the effect of adding decolourisers has to be calculated and optimised by an iterative approach. A further stage of development is to include an optimisation routine to facilitate the effective decolourising of a glass at minimum cost. A significant aspect of this programme is that the effect of adding several additives simultaneously is easily determined and parameters such as redox and melting temperature can be incorporated into the calculation. These latter two parameters are likely to be significant contributors to the behaviour of glass melts with large amounts of added external cullet and may well require further investigation for optimisation of decolourising.

[22] W. Simpson & D.D. Myers, The redox number concept and its use by the glass technologist, Glass Technol.,1978, Vol. 19, No 4, p. 82.

3.5.7 Programme Design

The programme is designed so that the user only inputs data from a front page and the key results are reported on the same sheet. Much of the working part of the programme is locked so that the various interconnections between the sheets cannot be accidentally overwritten. It is appreciated that some users may want the facility to be able to change the underpinning data and it is intended to allow this option by providing passwords for unlocking the sheets. It was also intended to continue developing the programme based on the results actually obtained in use. Further editions will therefore be published which: add new functionalities, give greater accuracy, and are individually tailored to the needs of different branches of the industry.

3.5.8 Worked Examples

The programme is available as a separate Microsoft Excel spreadsheet as part of this project. As a demonstration of the ability of the predictive model, a worked example in the form of screen shots is shown in Figure 56, Figure 57 & Figure 58. This example assumed 30.5% cullet in the final glass, of an average cullet quality (97.5% flint + 2% green + 0.5 amber cullet). Figure 56 shows the base glass without any decolouriser and Figure 57 shows the same base glass with a typical level of Se decolourisers (100g in 2000kg of sand). Then using the predictive model to optimise the glass colour without excessive cost (Figure 58), it is possible to considerably improve the glass colour with a small increment in price[23] from £40.40 to £40.56 (0.4% increase). This is only an example of the ability of the predictive model to improve colour without excessive cost, however, in practice it may not be necessary to significantly improve the glass colour.

INPUTS

Cullet loading	kg/mix	% of mix	% of final glass
internal cullet	0	0.0	0.0
external cullet	1250	27.0	30.5
plate cullet	0	0.0	0.0

External cullet quality	
flint %	97.5
green %	2
amber %	0.5
misc %	0
moisture %	0
organics %	0
ferrous metal %	0
Furnace pull	200
Furnace redox factor	1

Decolouriser addition	g/mix	weight g/2t sand
Selenium	0	0.0
Cobalt	0	0.0
Ceria	0	0.0
Neodymium	0	0.0
Erbium	0	0.0

OUTPUTS

Colour co-ordinates	40	mm
L	95	
a	-9	
b	2	
Cost / tonne batch	39.10	
Batch Redox	7.87	
Batch Fe2O3 %	0.044	
Batch Cr2O3 %	0.002	

Batch Recipe kg/mix	
Sand	2000.00
Soda ash	620.00
Limestone	480.00
Dolomite	115.00
UK dolomite	0.00
Neph syenite	60.00
Calumite	80.00
Salt cake	20.00
~	0.00
~	0.00
~	0.00
Sand carbon ppm	0.00
selenium	0.00
cobalt	0.00
ceria	0.00
neodymium	0.00
erbium	0.00

Figure 56: Predictive model example of the base glass without any decolouriser.

[23] The raw material prices used in the predictive model are estimates only to allow the model to predict a comparative batch price and are not a reflection of actual costs.

INPUTS

Cullet loading	kg/mix	% of mix	% of final glass
internal cullet	0	0.0	0.0
external cullet	1250	27.0	30.5
plate cullet	0	0.0	0.0

External cullet quality	
flint %	97.5
green %	2
amber %	0.5
misc %	0
moisture %	0
organics %	0
ferrous metal %	0
Furnace pull	200
Furnace redox factor	1

Decolouriser addition	g/mix	weight g/2t sand
Selenium	100	100.0
Cobalt	0	0.0
Ceria	0	0.0
Neodymium	0	0.0
Erbium	0	0.0

OUTPUTS

Colour co-ordinates	40	mm
L	88	
a	-3	
b	9	
Cost / tonne batch	40.40	
Batch Redox	7.87	
Batch Fe2O3 %	0.044	
Batch Cr2O3 %	0.002	

Batch Recipe kg/mix	
Sand	2000.00
Soda ash	620.00
Limestone	480.00
Dolomite	115.00
UK dolomite	0.00
Neph syenite	60.00
Calumite	80.00
Salt cake	20.00
~	0.00
~	0.00
~	0.00
Sand carbon ppm	0.00
selenium	0.10
cobalt	0.00
ceria	0.00
neodymium	0.00
erbium	0.00

Figure 57: Predictive model example of the base glass with typical Se decolouriser of 100g in 2000kg sand.

INPUTS

Cullet loading	kg/mix	% of mix	% of final glass
internal cullet	0	0.0	0.0
external cullet	1250	27.0	30.5
plate cullet	0	0.0	0.0

External cullet quality	
flint %	97.5
green %	2
amber %	0.5
misc %	0
moisture %	0
organics %	0
ferrous metal %	0
Furnace pull	200
Furnace redox factor	1

Decolouriser addition	g/mix	weight g/2t sand
Selenium	25	25.0
Cobalt	28	28.0
Ceria	3250	3250.0
Neodymium	0	0.0
Erbium	0	0.0

OUTPUTS

Colour co-ordinates	40	mm
L	85	
a	-2	
b	0	
Cost / tonne batch	40.56	
Batch Redox	10.63	
Batch Fe2O3 %	0.044	
Batch Cr2O3 %	0.002	

Batch Recipe kg/mix	
Sand	2000.00
Soda ash	620.00
Limestone	480.00
Dolomite	115.00
UK dolomite	0.00
Neph syenite	60.00
Calumite	80.00
Salt cake	20.00
~	0.00
~	0.00
~	0.00
Sand carbon ppm	0.00
selenium	0.03
cobalt	0.03
ceria	3.25
neodymium	0.00
erbium	0.00

Figure 58: Predictive model example of the base glass with revised decolouriser Se, CoO and CeO_2.

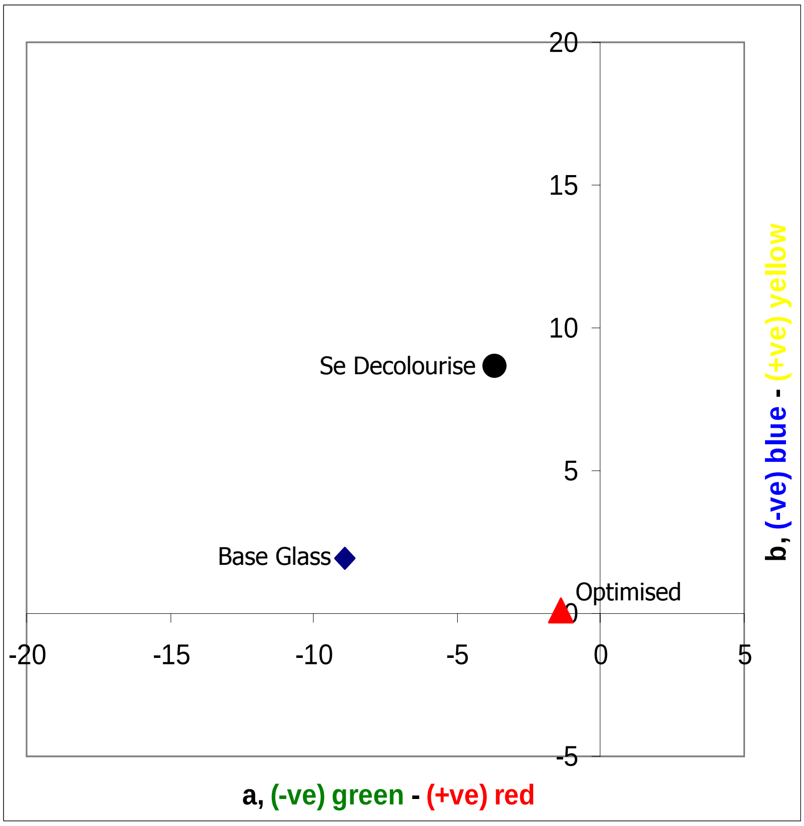

Figure 59: Predictive model prediction of the colour coordinates of the three examples, base glass, Se decolouriser and optimised.

3.5.9 Predictive Colour Model Summary

This predictive colour model was trialled by a number of container glass manufacturers and it allowed manufacturers to explore cost effective alternative decolourisers. The feedback was positive and the model will continue to be developed by GTS and University of Sheffield.

3.5 Industrial Decolouriser Trials

Feedback from the early stages of the laboratory scaled trials suggested that ceria showed the most potential as a decolouriser. However, the trials highlighted that ceria would require the presence of a physical decolouriser to mask the colour introduced by the trivalent chromium ion and the ferric ion. Therefore trials of ceria in combination with selenium were undertaken to try to minimise the addition of the physical decolouriser selenium and hence to reduce the decolourising costs. Between April and December 2005 GTS worked with two container glass manufacturers to provide advice and support during the selenium and ceria decolouriser trials.

In recent years selenium has been used to decolourise glass in industry but it has been necessary to trial a replacement decolouriser due to large increases in price. Ceria, CeO_2, has been chosen as a potential replacement for selenium and the laboratory work demonstrated that ceria may be a cost effective decolouriser. Trials of ceria were undertaken at two different project partners' sites; in order to protect commercially sensitive information the two trials will only be described as 'Factory 1' and 'Factory 2', as described below.

3.5.1 Factory 1

The trial at factory 1 was conducted between April and August 2005. The details of the decolouriser additions can be seen in Table 33; for reasons of commercial sensitivity the actual numbers have been normalised to 100.

Month	Se Factor	Ce Factor
April	100	0
May	47	100
June i	47	100
June ii	9	44
June iii	8	32
July	9	44
August	9	55

Table 33: Factory 1 decolouriser additions.

The colour of the bottles from the trials was measured using a UV-Vis to visible spectrophotometer at GTS. The results of the colour measurements can be seen in Figure 60, where 'a' is a measure of green (negative) to red (positive) and 'b' is a measure of blue (negative) to yellow (positive).

It can be seen that the replacement of selenium with ceria shifts the 'a' co-ordinate to be more negative, which results in the glass appearing greener. From the visual inspection of the bottles containing ceria not only did they appear greener but they also appeared brighter, as there is no dull grey tone introduced with selenium containing glasses. This is because selenium and ceria decolourise in different ways. Selenium is a physical decolouriser that adds a pink colour to the glass that counterbalances the green and blue colours, that iron and chromium bring, and produces a neutral grey colour. Whilst, ceria is a chemical decolouriser that oxidises the iron from the intensely coloured Fe^{+2} state to the less intense Fe^{+3} state. In sufficient quantity, ceria can counteract the Fe colouring ions by oxidation but will have little effect on the intensity of the Cr^{+3} colouring ions.

Another variable to be considered in the relationship between the decolouriser addition and the glass colour is the quantity of cullet used. Cullet can contain around 2% green glass and adds a considerable amount of iron and chromium to the final glass. From Figure 61 and Figure 62 it can be seen that as the cullet addition increases the 'a' coordinate becomes more negative and the glass has more intensity of green colour. However, all the containers produced during the trial were accepted by the customer.

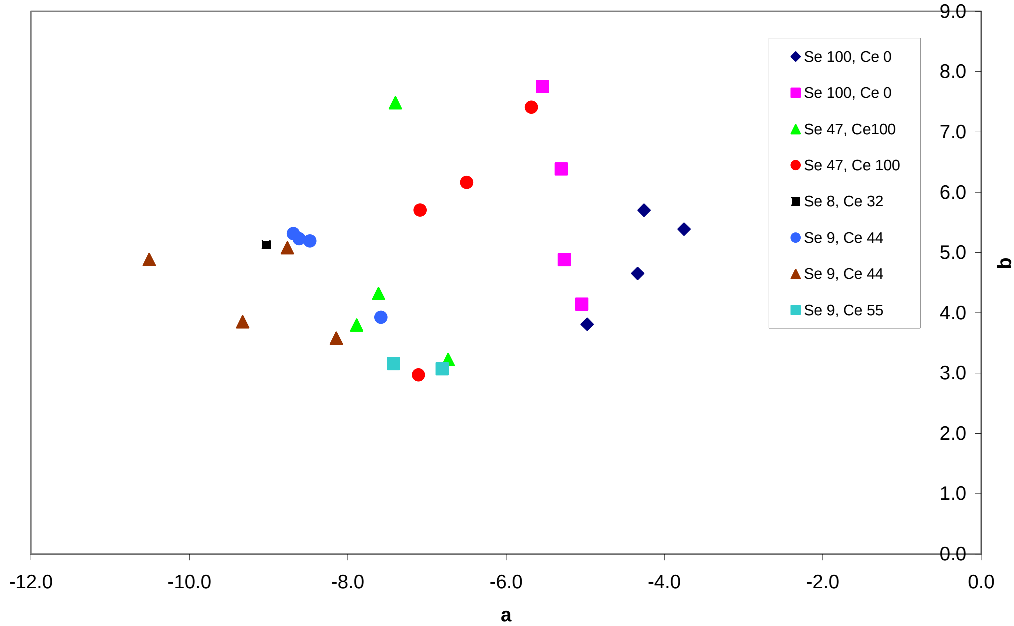

Figure 60: Colour measurements of trial bottles.

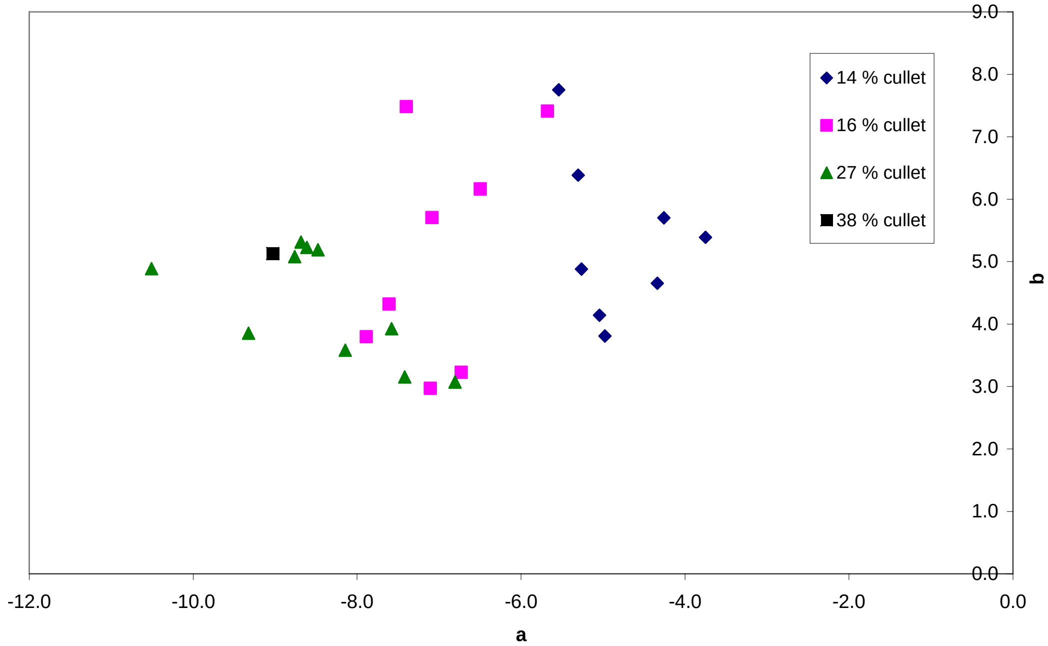

Figure 61: Colour and cullet addition of trial bottles

From Figure 60 it is unclear what effect the quantity of ceria used has on the glass colour as there is a reaction between the Se, CeO_2 and colouring ions. However, it was not possible to quantify the Se/Ce reaction on this industrial trial without additional trials which would not have been commercially practical. For the purposes of these mixed decolouriser trials ceria and selenium were used in conjunction in Se/Ce ratios of between 2:1 and 5:1. It is not therefore possible to determine the individual contribution of either decolouriser from the results. It can be concluded that ceria containing glasses do not decolourise as effectively as the selenium only containing glasses. The overriding conclusion drawn from this series is the dominant influence of cullet additions on glass colour. It should be noted that all the glasses in this series were the products of commercial production runs and all produced glasses of an acceptable quality and thus the measured differences were not perceptible to the eye.

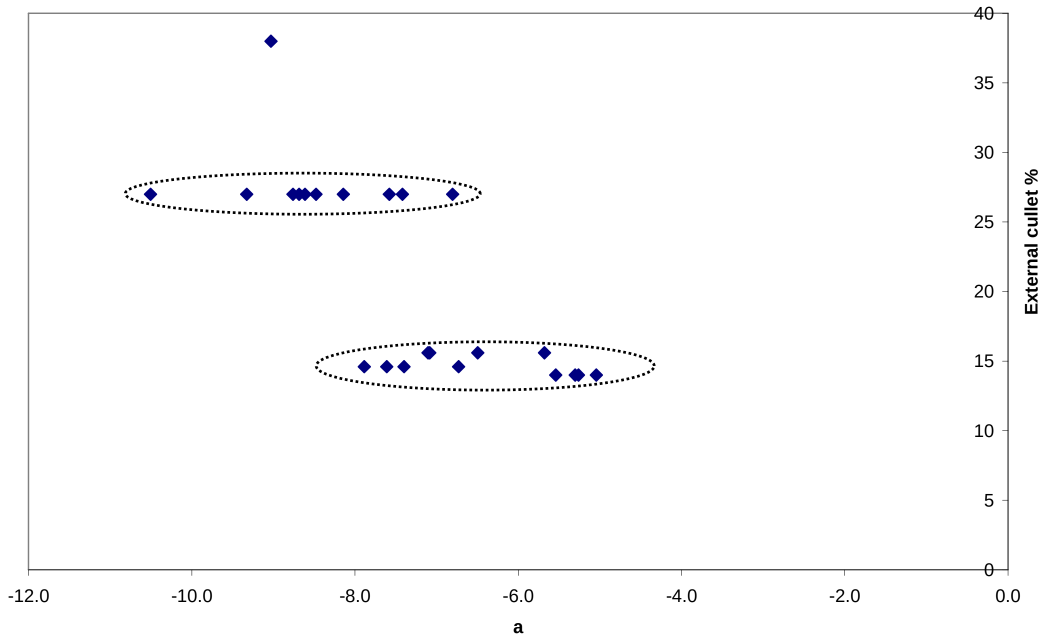

Figure 62: **Greenness ('a' CIE colour coordinate) of trial bottles against the cullet addition (%).**

3.5.2 Factory 2

GTS monitored the change in use of a decolouriser from selenium to selenium and ceria during the trial at Factory 2. Information was gathered in April 2005 before the change and in August 2005 a few months into the change to selenium and ceria decolouriser. The data for the change in decolouriser is shown in Table 34. The colour of the trial bottle is shown in Figure 63. Upon first inspection the colour data is surprising. The introduction of ceria has improved the colour of the glass and this contradicts the results from factory trial 1 and laboratory work done at GTS. But as with factory trial 1, cullet has a large part to play in influencing the colour of the final glass. The same cullet addition was used in April and August but the quality of the cullet varied hugely. In April the cullet had a green content of 2.5 % and an organic content of 0.25 %. In August the cullet had a green content of 0.9 % and an organic content of 0.10 %. So the April cullet had an iron and chromium level two and a half times larger than the August cullet. Also, the organic content of the April cullet is two and a half times larger than the August cullet. The result of this change in organic content is that the April glass will be more reducing, with more of the iron in reduced form which has a more intense colour than the oxidised from. Thus when due consideration is made for the cullet quality this trial would seem to confirm that controlling the quality of cullet is as important as controlling the type and quantity of decolouriser.

Month	Se Factor	Ce Factor
April	100	0
August	25	100

Table 34: **Factory 2 decolouriser additions.**

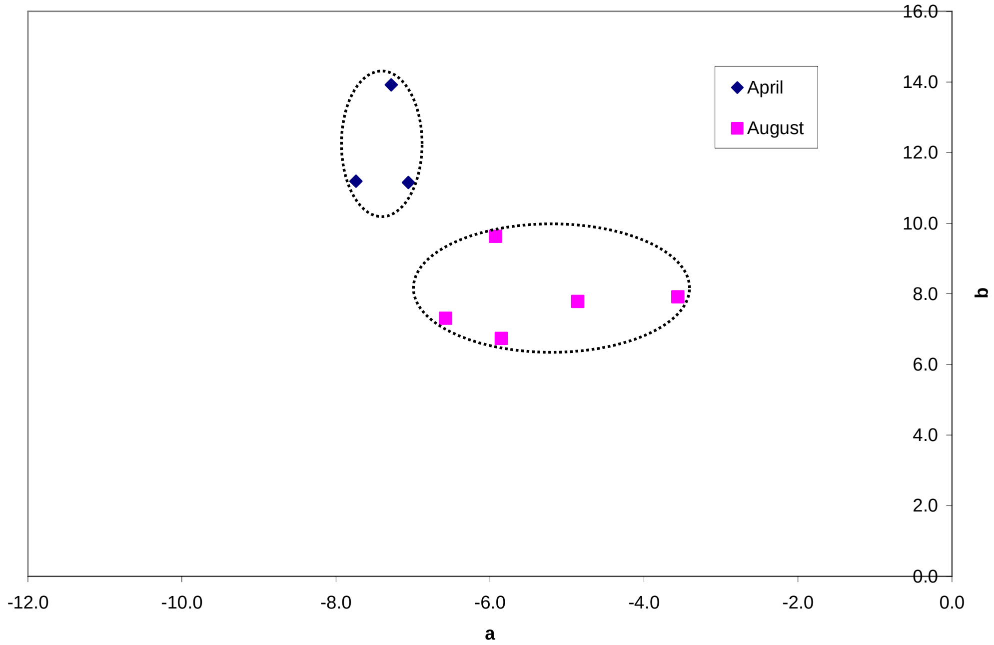

Figure 63: **Colour of factory 2 bottles before (April) and after (August) the change in decolouriser.**

3.5.3 Summary

From the industrial trials valuable knowledge and experience was gained which was also used to develop and verify the colour predictive model. The following information was gained:

A. Ceria is not a direct replacement for selenium or cobalt oxide as a decolouriser as it cannot physically mask the Cr colouring ion. Ceria is a chemical decolouriser that changes the oxidation state of the glass which is effective on reducing the impact on colour from the Fe ions but not Cr ions. Selenium and cobalt oxide are physical decolourisers that inhibit colour to mask the colour from both Cr & Fe ions.

B. Ceria decolouriser produces a glass that appears brighter due to the increase in light transmission through the glass.

C. The amount of Fe and Cr in the glass increases with the cullet addition and flint glass becomes more difficult to decolourise.

D. An effective decolouriser needs to have both a chemical and a physical action to counteract the colouring ions. Therefore, the Se/Co & Ce decolouriser appeared to be both effective and economic.

E. The colour introduced through high cullet additions outweighs the effect ceria and selenium has as a decolouriser when used at the current typical additions.

F. The quality of cullet has a large effect on the final glass colour; lower quality flint cullet contains more green glass contamination and thus has greater amounts of Fe and Cr present which leads to a glass that requires higher levels of decolouriser to achieve the desired final glass colour.

3.6 Impact of Recycling

The lead (Pb) and cadmium (Cd) levels in the three main glass colours manufactured in the UK have been determined by compositional analysis over the period of the project, only the Pb is considered significant due to higher content. Furthermore, the data from previous analyses prior to the start of the project have been included for comparison. Table 35 shows the level of Pb before and during the project and the number of samples analysed. Within experimental measurement there is no significant difference between the two periods.

Glass Colour	Pb level (ppm) Jan 03 to Oct 04	Pb level (ppm) Oct 04 to Dec 05	Number samples analysed
Flint	45	39	900
Green	88	86	300
Amber	32	32	300

Table 35: Pb level comparison over the two periods.

Figure 64, Figure 65 and Figure 66 shows the monthly average of Pb and Cd for all the glass containers analysed. However, it must be noted that the Pb for all three colours has on occasions exceeded 200 ppm. The Packaging Waste Regulations seeks to eliminate the presence of lead, cadmium, mercury & hexavalent chromium in packaging materials. However container glass has a derogation that has recently been reviewed by the Article 21 Committee which has recommended that the limit of 200 ppm be applied to container glass for an indefinite period. This recommendation is awaiting publication in the EU Formal Journal.

The Pb level for flint and amber is lower than the green glass which is what would be expected as flint and amber have lower cullet additions. The average external cullet addition, based on 2004 packed production figures, for flint and amber container glass is approximately 22%, whilst green glass typically has an external cullet addition of approximately 75%.

A study undertaken by SGT in 2000 (Table 36) identified that external cullet available in the UK had relatively high levels of Pb and this is likely to be the main contributor to Pb in container glass; probably from traditional wine bottle lead foil seals and leaded glass such as crystal glass in the cullet. During the same period SGT (Table 37) conducted analysis of the Pb content of UK produced containers and the average Pb content of flint, green and amber was 35 ppm, 100 ppm and 25 ppm respectively. As these values are very similar to the Pb content of UK manufactured container glass during the 2003 to 2005 period (Table 35), it can reasonably be concluded that the Pb in UK manufactured container glass has remained relatively constant over the past five years. The analysis technique in this project and that used by the SGT was XRF analysis calibrated against certified reference samples; therefore, within experimental measurement error the analyses from the different periods will be comparable.

Glass Colour	Pb level (ppm)		
	Average	Minimum	Maximum
Flint	150	25	315
Green	160	130	310
Amber	75	10	175

Table 36: Pb level in cullet available in the UK reported in a survey conducted by SGT in 2000.

Glass Colour	Pb level (ppm)		
	Average	Minimum	Maximum
Flint	35	10	115
Green	100	35	160
Amber	25	15	65

Table 37: Pb level in container glass reported in a survey conducted by SGT in 2000.

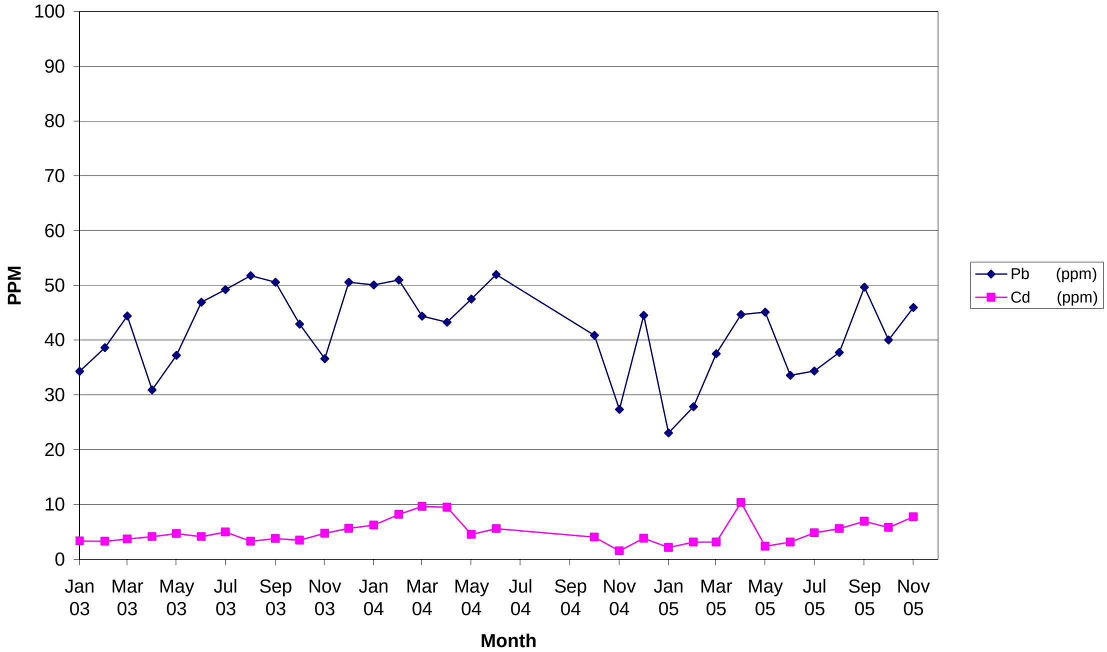

Figure 64: Pb & Cd analysis of UK produced flint colour containers.

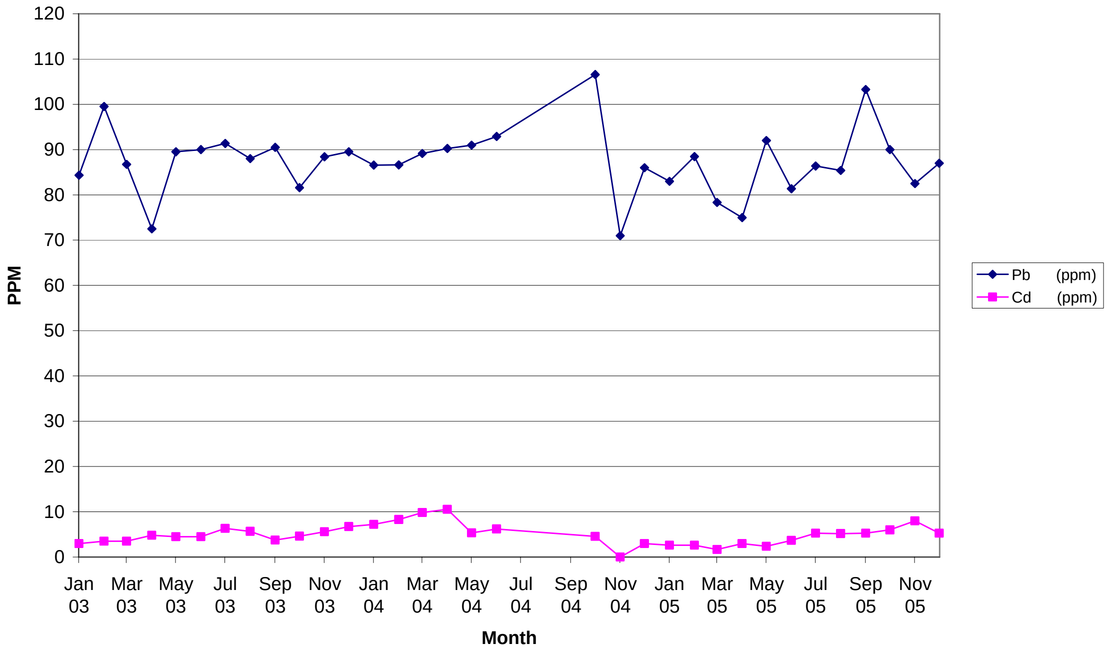

Figure 65: Pb & Cd analysis of UK produced green colour containers.

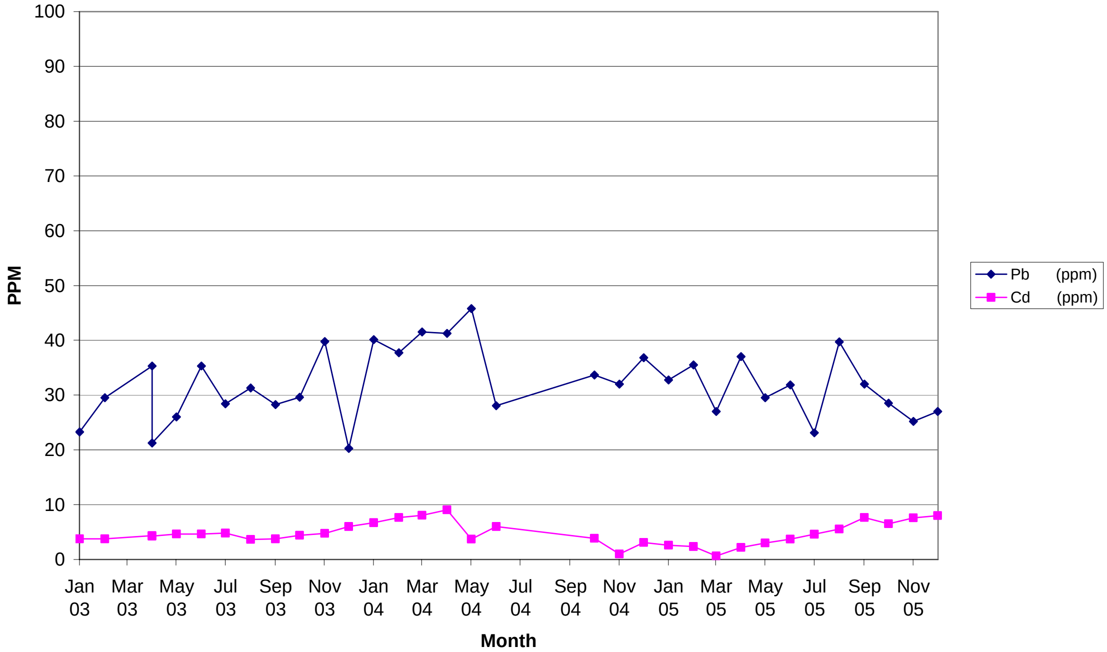

Figure 66: Pb & Cd analysis of UK produced amber colour containers.

Also the SGT analysed the Pb content of imported containers, both empty and filled. It was found that the Pb level in imported containers was higher than UK manufactured containers. It is estimated that approximately 1,200,000 tonnes of containers are imported into the UK. Unfortunately there is no reliable data source of the colour split of these import containers; however, it is thought that a majority will be green due to imports of beer and wine.

Glass Colour	Pb level (ppm)		
	Average	Minimum	Maximum
Flint	110	10	410
Green	160	20	370
Amber	100	10	160

Table 38: Pb level of imported glass containers, study conducted by SGT in 2000.

Table 38 shows the average and range of Pb level in imported containers. The explanation for the higher levels of Pb in green is probably contributed to the inclusion of Pb based wine sealing foils. However, an explanation for the relatively high levels in flint and amber is not so apparent, but could be partially due to lead crystal and/or other lead containing glasses and contamination from green in the cullet.

Whilst not a perfect correlation, the available data does suggest a strong relationship between the Pb level in container glass and the cullet level used in its manufacture. If the recycled glass content of flint and amber glass increases above the present addition it is likely that the Pb content in these glass colours will increase. According to the SGT survey the level of Pb in flint cullet is similar to that in green cullet, therefore, it would expected that a similar levels of cullet addition the Pb in final glass will match that found in green glass. The level of Pb in amber cullet is less than that in flint and green cullet and therefore the effect of Pb in amber glass is likely to be less pronounced.

4 Conclusion

Governmental and other drivers will ensure that the volume of waste glass recovered from the UK's waste stream will significantly increase. By the year 2008 it is estimated that some 2.7 million tonnes of packaging glass will be entering the waste stream and the government have set a corresponding target for glass recovery of 1.6 million tonnes. Ideally much of this recovered glass would be used as feedstock for the UK's domestic container production as this represents one of the better environmental options for the material. Unfortunately by 2008 much of this glass will be being collected in a colour mixed form which precludes its use for remelting unless it is subjected to a colour sorting process. The difficulties in obtaining good quality cullet to feed the melting furnaces are further exacerbated by the chronic colour imbalance suffered in the UK which produces an overabundance of green glass.

Glassmakers will have to accept that the supply of colour sorted glass from the bring sites will dwindle and techniques will have to be developed to utilise the new mixed sources, if the current trend towards mixed colour glass collection continues. Green glass contamination of the recycled clear glass supply will become the defining issue as to the level of cullet that will be available to the UK's melters.

The consumer perception study investigated the possible effect on the consumer buying decision with increased cullet additions in flint containers with cullet of a known colour contamination. It was found from the two studies conducted, that consumers' ability to detect a colour difference was markedly reduced when their attention was not drawn to this as a possible feature of presented glass containers. It is argued that this might be the more representative of consumer 'real world' settings. It was found that effects of glass tint can be magnified when containers are placed on a supermarket shelf, one in front of another. This is particularly so for clear products, such as water and vodka. Interestingly, when the green tinted bottle, or both bottles, had a red label participants reported a green tint more frequently. This may be a bias that relates to established mechanisms of colour perception. It was found that containers with intense tint of green could have both a positive and negative effect on the consumer's perception depending on product, age and sex. Therefore, it is necessary for product marketers to appreciate these effects and take advantage in order to increase desirability of products.

Container glass produced by our European neighbours proved to be a useful guide to acceptable quality. The colour of flint container glass across Europe tended to vary and no significant trend was discernable between glass colour tint and country of manufacture. Approximately 90% of flint containers manufactured in Europe had colour coordinates better than -11 a and +11 b. Furthermore, it was found that there was no significant correlation between glass colour tint and the type of product. However, it was observed that spirit and food containers tended to have slightly less glass colour tint than other flint containers.

The project has demonstrated that technical solutions can be found which will help maximise cullet additions. Clear glass of an acceptable quality can be produced from feedstock that contains significant proportions of colour-contaminated flint cullet. The desired quality can be achieved cost effectively by the addition to the melt of commercially available decolourisers. The investigation of glass colour identified possible decolourising options for flint container glass and these were taken from laboratory scale all the way through to full scale industrial trials. This investigation demonstrated the cost effective options for decolouring flint container glass at different cullet additions. During the industrial trials all the containers produced were supplied to the container manufacturer's customers for product filling and subsequent supply into the retail chain. This demonstrated that the industrial melting trails were successful as the customer did not notice a difference in colour and all containers produced were within acceptable limits for colour in flint containers.

The theoretical background to decolourisation is somewhat arcane but fortunately lends itself to computer modelling. An important output from the project is a very user-friendly EXCEL-based programme that will quickly guide busy furnace managers through this procedure. The programme was the subject of an industry workshop training session and the programme has proven to be popular with users and irrespective of the outcome of the present project will undergo further development. The predictive glass colour model used data from the laboratory work and industrial trials. The model has allowed container glass manufacturers to investigated different decolouriser system for varying levels of cullet and of known quality. It was found that a Se/Ce mix was an effective and economic decolouriser, Ce on its own had limited decolouring ability.

Successful control of a process usually requires measurements and in order to control the effects of cullet addition it will be necessary to determine its composition. Obtaining a representative sample of cullet for quality assessment is a difficult and labour intensive process. This work was able to demonstrate that adequate control could be obtained from simple colour measurements which can be made from a relatively small sample. A rapid test procedure was developed which allowed the container glass manufacturers to accurately calculate the appropriate level of decolourisers.

The cullet sampling identified that available cullet for container production was not of the desired and expected quality in terms of colour contamination. Therefore, UK glass container manufacturers have been using cullet of varying quality and continued to produce acceptable quality containers. It was found that the colour contamination could be 2 to 3 times greater than what was expected or specified. During the project period it was found that cullet quality in terms of colour contamination improved. This was partly due to increased awareness and promoting improvements in cullet quality. From the cullet sampling a Furnace Ready Cullet specification was devised, which has now been accepted by the project partners and is ready for publication. It is hoped that the specification will encourage improvements in furnace ready cullet.

The heavy metal content of UK produced container glass was monitored throughout the project period and it was found that there was no measurable increase in Pb or Cd over an 18 month period prior to the project. The average content of Pb was found to be below 100 ppm for flint, amber and green glass. However, on occasions the Pb content did peak close to the 200 ppm derogation limit set by the Article 21 Committee as part of the Packaging Waste Regulations. It is recommended that the limit for heavy metal content in container glass is not reduced below 200 ppm on any future revisions of the derogation.

Glass manufacturers instinctively strive to produce good quality product in all areas but are particularly sensitive to issues of colour. The customer perception studies have been invaluable in demonstrating that this discipline is not replicated by the buyers whose perception of colour is rather less demanding in most instances and who would not be perturbed if their clear glass jar or bottle lacked a little lustre or perhaps displayed a slight colouration. Based on these findings it should be possible to devise a control strategy which is limited by customer perception of an acceptable colour quality rather than the more demanding criteria currently set by the glassmakers and brand owners.

Finally, to maximise cullet additions there is a requirement to address the following:

- Consumer perception;
- Control of cullet quality;
- Selection of decolouriser to suit cullet quantity & quality.

By addressing the above criteria it should be possible to produce glass containers with the maximum available cullet addition, which are desired by the consumers without effecting perception of the product or brand.

5 Recommendations

This project has involved many different types of research and investigative approaches to identify the commercial and technical barriers to maximising cullet additions in container glass manufactured in the UK. The work undertaken has been comprehensive within the constraint of the project. However, during the course of the work other questions were raised, and further work to fully address these would consist of the following:

1) Ongoing frequent monitoring and measurement of glass colour and heavy metals content for a range of European manufactured container glasses.
2) Assessing the impact on colour of different glass container collection methods; and the changing availability of colour separated glass. It is essential to collate and process information on glass recovery and the collection methods employed, as the data presented in this report will rapidly become 'out of date'. It is also necessary to forecast projected waste arisings beyond 2008, which can then be used by the waste glass collection industry to prepare for future demand.
3) A consumer study on the implications of container colour within different brand contexts. i.e. What are the effects of colour on brand perceptions?
4) More work to better understand whether consumers' attitudes towards glass containers can be influenced by colour, even where they have not consciously realised that a colour difference exists.
5) Further, more detailed testing of on-shelf appearance of products, to quantify 'real world' situations and effects of colour manipulations on purchasing decisions.
6) The effects of label colour, for example is a red label just creating a bias to see green or is sensitivity also being altered? What are the effects of other colour labels? This might also be related to the consumer brand perception.
7) Product trials - examining effects of colour on 'real' sales and relating this back to the quantitative assessments of consumer perceptions. This will assist to improve the psychological model and heighten confidence.
8) To further improve the predictive colour model, a continuation of the industrial trails should be sought. This would provide additional data to refine and build confidence in the output of the model. The setting up of a working group with industrial partners for effective feedback to further develop the predictive colour model would be of great value.
9) Integration of consumer perception ratings into the predictive model. This will allow the impact on the consumer to be predicted as well as showing the actual colour measurement. In addition, the measurement of 'filled' container colour when on the supermarket shelf, needs to be assessed and included in the findings.
10) The redox factor of cullet needs to be determined in order to control the glass chemistry and to help achieve required glass colour, as well as to maximise cullet addition.
11) Cullet sampling for colour contamination needs to be adopted by the cullet processors and container glass manufacturers. The importance of cullet sampling and quality assessment needs to be better appreciated, and with the aim of cullet being classified as a glass making raw material, rather than waste.
12) There needs to be development of a suitable sampling method, appropriate for determining the level of all contaminants in furnace ready cullet. This is especially true for critical contaminants such as pyroceramics and refractories.
13) The findings of this work should be integrated into other approaches for reduction of waste and maximisation of cullet additions. The proposed 'lightweighting glass containers' project would be an ideal vehicle, helping with improving the ability to utilise more cullet through importing bulk wine for filling in UK manufactured glass containers.

14) High profile dissemination of the project work and findings through scientific and technical papers, Glass Action Forum, SGT conferences, training sessions, websites and British Glass Committees etc.

6 Acknowledgements

During the project period continual contact and input was sought and given from all project partners with regular meetings to disseminate findings, maintain support and direction. The support from the project partners was the key to this successful project. The project involved the discussion and solution to numerous controversial topics which was only possible with the openness and support from all project partners.

GTS would like to thank WRAP and all the project partners for their support during this 18 month project. This is only the precursor to the main objective of maximising cullet additions in the container glass industry and therefore GTS will continue to disseminate the findings and seek opportunities for continuing the work to fulfil the further work recommendations.

Appendix A – Colour Measurement on Glass Bottles

To be able to quantify the materials used in the consumer perception studies, and also as part of the process of developing and demonstrating approaches for the measurement of glass food and drink container colour, the team of Professor Ronnier Luo, of the Department of Colour Chemistry, University of Leeds, measured the stimuli used in the experimental studies described in subsequent sections.

1. INTRODUCTION

Six different kinds of glass bottles were tested: water bottles, spirit bottles, salad dressing bottles, wine bottles, beer bottles and jelly jars. The colours of the glass bottles in each kind changed from a clear (flint) to a greenish transparent colour. Nine samples with different degree of opacity were placed in different glass bottles. These are natural mineral water, orange cordial, whisky, vodka, Caesar salad dressing, Italian salad dressing, white wine, red wine and beer. Figure 1 shows three samples which were placed in different glass bottles, i.e. Caesar salad dressing, natural mineral water and whisky.

In order to investigate the influence of different depth of the products, two salad dressing samples and two spirit drinks were measured with either 1 bottle or 3 bottles arranged in a row (different depth). Also orange cordial and mineral water were measured with either 1 bottle or 2 bottles in a row. Table 1 lists all the combinations for different conditions. Only bottles lists in Table 1 have multiple bottle samples available in each kind, which enable multiple bottles testing to be carried out.

Table 2 lists the other 3 kinds of bottles: beer bottles either empty or with beer, empty wine bottle, wine bottle with either white wine or red wine, and empty jelly jar.

In this report, Bottle 0, 1 and 2 are hereafter designated as clear (flint), greener and greenest bottles respectively. For each situation, a name (a combination of letter and number) was given to indicate the conditions given in the tables.

Each sample was measured at the edge of a shelf with a height of 1.5 meter. The distance between the measuring instrument (a tele-spectroradiometer or a digital camera) and the sample was always fixed at 1 meter. In total, 79 measurements were taken.

	Empty		**Single bottle**	**multi bottles**
Water Bottles	WB0	with Orange Cordial	OR0	OR0×2
	WB1		OR1	OR1×2
	WB2		OR2	OR2×2
		with Mineral Water	MW0	MW0×2
			MW1	MW1×2
			MW2	MW2×2
Spirit Bottle	SP0	with Whisky	WH0	WH0×3
	SP1		WH1	WH1×3
	SP2		WH2	WH2×3
		with Vodka	VK0	VK0×3
			VK1	VK1×3
			VK2	VK2×3
Salad Dressing Bottle	SD0	with Caesar Salad Dressing	CS0	CS0×3
	SD1		CS1	CS1×3
	SD2		CS2	CS2×3

		with Italian Salad Dressing	IS0	IS0×3
			IS1	IS1×3
			IS2	IS2×3

Table 1: Six kinds of samples, placed in three kinds of glass bottles. The colour of the bottles changed from optical flint (clear) to a greenish transparent colour.

Beer Bottles		BB0	Beer Bottles with Beer		B0	
		BBD			BD	
		BBC			BC	
		BBB			BB	
		BBA			BA	
Wine Bottles	W0	Chardonnay	Wine Bottles with White Wine	WW0	Wine Bottles with Red Wine	WR0
	W1	06/05/2005 08:00		WW1		WR1
	W2	05/05/2005 14:00		WW2		WR2
	W3	03/05/2005 22:00		WW3		WR3
	W4	02/05/2005 22:00		WW4		WR4
	W5	02/05/2005 16:00		WW5		WR5
	W6	Merlot		WW6		WR6
Jelly Jars		J0				
		J1				
		J2				

Table 2: The combination of beer bottles with beer, wine bottles with either white wine or red wine, and empty jelly jars.

Figure 1: Three kinds of products, each was put into 3 different bottles with slightly different green colours and measured either single or in a row.

2. INSTRUMENT

Two measuring devices were used. The samples were measured using a Photo Research PR-650 tele-spectroradiometer (Figure 2 left) and a Nikon Coolpix 5700 digital camera (Figure 2 right).

Figure 2: **A Photo Research PR-650 tele-spectroradiometer (left) and a Nikon Coolpix 5700 digital camera (right).**

2. BASIC COLORIMETRY

The human visual perception must include three elements. These are: light source, object and an observer (Figure 3). All three elements influence the appearance of the object, as perceived by observers. A light source illuminating an object can be characterized by the energy present at different wavelengths. This is known as the spectral power distribution (SPD). When light falls on an object, absorption, scattering, transmission and other physical properties modify it. The specific processes are dependent upon the physical and chemical composition of the object. The modified light reaches the human eye by means of reflection, refraction or transmission. Photoreceptors (S, M and L cones for photopic vision and rods for scotopic vision[24,25]) in the eyes absorb the light energy and convert this into a signal which is then interpreted by the brain. The human eye-brain mechanism (visual system) makes rapid and almost continuous evaluation (when it is necessary) of the object's appearance and colour[2627].

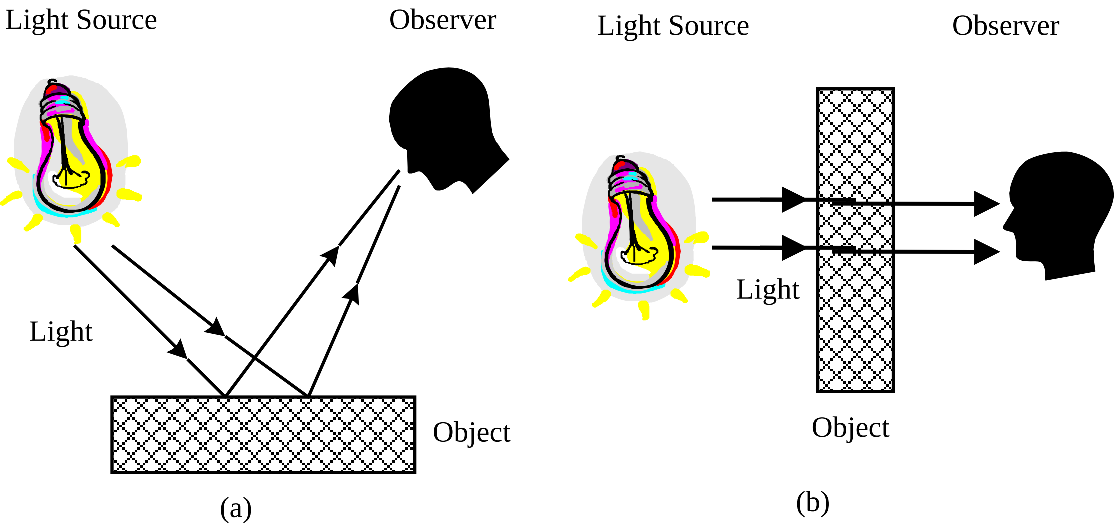

Figure 3: **Three elements of object recognition by means of (a) reflection and (b) transmission.**

Light source is normally characterised by its spectral power distribution (SPD). For accurate colour reproduction purposes, the international organisation CIE (Commission Internationale de l'Éclairage, or International Commission on Illumination) recommended several illuminants by defining their SPD. These

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[24] Hunt, R.W.G. (1998). Measuring colour, 3rd Edition. Fountain Press.
[25] Wandell, B.A. (1995). Foundations of Vision. Sinauer Associates Inc. 387.
[26] Battle, D.R. (1997). The measurement of colour. Colour Physics for Industry. McDonald, R., Ed., Society of Dyers and Colourists. 57-80.
[27] Wyszecki, G. (1973). Current developments in colorimetry. AIC Colour 73, 21-51.

include CIE Illuminant A, Illuminant C, D65, D50, F2, F8, and F11. From this set, the CIE also standardised two illuminants: one representing a phase of daylight with a correlated colour temperature of 6500K (D65) and a second representing incandescent illumination (S_A) as used in indoor lighting. There are also a set of standardised geometries for measurement.

When light falls on an object, the interaction of radiant energy with the material obeys the law of conservation of energy. The amounts of absorbed, reflected and transmitted radiant power must sum to the incident radiant energy at each wavelength. A spectroradiometer can be used to measure surface reflectance or transmittance. The measured spectral data, R(λ), then can be integrated with CIE standard observer, $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$, and SPD, S(λ), of the light source to produce a set of tristimulus values, X, Y, Z, to represent the colour of the object under investigation. These three numbers, known as the tristimulus values, are obtained that uniquely define a colour as viewed in the given environment. These are similar for X_{10}, Y_{10}, Z_{10}, where supplementary standard colorimetric observer is used.

$$X = k\int R(\lambda)S(\lambda)\bar{x}(\lambda)d\lambda$$
$$Y = k\int R(\lambda)S(\lambda)\bar{y}(\lambda)d\lambda$$
$$Z = k\int R(\lambda)S(\lambda)\bar{z}(\lambda)d\lambda$$
$$where\ \ k = 100 / \int S(\lambda)\bar{y}(\lambda)d\lambda$$

The CIE system is configured such that the Y tristimulus value correlates approximately with perceived brightness or, more usually with lightness (L). In order to represent colours in both chromaticity and luminance, the CIE has recommended the use of one of two alternative colour spaces in 1976[28], designated as the CIELAB colour space and CIELUV colour space for industries concerned with subtractive mixture (surface colourant) and the additive mixtures (TV) of coloured light respectively. The most widely used space for surface colour applications is CIELAB. The coordinates of the CIELAB colour space are L*, a*, and b*. These are, or can be combined to be, correlates of the perceptual quantities lightness, chroma and hue.

There are a set of definitions of the perceptual attributes associated with many colour spaces. These definitions were given by CIE in 1987:

Lightness	**the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting.**
Chroma	**the colourfulness of an area judged in proportion to the brightness of a similarly illuminated area that appears to be white or highly transmitting.**
Hue	**the attribute of a visual sensation according to which an area appears to be similar to one, or to proportions of two, of the perceived colours red, yellow, green and blue.**

3. MEASUREMENT

3.1 Lighting and background

A set of Philips fluorescent lamps were used in the experiment. These are Polylux XL® F36W/840, which are the standard lightings used in TESCO stores. The spectral power distribution (SPD) of the lighting was measured using the same tele-spectrophotometer as shown in Figure 4. The measured colour temperature is 3845 K and luminance is 722.92 candela/m^2. It can be seen that there are 5 peak wavelengths in the power spectrum and this lighting represents one kind of cool white lighting in general.

[28] CIE (2004). CIE Publication 15:2004, Colorimetry 3rd Edition, Vienna. CIE Central Bureau.

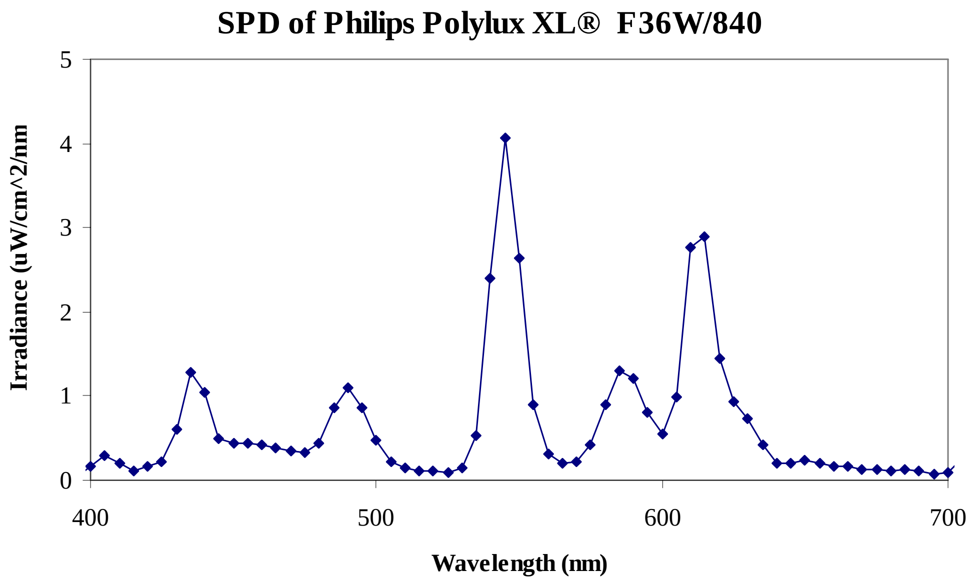
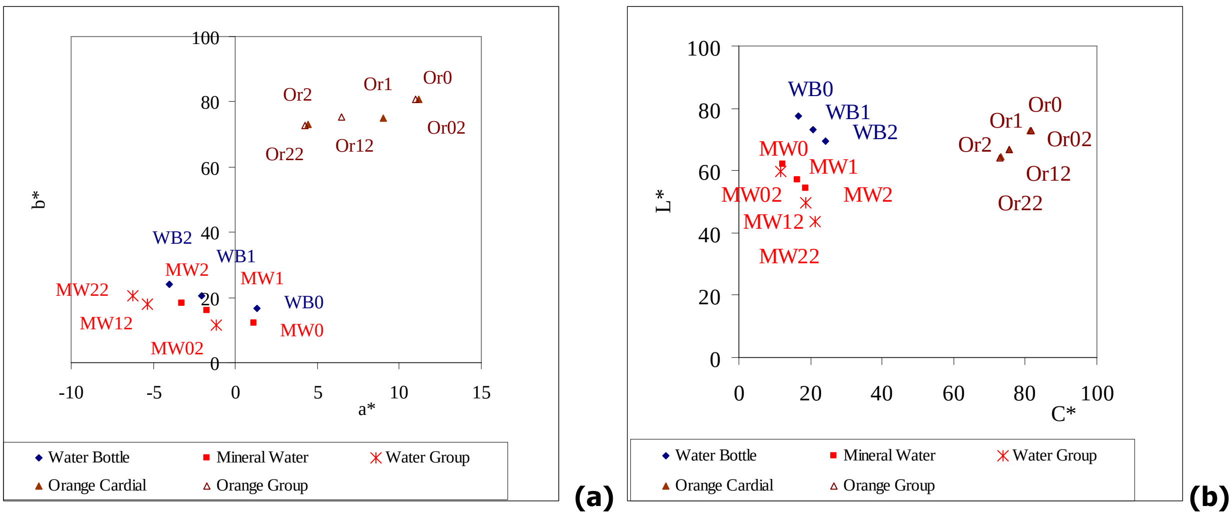


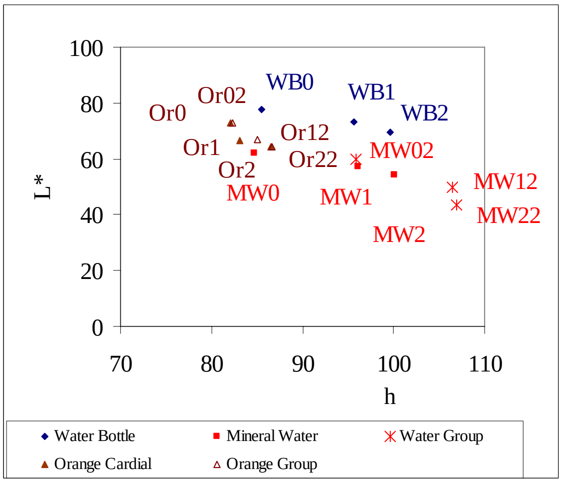
Figure 4: The Spectral Power Distribution of Philips Polylux XL® F36W/840 measured using a PR-650 tele-spectroradiometer.

The background wall of the experiment was painted in light yellow. The colour of the background was also measured using PR-650. The CIE standard XYZ values for this background was measured using CIE 1931 standard 2° observer and the results are X of 85.3, Y of 83.4 and Z of 34.8 with a colour temperature of 3368 K. Under the same condition, the white point was defined using the white patch in a Macbeth® ColorChecker® chart. The calculated white has a set of CIE tristimulus values of X 138.00, Y 138.00 and Z 76.00 with the settings of CIE 1931 standard 2° observer.

3.2. Multiple measurements

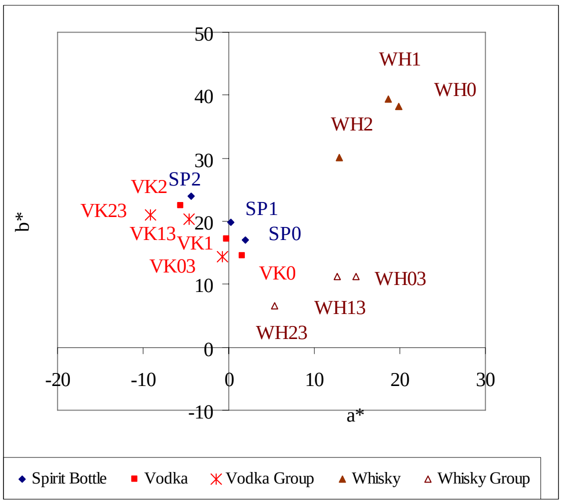
As mentioned in introduction, all samples were measured using the PR-650. The results are shown in Figure 5 to Figure 10 for CIE a*b*, L*C* and L*h colour planes respectively. The names of the samples are also marked with colour coding.



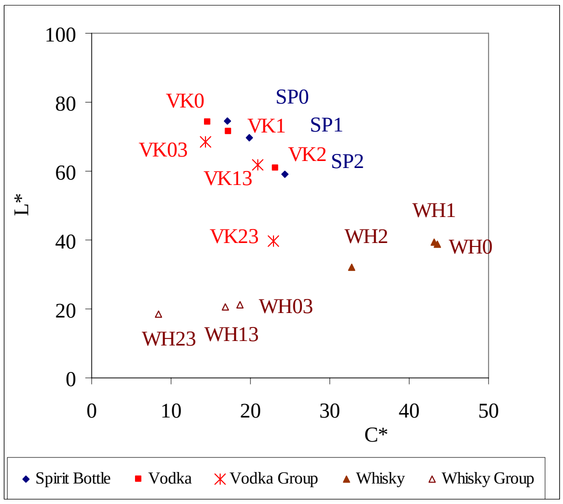


(c)

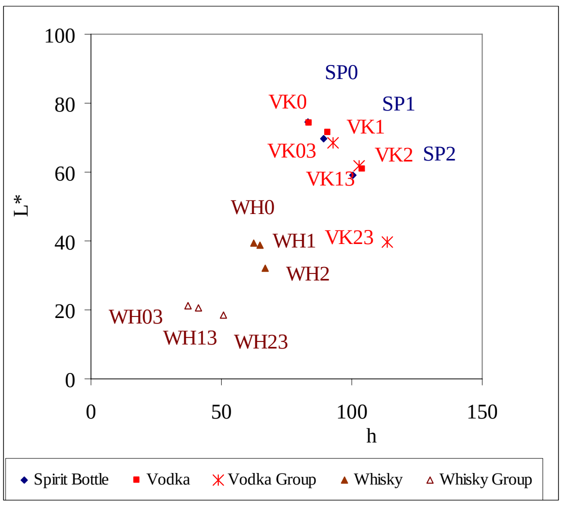
Figure 5: **The colours of the samples, Water Bottles, Mineral Water and Orange Cordial, measured using PR-650 plotted in CIE *a*b**, *L*C** and *L*h* colour planes. The names of the samples are marked with colour coding.**



(a)



(b)



(c)

Figure 6: The colours of the samples, Spirit Bottles, Whisky and Vodka, measured using PR-650 plotted in CIE *a*b, *L*C** and *L*h* colour planes. The names of the samples are marked with colour coding.**

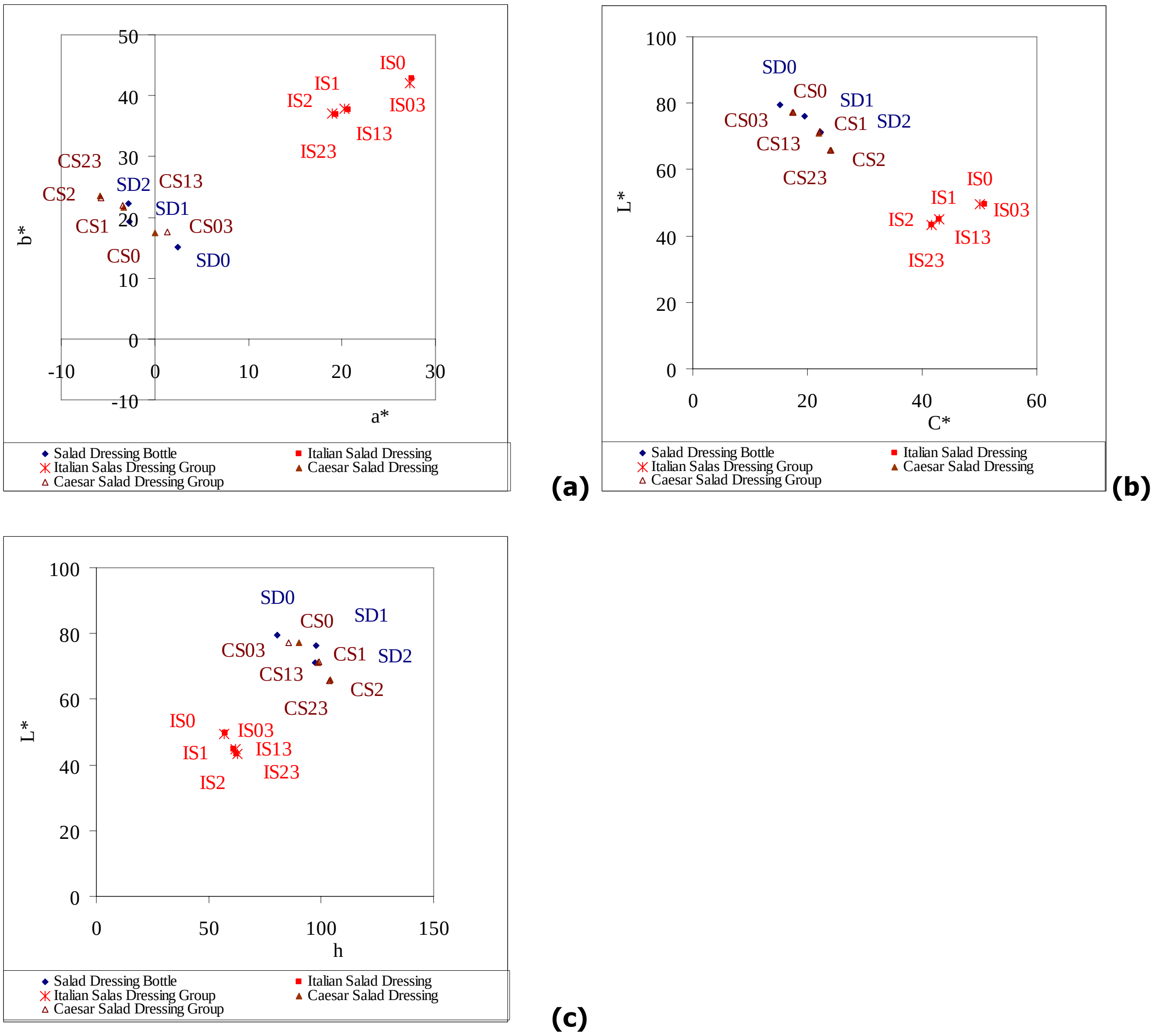


Figure 7: The colours of the samples, Salad Dressing Bottles, Caesar Salad Dressing and Italian Salad Dressing, measured using PR-650 plotted in CIE *a*b, *L*C** and *L*h* colour planes. The names of the samples are marked with colour coding.**

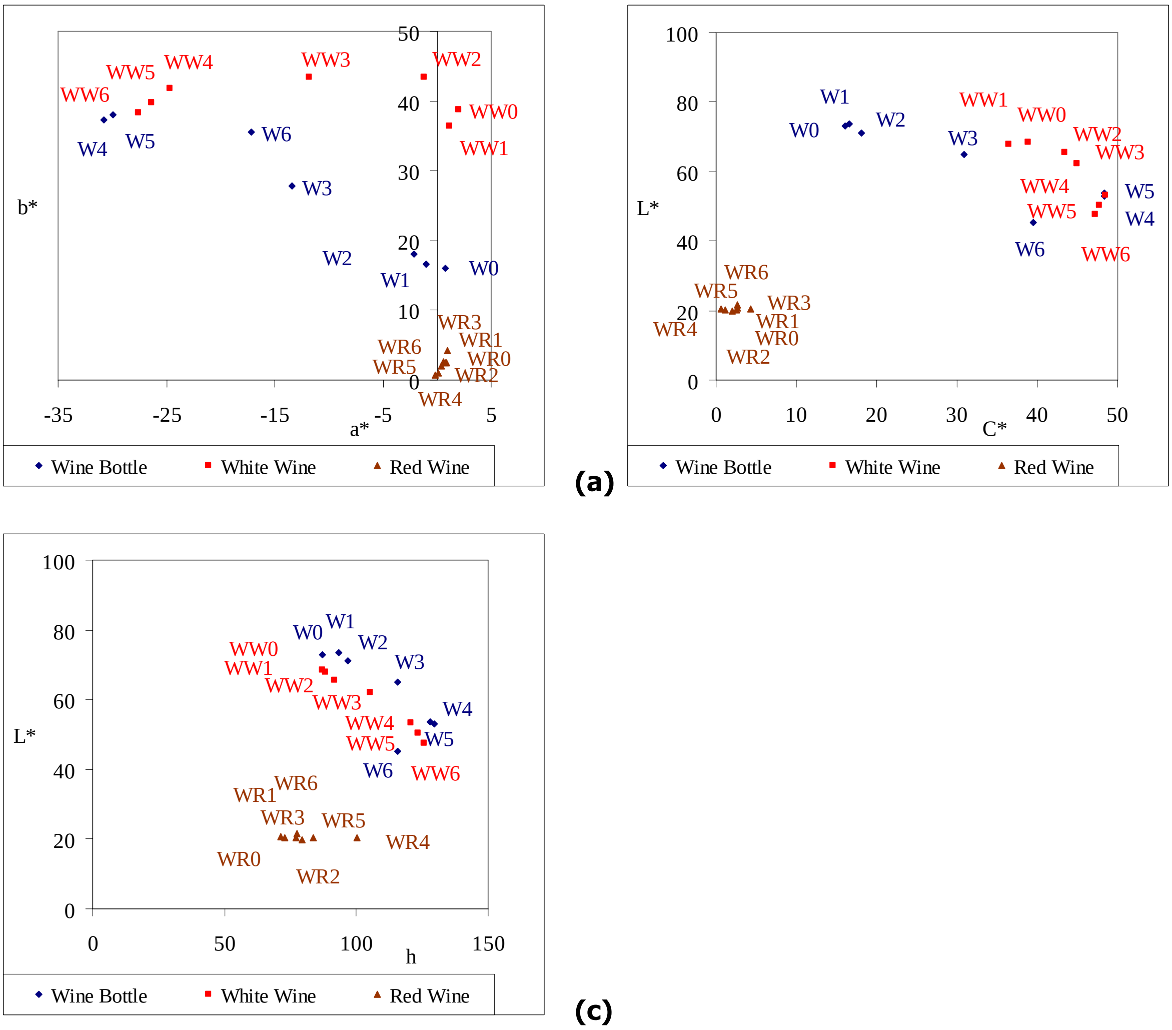
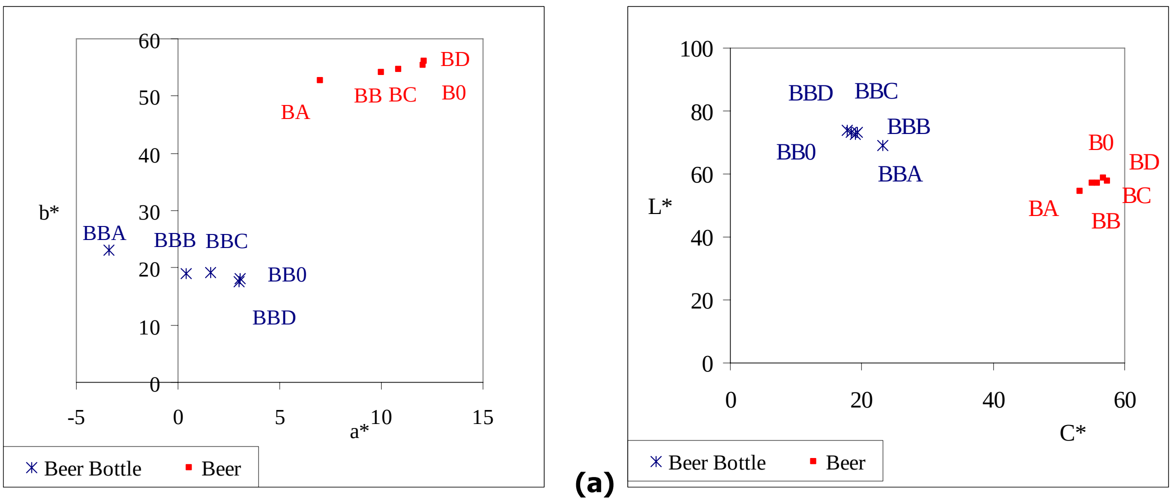
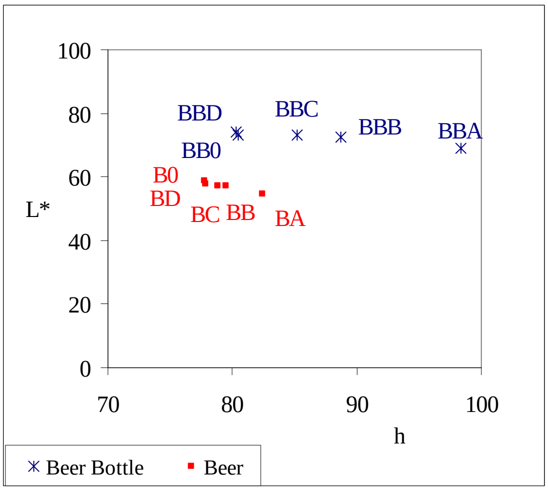


Figure 8: **The colours of the samples, Wine Bottles, White Wine and Red Wine, measured using PR-650 plotted in CIE *a*b**, *L*C** and *L*h* colour planes. The names of the samples are marked with colour coding.**





(c)

Figure 9: **The colours of the samples, Beer bottles and Beer, measured using PR-650 plotted in CIE a*b*, L*C* and L*h colour planes. The names of the samples are marked with colour coding.**

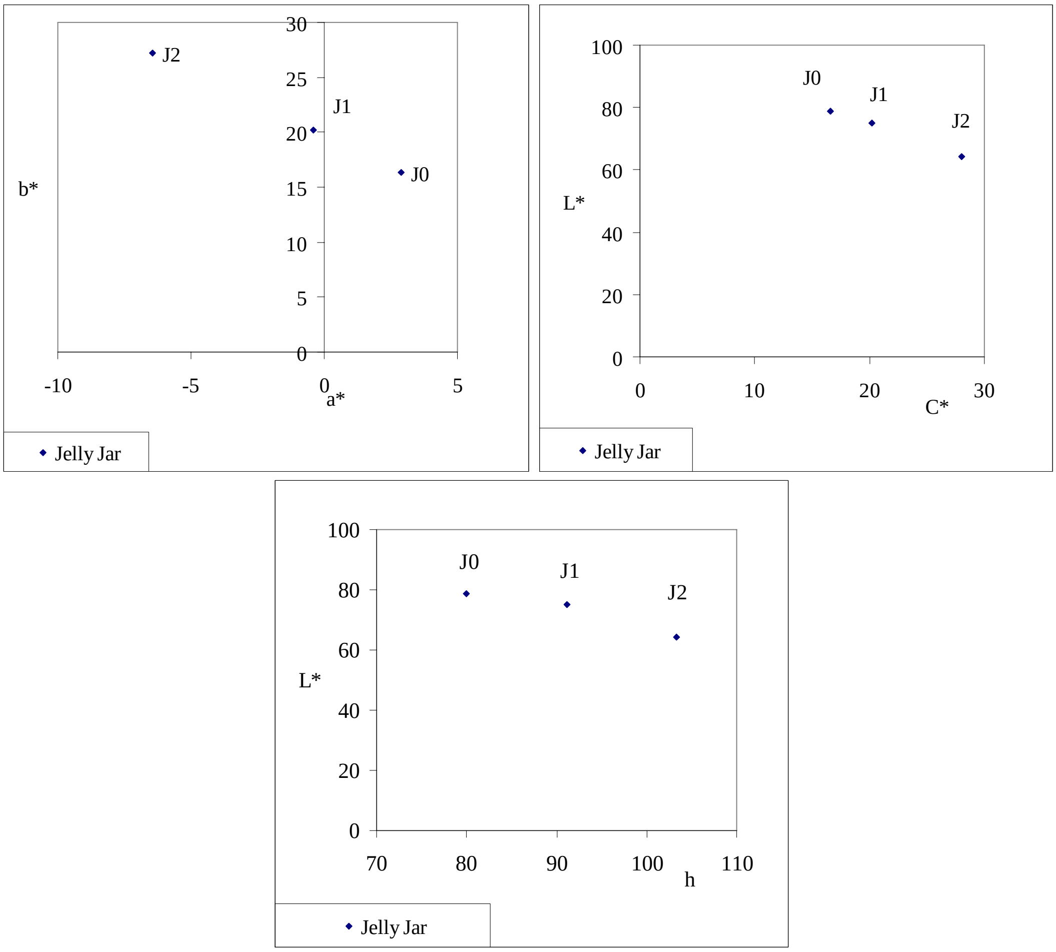


Figure 10: **The colours of the Jelly Jars, measured using PR-650 plotted in CIE a*b*, L*C* and L*h colour planes. The names of the samples are marked with colour coding.**

3.3 Results and Discussion

3.3.1 Empty bottles

For 6 kinds of bottles, each kind has 3 to 7 bottle samples. The designation is to have these bottle samples to change colours from flint (clear) to greenish transparent. The empty bottles were measured against a yellowish wall. The setup is the same as that used in psychophysical experiment. Figure 11 shows that the lightness of each empty bottle plots as functions against hue values for the same empty bottle with a yellowish wall as a background. It can be seen that all bottles follow the same trends: i.e. their colours shift from reddish yellow towards greenish yellow hue, except wine bottle W6 with the opposite direction of colour shift (this result was confirmed with a 2nd measurement on the same kind of bottle, a so-called white wine in red wine bottle, and the result is very close with the 1st measurement with 1 week interval).

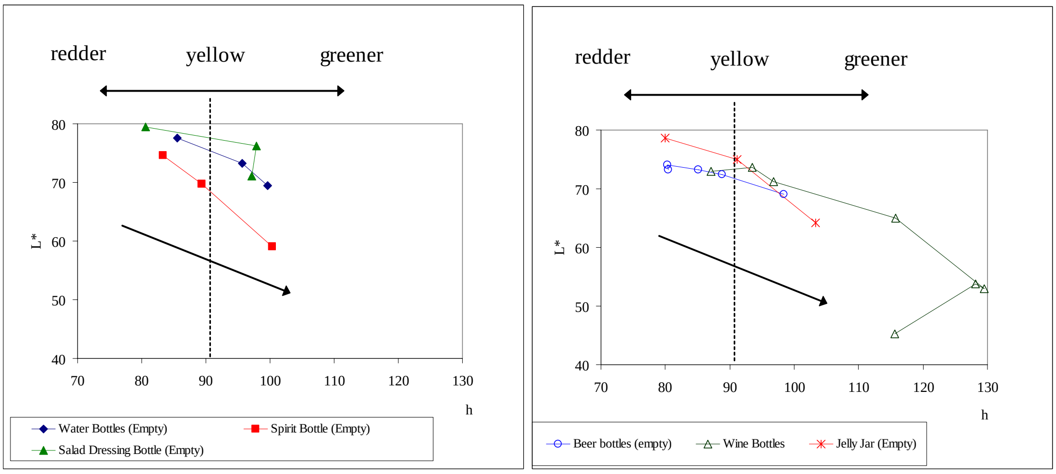


Figure 11: The lightness of each empty bottle plots as functions against hue values for the same empty bottles with a yellowish wall as a background.

Colour difference was calculated by the Euclidean distance between pairs of samples. Here CIE colour difference ΔE_{00} was applied[29], which is the latest and most reliable CIE colour difference formula as CIE recommended standard. Different combinations of ΔE_{00} for pairs of samples are also compared. The reference white used in calculation is always the white patch in a Macbeth® ColorChecker® reference chart with 24 coloured patches. Each of the 24 patches in this reference chart was also measured using the PR-650 in terms of CIE XYZ. This set of XYZ values was used for digital camera characterisation described in Section 4.

3.3.2 Water bottles with mineral water and orange samples.

In order to investigate the colour change for different samples using different bottles, the colour differences are calculated between sample pairs. The colour differences are calculated between the samples in Bottles 0 and 1, and Bottles 0 and 2 respectively within the sample group, i.e. empty water bottles, orange cordial in the bottles and mineral water in the bottles. Also the colour differences are calculated between one bottle and a group of multiple bottles placed in a row (Table 3).

From Table 3, the results show that the 3 empty bottles are almost equally spaced, i.e. the colour difference between WB0 and WB1, and WB1 and WB2 are almost equal. When put mineral water or orange cordial in the bottles, the colour differences between samples in Bottles 0 and 1 are larger than the colour difference between samples in Bottles 1 and 2. There are not much colour differences between 1 bottle and 2 bottles with orange cordial. This is because that the depth of 1 bottle with orange is already thick enough that the colour will not change if further increasing depth of a sample using 2 bottles. For mineral water samples, the

[29] Luo, M.R., Cui, G. and Rigg, B. (2001). The development of the CIE 2000 colour difference formula. Color Res. Appl. 26: 340-350.

colour differences between 1 bottle and multiple bottles are much larger. This is because of the light scattering with multi light transmission/reflection interface.

	Sample pairs	ΔE_{00}	Sample pairs	ΔE_{00}
Water bottles	WB1 vs. WB0	6.8		
	WB2 vs. WB0	12.2		
Orange Cordial	OR1 vs. OR0	8.6	OR0 vs. OR0x2	0.4
	OR2 vs. OR0	13.2	OR1 vs. OR1x2	2.6
	OR1×2 vs. OR0×2	9.4	OR2 vs. OR2x2	0.5
	OR2×2 vs. OR0×2	13.8		
Mineral water	MW1 vs. MW0	6.1	MW0 vs. MW0x2	3.7
	MW2 vs. MW1	9.4	MW1 vs. MW1x2	8.1
	MW1×2 vs. MW0×2	11.1	MW2 vs. MW2x2	11.4
	MW2×2 vs. MW0×2	17.4		

Table 3 The colour differences between sample pairs of water bottles, mineral water and orange cordial in terms of ΔE_{00}.

3.3.3 Spirit bottles with whisky and vodka samples.

Table 4 shows the results of colour differences for spirit bottle, whisky samples and vodka samples. The colour differences of bottles SP0 and SP1 are not the same of bottles SP1 and SP2. Because of the translucency property of whisky and vodka samples, the colour differences between samples in Bottles 0 and 1 are not the same as the colour differences between samples in Bottles 1 and 2. Also there are large colour differences between the measurements on a single bottle and a group of bottles.

	Sample pairs	ΔE_{00}	Sample pairs	ΔE_{00}
Spirit bottles	SP1 vs. SP0	5.9		
	SP2 vs. SP0	18.2		
Whisky	WH1 vs. WH0	1.4	WH0 vs. WH0x3	22.3
	WH2 vs. WH0	8.5	WH1 vs. WH1x3	22.2
	WH1×2 vs. WH0×2	1.9	WH2 vs. WH2x3	18.1
	WH2×2 vs. WH0×2	9.1		
Vodka	VK1 vs. VK0	4.4	VK0 vs. VK0x3	6.2
	VK2 vs. VK0	17.2	VK1 vs. VK1x3	10.9
	VK1×2 vs. VK0×2	9.8	VK2 vs. VK2x3	21.4
	VK2×2 vs. VK0×2	30.7		

Table 4: The colour differences between sample pairs of spirit bottles, whisky and vodka in terms of ΔE_{00}.

3.3.4 Salad dressing bottles with 2 kinds of salad dressing.

Table 5 shows the colour difference results for salad dressing bottles and 2 different salad dressing samples. There is not much colour difference between using single bottle and using multi bottles for these samples as salad dressing samples are opaque. For both samples, the colour differences between samples in Bottles 0 and 1 are always larger than those of samples in Bottles 1 and 2.

	Sample pairs	ΔE_{00}	Sample pairs	ΔE_{00}
Salad Dressing bottles	SD1 vs. SD0	6.8		
	SD2 vs. SD0	12.2		
Caesar Salad Dressing	CS1 vs. CS0	6.0	CS0 vs. CS0×3	1.5
	CS2 vs. CS0	10.6	CS1 vs. CS1×3	0.4
	CS1×2 vs. CS0×2	6.8	CS2 vs. CS2×3	0.2
	CS2×2 vs. CS0×2	11.4		

Italian Salad Dressing	IS1 vs. IS0	9.7	IS0 vs. IS0×3	0.8
	IS2 vs. IS0	11.9	IS1 vs. IS1×3	0.4
	IS1×2 vs. IS0×2	9.3	IS2 vs. IS2×3	0.5
	IS2×2 vs. IS0×2	11.5		

Table 5: The colour differences between sample pairs of salad dressing bottles, Caesar salad dressing and Italian salad dressing in terms of ΔE_{00}.

3.3.5 Wine bottles with either white or red wine, and beer bottles with beer, and empty Jelly Jars.

For wine and beer samples, there are no multi bottles available. Only samples with single bottle were measured as shown in Table 6. The measurement results for 3 jelly jars are also listed, where only empty jars were measured with no samples been put inside.

Wine Bottles	ΔE_{00}	**White Wine**	ΔE_{00}	**Red Wine**	ΔE_{00}
W1 vs. W0	2.0	WW1 vs. WW0	2.6	WR1 vs. WR0	0.3
W2 vs. W0	4.0	WW2 vs. WW0	6.4	WR2 vs. WR0	0.6
W3 vs. W0	20.1	WW3 vs. WW0	16.0	WR3 vs. WR0	1.8
W4 vs. W0	43.0	WW4 vs. WW0	30.9	WR4 vs. WR0	1.9
W5 vs. W0	42.4	WW5 vs. WW0	33.7	WR5 vs. WR0	1.5
W6 vs. W0	38.4	WW6 vs. WW0	36.2	WR6 vs. WR0	1.2

Beer Bottles	ΔE_{00}	**Beer**	ΔE_{00}	**Jelly Jars**	ΔE_{00}
BBD vs. BB0	1.0	BD vs. B0	1.2	J1 vs. J0	5.2
BBC vs. BB0	1.8	BC vs. B0	2.1	J2 vs. J0	15.2
BBB vs. BB0	2.9	BB vs. B0	2.9		
BBA vs. BB0	9.1	BA vs. B0	7.1		

Table 6:. The colour differences between sample pairs of wine bottles, white wine samples, red wine samples, beer bottles, beer samples and Jelly Jars in terms of ΔE_{00}.

From this table, the colour changes for wine bottles are regular except the last bottle, W6, which shifts its hue back to yellow region. When put white wine in the bottles, the colours of bottles shift from yellow hue to greenish-yellow hue. This is not the case when put red wine in the bottles, where the colours of samples are always with lower lightness, i.e. from 19.96 to 21.52, and with lower chroma, i.e. 0.69 to 4.31. The hues of samples are changed around reddish-yellow region, i.e. 71.16 to 100.29, with no clear trend.

For 3 empty jelly jars, the colours of samples change from reddish-yellow to greenish-yellow.

Without wine bottles with their related samples and beer bottles with their associated samples, Figure 12 shows the hue angles (h) in top diagram for each of the measured samples and hue difference (□H*) in bottom diagram for each of the sample pairs. From these diagrams, it concludes that the changes of hue angles for all the samples are more consistent than those of change in L* and C*. The magnitudes of hue changing are almost constant.

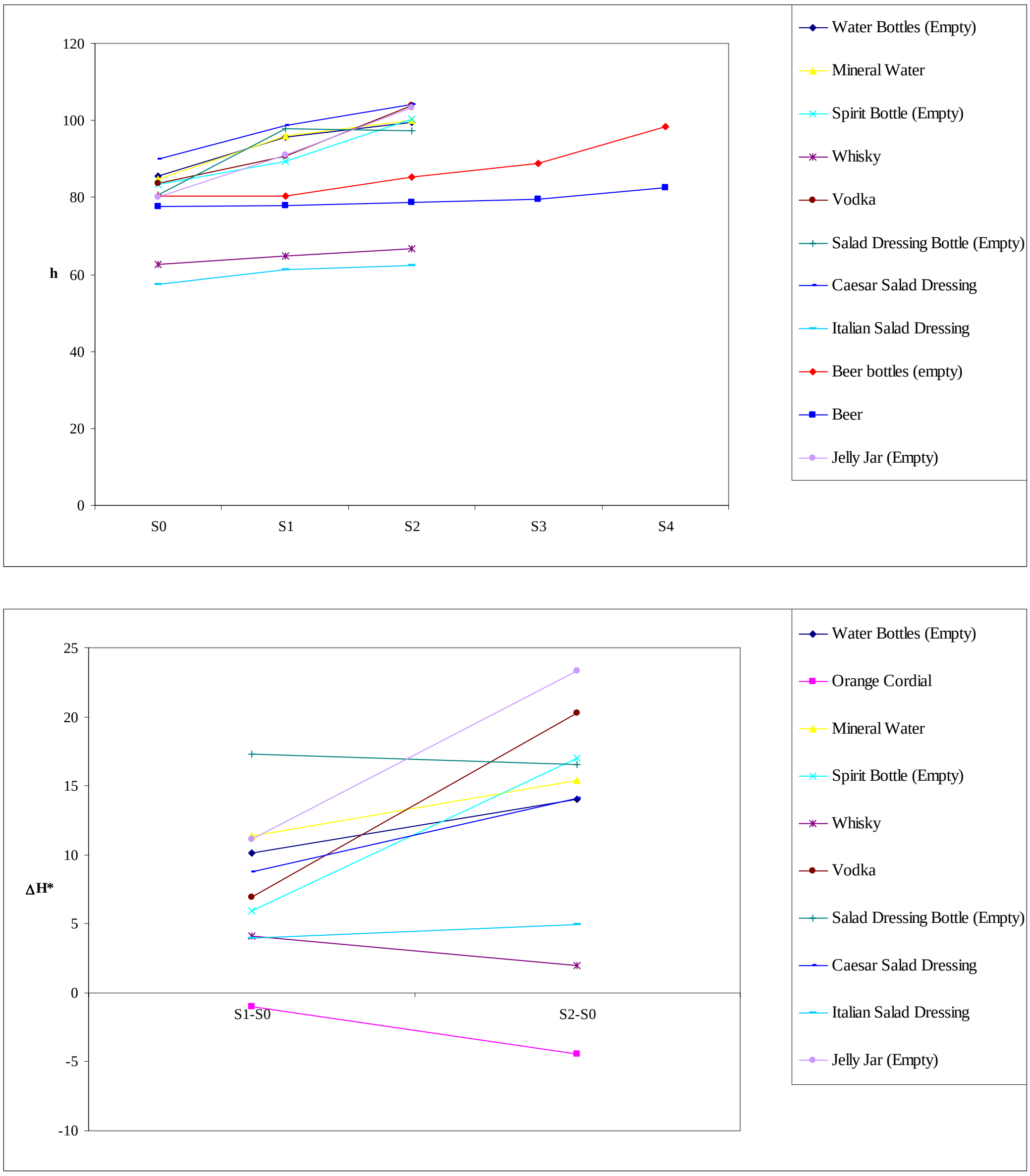


Figure 12: CIE hue angle (top) and hue difference (bottom) for most of the samples (no wine and beer samples) plot as functions of sample sequence.

From above, it concludes that:

(1) The colour measurements for coloured bottles with different samples show different trends. In general, the greener the bottle is, the lower the lightness is. When the bottles getting greener, the measured hue angle for the sample agrees with what we see. When the bottle getting greener, chroma values, however, increase for Caesar salad dressing, white wine and water samples, but opposite trend was found for whisky, orange, Italian salad dressing and beer samples. For vodka and red wine samples, their chroma values changes irregularly.

Overall, hue shows a better consistency for almost all samples than lightness and chroma in this experiment. This indicates that the CIELAB hue angle or hue difference could be the most reliable measure to indicate the colour of the bottles, except red wine samples.

(2) There is not much colour difference between arrangements of 1 bottle and multiple bottles of orange cordial samples and two salad dressing samples as the colour differences are small, i.e. 0.4, 2.6 and 0.5 units for Sample 0, Sample 1 and Sample 2 for orange cordial; 1.5, 0.4 and 0.2 units for Caesar salad

dressing and 0.8, 0.4 and 0.5 units for Italian salad dressing for Sample 0, Sample 1 and Sample 2 (see Table 3). These are expected as orange samples have larger depth and salad dressing samples are opaque. Light can not be transmitted trough these bottles. The colour of 1 bottle is perceived the same as the colour in a row of multiple bottles.

This effect was not found for mineral water. For mineral water, the colour differences are moderately large as 3.7, 8.1 and 11.4 units between the single and multiple bottles for Bottles 0, 1 and 2 respectively. These are also understandable as water is transparent and it transmitted most light. When a row of 2 bottles is used, the transmission of the light passes through many curved bottle surfaces. There are a lot of reflections, refractions and scattering occurred at each of the interfaces.

For vodka and whisky samples, colour differences are the largest as 22.3, 22.2 and 18.1 units for whisky, and 6.2, 10.9 and 21.4 units for vodka, using Bottles 0, 1 and 2 respectively. This is because the translucent property of these spirit samples, together with the similar property of the bottles as in water situation. A lot of small particles exist in the liquid body, which also absorb, reflect, and transmit light.

For white wine and beer samples, the translucency properties also largely influence the measurement results as shown in Table 6. The colour differences between sample pairs can be as large as 43 units (between wine Bottles 4 and 0).

(3) For Caesar salad dressing samples, orange cordial samples and mineral water samples, the colour differences between samples in Bottles 1 and 2, and between samples in Bottles 2 and 3 are very close. This means that the colour differences between samples in Bottles 0, 1 and 2 are almost equally spaced. However, this is not the case for whisky and vodka samples as the colour differences between samples in Bottles 1 and 2 are several times larger than the colour differences between samples in Bottles 0 and 1.

(4) The colour differences using 1 bottle are always smaller than or similar to those using multiple bottles. This is caused by the depth of the sample affecting the colour perception. For the measurement concerned, one bottle should be good enough.

4. DIGITAL IMAGING METHOD

Since spectrophotometer can only measure a small dot area on a sample at a time and the shape of the sample influences the measuring results a lot, digital imaging method is another way to do the measurement with quick reaction time and there is small influence with the measurement for the shape of the sample. This section of experiment was done only with Mineral Water samples, Whisky samples and Caesar salad dressing samples.

Similar colour measurements with Section 3 were carried out using digital imaging method. The processes are: place the samples at the same position as in the measurements using PR-650; replaced PR-650 with a Nikon CoolPixel 5700 digital camera to take digital images, together with a Macbeth® ColorChecker® reference chart with 24 coloured patches.

The digital camera was characterised using 3×11 polynomial regression method to build a transformation coefficient matrix[30]. Then each of the digital images was calibrated from camera RGB image to CIE XYZ. An uniform square in the middle of each of the XYZ images was sub-sampled and the averaging results, $\overline{X}\,\overline{Y}\,\overline{Z}$, of all the pixels in that square were used to represent that sample under the investigation. The results are again plotted in Figure 13 on CIE a*b*, L*C* and L*h colour planes respectively. The names of the samples are also marked with colour coding. These three diagrams indicate that digital image is a good substitution for the conventional colour measurement.

[30] Hutchings, J.B., Luo, M.R. and Ji, W. (2002). Chapter 14: Calibrated colour imaging analysis of food. Colour in Food, Improving Quality. MacDougall, D.B., Ed., Woodhead Publishing Ltd (Cambridge, England) and CRC Press LLC (USA). 352-365.

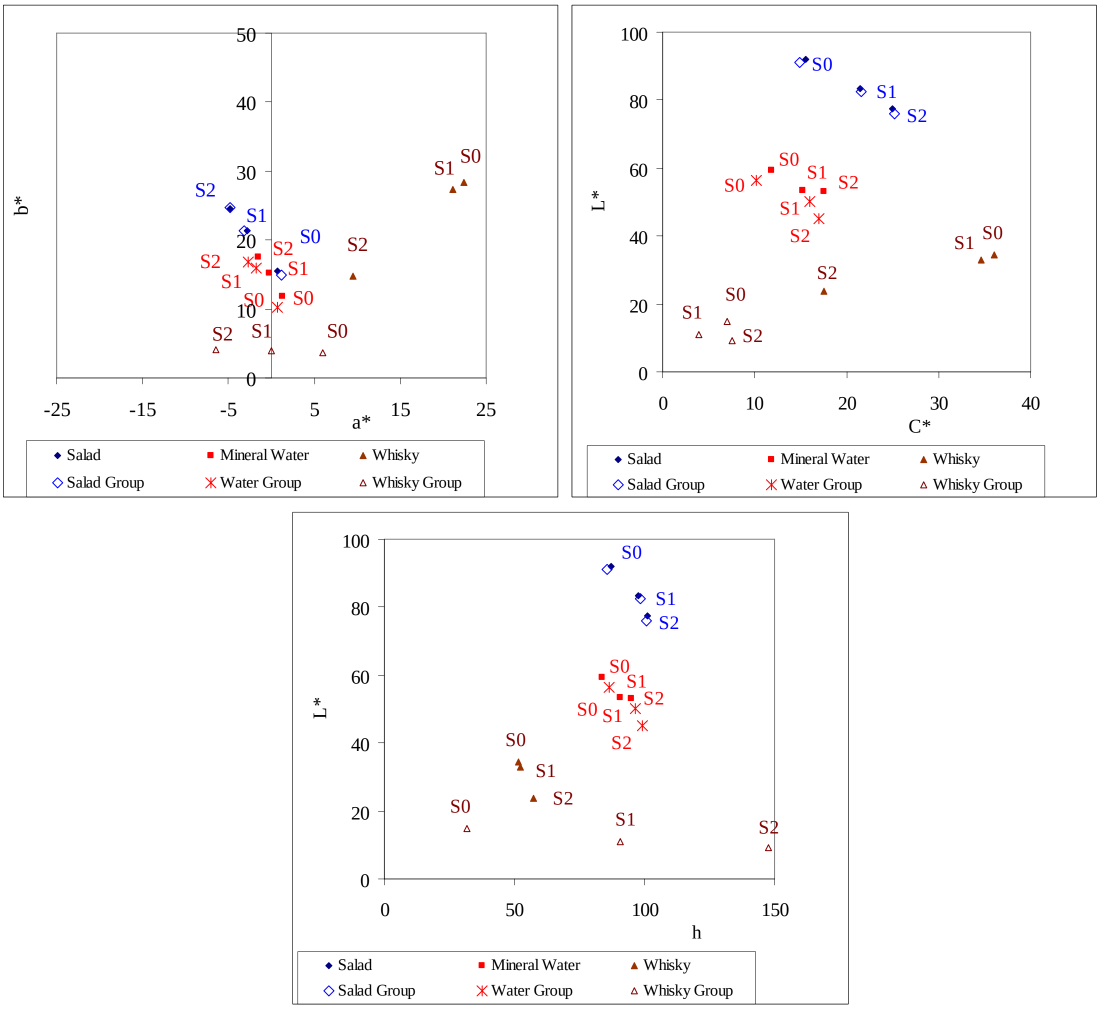


Figure 13: The colours of the samples measured using digital imaging method plotted in CIE *a*b, *L*C** and *L*h* colour planes.**

Colour difference was also calculated between pairs of samples and the results are listed in Table 7 for three kinds of samples.

	ΔE_{00}	1 bottle	Multi bottles	Single vs. Multi bottles	
Salad Dressing	S0 vs. S1	7.45	8.15	S0	0.98
	S0 vs. S2	12.04	12.82	S1	0.77
	S1 vs. S2	4.69	4.99	S2	1.12
Mineral Water	S0 vs. S1	6.26	7.63	S0	3.04
	S0 vs. S2	7.78	12.73	S1	3.74
	S1 vs. S2	2.06	5.23	S2	8.03
Whisky	S0 vs. S1	1.29	8.31	S0	21.33
	S0 vs. S2	12.09	17.35	S1	25.11
	S1 vs. S2	10.92	7.99	S2	23.09

Table 7: Colour differences using digital imaging method between sample pairs in terms of CIE colour difference ΔE_{00}

5 COMPARISON BETWEEN PR-650 AND DIGITAL IMAGING METHOD

Figure 14 compares the measurement results between PR-650 and digital method in terms of CIELAB L*, C* and h. The top three diagrams are for single bottle with all the food samples and the bottom three diagrams are for multi overlapping bottles with colour coding.

If the two methods agree with each other, all data plots should lie on the 45° line. For lightness, the PR-650 measurement data are agreed well with digital method with a coefficient of determination of 0.981 for single bottle and a coefficient of determination of 0.987 for multi bottles. These are rather good results. For chroma and hue angle, however, the results are not as good as lightness, especially for whisky samples. This was further illustrated in Figure 15 below.

Figure 15 plots CIE ΔE_{00} colour difference between sample pairs using PR-650 against those between sample pairs using digital method. Again, the top four diagrams are for single bottle and the bottom four diagrams are for multi bottles. The most left-hand diagrams are including all the food samples followed by three diagrams for each of the three kinds of food samples, i.e. salad dressing, mineral water and whisky. This figure shows clearly that digital method has good coherence with conventional spectroradiometric measurements for salad dressing and water samples.

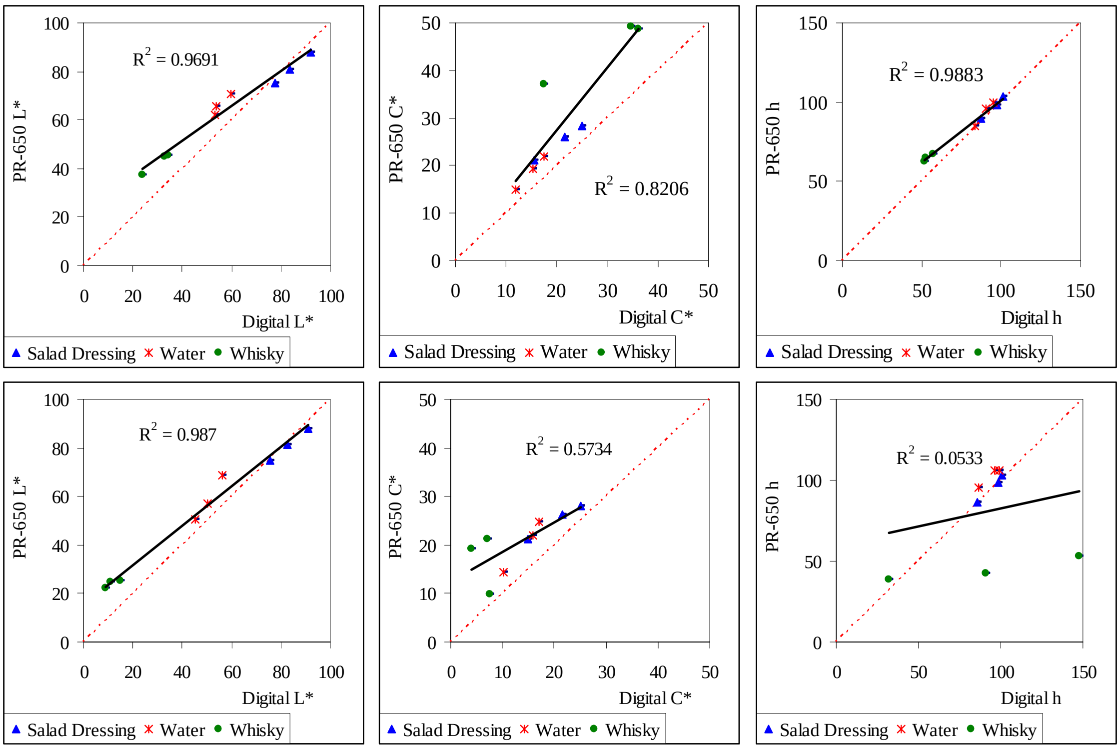


Figure 14: Comparison between PR-650 measurement with digital imaging measurement in terms of CIELAB *L*, C and *h*. The top three diagrams are for single bottle and bottom three diagrams multi bottles.**

For whisky samples, however, large discrepancy exists between digital measurement and conventional measurement. This is because of the translucency property of whisky samples. With the refraction and scattering of many small particles in the whisky samples, large amount of light is lost if comparing with the amount of incident light. This loss of light occurs both at the bottle wall and inside the liquid sample. The better technique for measuring translucent sample is to use trans-reflectance measurement with over black-

/ white- backings[31,32]. This are based on Kubelka-Munk theory with absorption coefficient K, scattering coefficient S and internal transmittance Ti[33]. Earlier similar research works were done with orange juice samples[34] and wine samples[35].

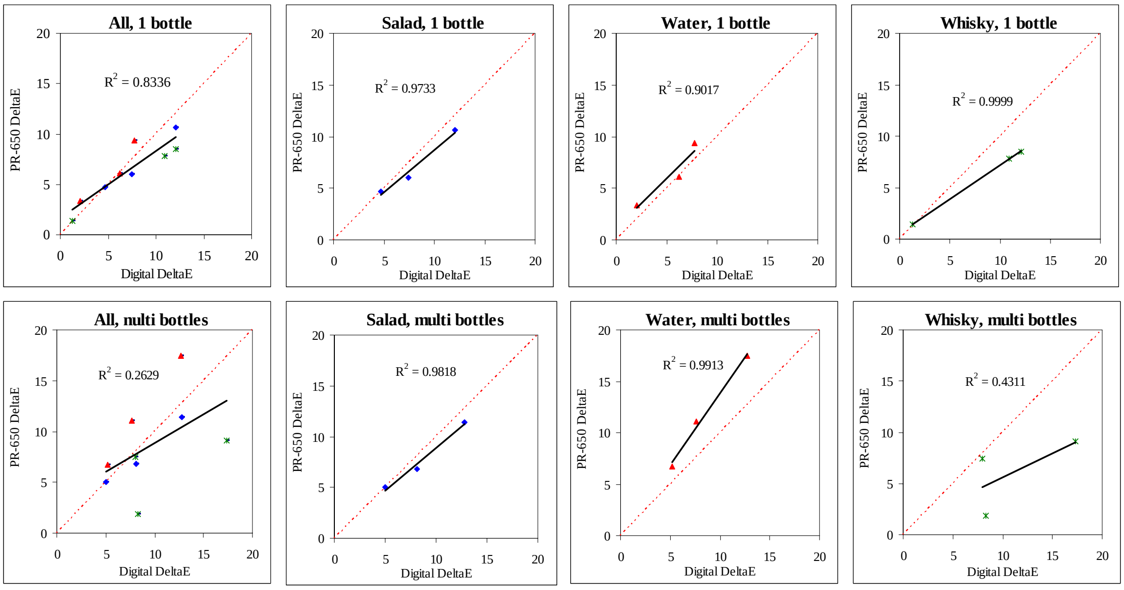


Figure 15: **Comparison between PR-650 measurement with digital imaging measurement in terms of CIE ΔE_{00} colour difference. The top row diagrams are for single bottle and bottom row diagrams multi bottles.**

6 CONCLUSION

As discussed before, the tasks for measuring bottles which contain orange cordial, mineral water, whisky, vodka, solid salad dressing, wine (white or red wine), and beer are very complicated.

Firstly, it involves curvature surface of the bottle with solid salad dressing in. Since salad dressing can be considered as almost opaque, light only partly pass through the glass wall, partly refracted by the glass wall and partly reflected by the salad dressing. This is the simplest situation in this experiment. This can be termed as measuring opacity. For orange cordial samples, since the depth of samples is very larger (which can be treated as infinite depth if comparing with the size of particles in the liquid body), the bottles are opaque from the measurement results.

Further more, when put water in the glass, light passes through the glass wall, passes through the water (partly be refracted), passes through the glass wall again and be reflected by the background. This adds the complication on top of the previous salad dressing situation. This can be termed as measuring transparency.

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[31] Ji, W., Luo, M.R., Hutchings, J.B. and Dakin, J. (2005). Scaling Transparency, Opacity, Apparent Flavour Strength and Preference of Orange Juice. The 10th Congress of the International Colour Association (AIC Colour 05), Granada, Spain, 729-732.

[32] Hutchings, J.B. and Luo, M.R. (2005). Translucency, its Perception and Measurement. The 10th Congress of the International Colour Association (AIC Colour 05), Granada, 835-838.

[33] Kubelka, P. (1948). New Contributions to the Optics of Intensely Light-Scattering Materials, Part I. J. Opt. Soc. Am. 38 (5): 448-457.

[34] Little, A.C. (1973). Color Evaluation of Foods - Correlation of Objective Facts with Subjective Impressions. Sensory evaluation of appearance of materials, Philadelphia, E-12 and E-18, American Society for Testing and Materials.

[35] MacDougall, D.B. (1987). Effect of Pigmentation, Light Scatter and Illumination On Food Appearance and Acceptance. in Food Acceptance and Nutrition. Solms, J., Booth, D.A., Pangborn, R.M. and Raunhardt, O., Eds., Academic Press. 29-46.

Lastly, keeping all above complication in mind, it involves the translucency property of the vodka, whisky, white or red wine and beer. A lot of small particles (and/or air bubble) in the sample liquid refracted and reflected the light when light pass through them, where a proportional light can transmit through the liquid. This portion of light named as internal transmittance by Kubelka-Munk[10]. Further work can be done based on this technique.

In summary, the following conclusions can be drawn:

1) Coloured bottles can be measured using CIELAB hue angle or hue difference.
2) Colour measurement results using one bottle are more consistent than those using multi bottles in most situations, except translucency whisky.
3) When using one bottle, tele-spectroradiometer results are correlated with digital imaging method results. PR-650 results slightly larger than digital imaging method rustles with around 10%.

Overall, digital imaging method can be applied in the measurement. The more advanced technique is to use trans-reflectance measurement. This technique is based on Kubelka-Munk theory with calculation of absorption coefficient K, scattering coefficient S and internal transmittance Ti. One of the requirements for applying this technique is that the sample under consideration must be flat.

Appendix B – Data sources and calculations

Reference 1 UK Sales:

Supplied by members to BGMC

Reference 2 Exports (Empty):

Supplied by members to BGMC

Reference 3 Exports (Filled):

3rd Party Export figures EA approved protocol. %'s taken from Third Party. Export Protocol as agreed by the Environment Agency. Production Total supplied by BGMC

Filled Exports Tonnage	Production Total	3rd Party %'s	Filled Export Total	Adjusted Values
Spirits	587306.9	83	487464.7	480,620
Wines	89527.11	2	1790.542	1,797
Alcoholic Beverages	669653.4	9	60268.81	60,277
Soft Drinks	175847.5	0.03	52.75425	61
Foods	323185.8	5	16159.29	16,159
Toiletries, Cosmetics & Pharmaceuticals	37819.3	(40 = Pharmaceuticals) 38	14371.33	11,716

* Alcoholic Beverages % is an average of the 3rd Party %'s

Alcoholic Beverages	3rd Party %'s	Average %
FAB's	8	
Beers	11	
Ciders	7	
Total	26	9

An assumption has been made regarding the average weight of some containers. The weight has been calculated by taking an average weight of returns made to British Glass in the specific sector.

Reference 4 Empty imports:

The total figure for empty imports is taken from Business and Trade Statistics, and then agreed by sector by members of British Glass.

Conversions

1 Barrel = 1.63659 Hectolitres (BBPA – Statistical Handbook)
1 hectolitre = 100 litres (BBPA – Statistical Handbook)

Average Bottle sizes =	Beer =	33cl
	Spirit =	70cl
	Wine =	75cl

Average Weight =	Beer =	200g
(Supplied by members)	Spirit =	5% NNPB 380g
		95% Std 480g
	Wine =	10% NNPB 375g
		90% Std 475g

Reference 4 – Imports (Filled):

Beers

Source: British Beer and Pub Association – 2004 Statistical Handbook (P 18)

2003
1,483,100 Barrels of beer (in bottles)
2,427,228.956 hectolitres
242,722,895 litres

Number of bottles
242,722,895 / 0.33 = 735,523,924 bottles

Weight
735,523,924 * 200g = 147,104 tonnes

Wines

Source: AC Neilsen – The Drink Pocket Book 2005 – Foreign Trade Statistics (P 117)

2003
12,240,800 hectolitres
1,224,080,000 litres

Number of bottles
1,224,080,000 / 0.75 = 1,632,106,666 bottles

Weight
10% = 163210666 * 375g = 61,204 tonnes
90% = 1,468,896,000 * 475g = 697,725 tonnes
Total = 758,929 tonnes

Spirits

Source: A C Neilsen – The Drink Pocket Book 2005 – Foreign Trade Statistics (P154)

2003
1,818,300 hectolitres
181,830,000 litres

Number of bottles
181,830,000 / 0.70 = 259,757,143 bottles

Weight
5% = 12,987,857 * 380g = 4,935 tonnes
95% = 246,769,286 * 480g = 118,449 tonnes
Total = 123,384 tonnes

Appendix C – Waste Stream Data

WASTE STREAM	2002			
Tonnages	Clear	Brown	Green	Total
Spirits	94,003	69,231	65,944	229,177
Wines	204,708	4,336	428,109	637,153
Beer/Alc. Beverages	279,686	161,147	349,620	790,453
Soft Drinks	256,571	31,910	30,759	319,240
Foods	486,581	6,433	11,986	505,001
TCP	47,555	24,818	4,498	76,871
Total	**1,369,105**	**297,876**	**890,915**	**2,557,896**
	2003			
Tonnages	Clear	Brown	Green	Total
Spirits	99,753	60,112	47,885	207,751
Wines	207,735	6,752	432,689	647,176
Beer/Alc. Beverages	254,522	135,538	339,103	729,163
Soft Drinks	287,837	27,608	23,555	339,000
Foods	463,680	8,615	10,999	483,293
TCP	48,823	28,389	4,559	81,772
Total	**1,362,350**	**267,013**	**858,791**	**2,488,154**
	2004			
Tonnages	Clear	Brown	Green	Total
Spirits	74,959	40,638	73,847	189,444
Wines	221,508	1,087	481,698	704,293
Beer/Alc. Beverages	204,575	169,401	341,475	715,451
Soft Drinks	290,260	21,607	19,724	331,592
Foods	466,692	6,360	11,521	484,573
TCP	44,416	16,714	16,657	77,786
Total	**1,302,409**	**255,807**	**944,922**	**2,503,138**

	2005			
Tonnages	Clear	Brown	Green	Total
Spirits	95,089	39,816	72,910	207,815
Wines	241,094	0	490,040	731,133
Beer/Alc. Beverages	208,674	158,740	343,638	711,052
Soft Drinks	289,662	21,307	20,051	331,020
Foods	472,298	7,149	12,530	491,977
TCP	44,294	18,023	14,744	77,061
Total	**1,351,111**	**245,035**	**953,912**	**2,550,058**
	2006			
Tonnages	Clear	Brown	Green	Total
Spirits	89,247	41,018	83,214	213,479
Wines	229,391	0	523,804	753,196
Beer/Alc. Beverages	231,249	174,589	343,161	748,999
Soft Drinks	277,291	19,325	20,323	316,939
Foods	491,066	5,418	12,925	509,409
TCP	46,945	20,911	15,646	83,502
Total	**1,365,190**	**261,260**	**999,073**	**2,625,523**
	2007			
Tonnages	Clear	Brown	Green	Total
Spirits	67328	41571	105508	214407
Wines	236305	0	537921	774227
Beer/Alc. Beverages	216897	184823	360759	762479
Soft Drinks	288399	21137	20256	329791
Foods	485160	5746	15450	506356
TCP	46923	21409	14892	83224
Total	**1,341,013**	**274,686**	**1,054,786**	**2,670,485**
	2008			
Tonnages	Clear	Brown	Green	Total
Spirits	83,917	47,247	85,820	216,984
Wines	253,801	0	559,981	813,782
Beer/Alc. Beverages	222,281	187,355	362,002	771,639
Soft Drinks	271,882	19,409	19,540	310,831
Foods	496,176	6,010	15,574	517,761
TCP	45,706	21,093	14,585	81,385
Total	**1,373,764**	**281,115**	**1,057,503**	**2,712,382**

Appendix D – Container Manufacturers Questionnaire

DECOLOURISERS

What decolouriser(s) are in current use?	
Why?	
What levels do you use? What units?	
Does the level vary with cullet content?	
Have you tried different mineral forms?	
What difficulties have been experienced using this decolouriser? E.g. environmental, price, redox, effectiveness	
What decolourisers have previously been used? At what level?	

Which of the following decolourisers have potential for industrial use? Why/why not?

Cerium	
Manganese	
Neodymium	
Erbium	
Nickel	
Tellurium	
Didymium (neodymium and praseodymium)	
Any others?	

CULLET

Sampling

What method is used in the sampling of cullet?	
How often do you sample it?	
Who is responsible for sampling? You or the supplier?	

Colour splits

What are the typical levels of: (how is this measured?)

green in flint cullet	
amber in flint cullet	
green in amber cullet	
flint in amber cullet	
amber in green cullet	
flint in green cullet	

Contaminants

What levels of contaminants are typically present? Are they measured? If so how?

Ferrous metals – in flint cullet	
- in amber cullet	

- in green cullet	
Non-ferrous metal	
Ceramics and stones – in flint cullet	
- in amber cullet	
- in green cullet	
Organics – in flint cullet	
- in amber cullet	
- in green cullet	
Moisture	

Typical cullet size?	

What is the maximum cullet level to get good production for each colour?

Flint	
Green	
Amber	

How do cullet levels vary?	
Do you have any problems sourcing cullet?	

COMPOSITION

How does your batch composition vary with cullet content?	
What is the long term result on glass composition of this variation?	

OPERATING PARAMETERS

Do the following parameters vary with cullet level? If so how?

Furnace temperature	
Emissions	

SAMPLES

Do you have samples from colour changes?	
Do you have any colour changes planned?	
Can we have samples of cullet (5-10kg)?	
Can we have samples from normal production? Can we have production data for the samples? – tpd (pull) - cullet level - batch composition - melting temp and place of measurement	

Appendix E – Cullet Specification

The specification below is available as a complete document.

"Furnace Ready Cullet"

Specification for Processed Cullet

for

Container Glass Manufacture.

February 2006

1 Introduction

This specification specifies the colour quality of processed glass at the point of delivery to a container glass manufacturer. This specification is based on the suitability of the processed cullet for container glass manufacture and reflects contamination levels that can be achieved under best practice. The quality of the pre-processed cullet is a commercial and technical consideration for the cullet processor. The appendices include testing procedure for assessment and classification of the cullet. The sampling method described in this specification is for colour contamination determination only. For determination of the other contaminants, then a larger cullet sample will need to be taken and as such is not covered by this specification.

2 Container Glass Manufacture Cullet

For container glass manufacture either processed container or flat glass can be used. However, due to chemical composition differences between the two glass types it is essential to maintain separate cullet streams. Flat flint cullet may also be recycled to flat glass manufacture, so its specification recognises the markets to which it could be supplied. The container and flat cullet are different products and separate streams enable the glass manufacturer to make controlled additions of each product to achieve the desired glass composition.

2.1 Processed Container Glass

2.1.1 Colour Contamination

Upon visual inspection in accordance with appendix A, the lot shall be classified by colour and shall be within the limits specified in table 1.

Glass Production - Colour	Coloured contaminants			
	Flint	Green	Amber	Other
Flint	Min 97%	Max 1.5%	Max 2.5%	Max 1.0%
Green	Max 10%	Min 70%	Max 20%	Max 1.5%
Amber	Max 10%	Max 20%	Min 80%	Max 1.0%

Table 1 Colour classification and colour contamination of processed cullet for container glass manufacture.

2.1.2 Contamination

The determination of the contaminant levels shall be within the limits specified in table 2 and shall be carried out on a larger sample (not part of this specification). In addition the lot shall not contain any medical refuse (e.g. needles or syringes), chemical refuse, toxic or hazardous materials.

Contaminant	Maximum permissible leve
Moisture	2 wt%
Organic	0.3 wt%
Inorganic including refractory material	0.001 wt%
Ferrous metals	0.002 wt%
Non-ferrous metals	0.002 wt%
Other glass types (Pyrex, crystal, ovenware, cooker top, plate, lighting, mirror, art, auto windscreen, opal, medical etc)	0.001 wt%

Table 2 Cullet contamination limits for container glass manufacture.

2.1.3 Particle Size

Upon assessment of the lot in accordance with appendix A, the particle size distribution shall be within the limits specified in table 3.

	Maximum Passin	
Size (mm)	**A (Fine**	**B (Coarse**
>32	0.5%	5%
>16	10%	50%
>8	40%	45%
>4	50%	25%
<4	40%	1%

Note – It shall not be possible to inspect either by hand or processing equipment, cullet with a particle size <4 mm and therefore it will not be possible to assess this size fraction against the specification.

Table 3 Cullet particle size distribution for container glass manufacture.

2.1.4 Glass Composition

Upon analysis of the lot in accordance with appendix A, the lot shall be within the compositional limits specified in table 4 and not exceed the limits in table 5.

Oxide	Container Glas	Variability	
	Compositio (wt%	+ wt%	- wt%
SiO_2	72.0	+1.0	-1.0
Na_2O & K_2O	14.0	+1.5	-2.0
CaO	10.5	+2.0	-2.0
MgO	2.0	+1.0	-2.0
Al_2O_3	2.0	+0.5	-2.0
SO_3	0.3	+0.1	-0.3
BaO	0.2	+0.1	-0.2
TiO_2	0.1	+0.1	-0.1

Table 4 Chemical composition of container glass cullet for container glass manufacture.

Oxide	Maximum permissible level /wt%		
	Flint	Green	Amber
Fe_2O_3	0.06	0.35	0.40
Cr_2O_3	0.002	0.20	0.02
PbO	0.01	0.01	0.01

Table 5 Maximum permissible level of colouring oxides and heavy metals in cullet.

2.2 Processed Flat Glass

Processed flat glass is predominantly clear glass; therefore processed flat glass should wherever practical be used for flint container manufacture or flat glass manufacture.

2.2.1 Colour Contamination

Upon visual inspection in accordance with appendix A, the lot shall be classified by colour and shall be within the limits specified in table 6.

Glass Production - Colour	Colour contaminants	
	Flin	Other
Flint	Min 99%	Max 1.0%

*There shall only be coloured flat glass within the lot such as green windscreen flat glass. Coloured containers within the lot will imply that there is cross-contamination.

Table 6 Colour classification and colour contamination.

2.2.2 Contamination

The determination of the contaminant levels shall be within the limits specified in table 2 and shall be carried out on a larger sample (not part of this specification). In addition the lot shall not contain any medical refuse (e.g. needles or syringes), chemical refuse, toxic and/or hazardous materials.

2.2.3 Particle Size

Upon assessment the lot in accordance with appendix A, the particle size distribution shall be specified to the appropriate particle category within the limits specified in table 3.

2.2.4 Glass Composition

Upon analysis of the lot in accordance with appendix B, the lot shall be within the compositional limits specified in table 7.

Oxide	**Container Glas**	**Variability**	
	Compositio (wt%	**+ wt%**	**- wt%**
SiO_2	72.0	+1.5	-1.5
Na_2O & K_2O	13.0	+1.5	-1.0
CaO	10.0	+2.0	-2.0
MgO	2.0	+2.5	-2.0
Al_2O_3	2.0	+0.5	-2.0
SO_3	0.3	+0.1	-0.3
BaO	0.2	+0.1	-0.2
TiO_2	0.1	+0.1	-0.1
Fe_2O_3	0.1	+0.0	-0.1
Cr_2O_3	0.002	+0.0	-0.002

Table 7 Glass composition of flat glass for container glass manufacture.

Appendix A – Analysis Methods

A representative sample of a cullet pile is taken by using a scoop (approximately 800g) and taking scoops from around the pile, from the base to the top. 10 to 12 scoops gives approximately 8-10kg of cullet, which is then reduced in size by the 'cone and quarter' method. The cullet is piled up, split in four and opposite quarters are removed. The process is then repeated - leaving approximately 2 kg cullet. A general observation of the cullet is made during this process to look for any major contamination (such as tamper rings, caps or plastic inserts such as in olive oil caps). This contamination may well not end up in the final sample, but is worth noting. Figure 1 shows the flow chart of cullet sampling and analysis.

This cullet is weighed into trays of a known weight (with a 2kg sample being split into three trays) and dried in an oven at 110°C for at least 1 hour. This ensures the cullet is dry, and it is then weighed again. The cullet is taken to 550°C and held at that temperature for at least an hour - burning off any organic substances that may be present. The cullet is then weighed again. Note there is no point burning off large organic pieces; they can be removed before heating and the effect will be the same.

Percentage weight losses on drying and ignition can then be calculated, where:

$$Weight\ loss\ (\%) \frac{Initial\ weight\ = Final\ weight}{Initial\ weight} \times 100$$

The weight used is the sample weight, calculated by subtracting the weight of the tray from the total weight.

Once the cullet has cooled, it can be analysed for size distribution. This is done by using large stackable sieves, with apertures of:

- 31.5 mm
- 16 mm
- 8 mm
- 4 mm

Using a suitable sieve shaker, the cullet is shaken for 5 minutes to ensure size separation. The individual size fractions are then weighed, and recorded.

The ferrous contamination is removed by passing a large magnet through the cullet. The remaining cullet is then spread on a light coloured flat surface and separated by hand in to:

- Flint
- Green
- Amber
- Misc (colour)
- Misc (other glass types)
- Stone
- Non ferrous contamination

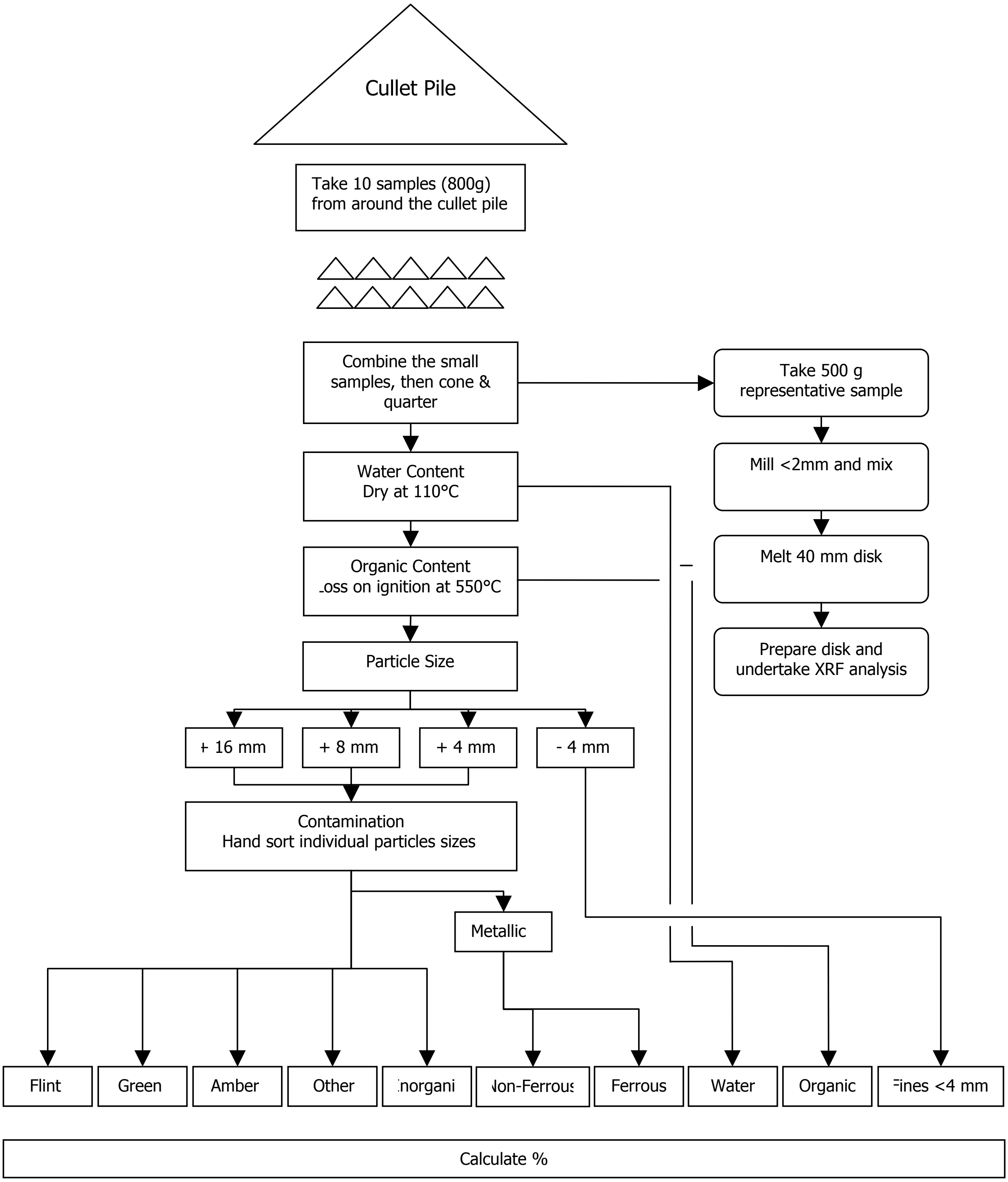

Figure 1 Flow diagram of the sampling method and quality assessment used in the collection and analysis of cullet samples.

Appendix B – Glass Composition Determination

A representative sample of the left over cullet is taken by using the 'cone and quarter' method further until a sample of approximately 400 grammes is reached. This cullet is then ground to a finer grade using suitable pestle and mortar or milling techniques. After grinding, particle size should not exceed around 5mm

This ground cullet can then be melted at 1450°C in an alumina crucible for 4 hours, before being poured into a 40mm diameter disc. Once annealed the sample is ground and polished until it is of a suitable standard for compositional analysis using a technique such as XRF.

End of Cullet Specification

Appendix F – Materials Safety Data Sheet

The material safety data sheet below is available as a complete document.

Materials Safety Data Sheet

Recovered and Processed Container Glass 'Cullet'

Material Safety Data Sheet

Section 1: Substance Identification

Product name:	Processed Container Glass
Common name:	Cullet
Product use:	Glass manufacture
Product origin:	Recovered glass from the collection of container glass from domestic and commercial waste streams, including bring sites, kerbside collections and commercial premises.
Manufacturers name:	Various suppliers
Manufacturers address:	Various suppliers

Section 2: Composition

Inorganic amorphous (glass) solid

Oxide	Composition wt%	
	Minimum	Maximum
SiO_2	73	74
Na_2O & K_2O	12	16
CaO	8.5	12.5
MgO	0	4
Al_2O_3	0	3
SO_3	0	0.5
BaO	0	0.5
TiO_2	0	0.5
Minor oxides	0	0.5

Section 3: Hazards Identification

Overview:	It is odourless and not flammable, combustible or explosive.
Potential Health Effects:	No data available.
Inhalation:	No data available.
Eye Contact:	May cause abrasion to the eye
Skin Contact:	May cause abrasion to the skin
Ingestion:	No data available.

Section 4: First Aid Measures

There is no specific treatment because the health effects associated with this material have not been documented.

Inhalation:	Remove from exposure and seek medical attention.
Eye Contact:	Irrigate thoroughly with clean water for at least 10 minutes. If irritation persists, seek medical attention.
Skin Contact:	If abrasion occurs, seek medical attention.
Ingestion:	Wash loose fragments from mouth and seek medical attention

Section 5: Fire Fighting Measures

All types of extinguisher can be used, use suitable extinguisher for the surroundings. This material is non-flammable and will not support combustion.

Section 6: Accidental Release Measure

Wear appropriate clothing and personal protection as directed below, vacuum up or where appropriate dampen with water to control dust and sweep up.

Section 7: Handling and Storage

Avoid generating dust, stored in a cool and dry place.

Section 8: Exposure Controls / Personal Protection

The material contains dust, where practical dust must be contained at source.

Ventilation:	Extraction should be used wherever dust is generated.
Respirator:	Dust respirator required when dust is generated.
Gloves:	Appropriate gloves that provide abrasion protection.
Eye Protection:	Goggles or face shield appropriate for the task.
Other:	Use protective clothing as appropriate for the work environment.

Section 9: Physical and Chemical Properties

Appearance:	Granular powder
Odour:	Odourless
Physical State:	Granular solid.
pH:	Not applicable
Density:	2.5 g/cm^2
Melting Point	≈1300°C (glass does not have a specific melting point).
Water solubility (25°C):	Insoluble
Alcohol solubility (25°C):	Insoluble
Flash Point:	Not applicable
Flammability:	Not applicable

Section 10: Stability and Reactivity

Stability:	Stable
Materials to avoid:	Fluorides such as chlorine trifluoride, hydrogen fluoride etc
Hazardous Products:	Material will dissolve in hydrofluoric acid and produce a corrosive gas – silicon tetrafluoride.

Section 11: Toxicological Information

No data available.

Section 12: Ecotoxical Information

No data available.

Section 13: Disposal Considerations

The material will need to be classified by local waste disposal authority before disposal by an appropriate method. Duty of care must be observed at all times.

Section 14: Transport Information

Not subject to transport regulation.

Section 15: Regulatory Information

Not subject to any know regulations.

Section 16: Other Information

The material is made from recovered container glass collected from the domestic and commercial waste stream such as bring sites, kerbside collection and collections from licensed and commercial premises. The glass has been processed to reduce contamination and processed to an acceptable quality and suitable particle size for feedstock material for container glass manufacture.

End of Materials Safety Data Sheet