Dr. Tyra Oseng, Prof. Kelvin Donne and Rodney Bender

Physical and Aesthetic Properties of Fused Recycled Bottle Glass

Abstract

This paper presents the results of a systematic investigation into the material properties of fused recycled bottle glass. From the outset, it was recognised that recycled bottle glass was being used in applications such as aggregate, filter-beds and some novel tiles. This limited range of applications and the lack of published data on factors such as sourcing, fusion methods and strength, led to the rationale for this project. The objective was to explore systematically the variation of parameters such as grain size, frit colouring, fusion temperatures and fabrication methods in order to be able to predict aesthetic and physical properties of the fused material. As a consequence, this provided data upon which a rational choice of fused recycled bottle glass could be made for specific applications.

The research concludes through a major case study. Interior tiles were developed and produced to an architect's specification and installed in a show apartment, which is being used to market low cost sustainable housing for a new development in Swansea in Wales. In conjunction with the major case study, which also included the creation of a sculptured artefact, robustness test of the interior tiles were conducted in line with the commissioning architect's specifications. The purpose of the case study was twofold. First, to show that it is possible to reproduce, in a predictable way, the properties of the material to meet the requirements of the application. Secondly, to establish if the use of recycled glass in any way affects subjective opinions about the aesthetic and physical properties of the material. This was investigated through the use of a questionnaire.

Introduction

This paper presents result from an investigation of the use of fused recycled bottle glass with the prospect of developing architectural applications, and builds on a PhD project with similar title.

The study focuses on variables which would affect both the structural/mechanical and aesthetic properties of the material, with the aim of investigating the conditions under which the recycled material could be a viable material for use in design applications. Prior to investigating these variables, it was necessary to establish means whereby waste glass bottles could be sourced, cleaned, crushed, mixed and fused in order to produce a viable material for use in novel designs.

Only flint coloured bottles were used for this investigation, combined with commercial frits of three primary colours. The frits were mixed with the raw broken glass in order to establish a wider range of predictable colours. Of course, colour is an important visual characteristic. However, texture is equally important. Texture is dependent on fragment sizes and fusion temperature and this paper presents results of colour and texture as a function of fragment size, fusion temperature and choice of commercial coloured frit. Similarly, the final shape of the material can be changed using the processes of slumping and casting. Using basic glass fusion methodology, various glass-forming processes have been explored, and a commercial application is presented as a result from this investigation.

At the beginning of the research it was recognised that bottle glass was used in wide range of applications for the construction industry. Currently, major uses of recycling methods for waste glass involve using it in bulk for aggregate, for example mixed with either concrete or asphalt (Aggregain, 2003). Other more refined methods have been developed such as fibreglass for insulation (WRAP, 2004) and foam glass (Aabøe, Oyseth, & Hägglund, 2005). It was notable at the beginning of this project, that there were only a few examples of designs where aesthetic qualities of recycled waste glass were important (Reindl, 2003). None of the large scale developments has needed to consider the aesthetic requirements of the product except for some production tiles (Andela & Kirby, 2007). Smaller scale developments have been reported. For example, some small glass studios have used bottle glass in hot glass processing (Tangrand, 2006). Tangrand has managed to create a successful glass blowing business in the north of Norway, trading products made from recycled packaging glass (Solbakk, 2005). The potential use of recycled bottle glass has been investigated and published by Clean Washington Center (Morrison, 2001), and products made from fused bottle glass have also been seen in various public domains (Enqvist, 2001; Watson, 2007; Melrose, 2008). In these cases, there was no detailed published investigation about the manufacturing processes or rationale behind the design visualisation. This lack of information offered the opportunity, resolved in part within this research project, for detailed investigation of the wider potential use of waste glass, when approached from an industrial design perspective.

Research by practice

Glass bottles were collected from local clubs and wine bars. The labels of the bottles were removed by washing in hot water. The bottles were then cleaned again with hot water to remove all residues from the glue. The bottles were sorted by colour of the glass, and divided by punt marks. With the use of *'Little Smasher'* a bottle crusher from a company called Smash & Grab Ltd, the bottles were pre-crushed to cullet size, and then allowed to air dry for ease of crushing (Figure 1). The next stage of preparation was to crush the glass to specific fragment sizes. This was done using a laboratory scale glass crusher purchased from P.V.S. (UK) Ltd. Two ranges of grain sizes were produced, namely, 0-2 mm, and 6-12 mm. The raw glass was then ready to be fused.

The issue of compatibility of bottle glass was overcome by the identification of punt marks (Emhart Glass SA, 2000), and then carefully selecting bottles based on the punt marks. The methodology and result of this experiment is beyond the scope of this paper and is presented in the main doctoral thesis (Oseng, 2009), and could form the subject of a different paper. The evaluation of the carbon footprint is also beyond the scope of this paper and could form the subject of further work.

Figure 1, Cullet let to air-dry

Texture and Colour creation

Aesthetic properties were investigated in term of texture and colour. Using the various fragment sizes, combined with various top fusing temperatures, a variety of textures were identified. Frit of three primary colours was mixed with the raw glass in various amounts to create a full colour circle. The hypothesis that two primary coloured frits could be mixed to create a secondary colour was tested. Parameters such as fragment sizes, ratio frit to glass, top temperatures and fusing cycles was combined in a extensive diversity to create a wide range of colours and textures that also was reproducible.

The first set of tests was designed to identify the kind of textures possible to produce using the fragment sizes as a function of various fusing temperatures. The mould was filled with 175g glass using the two fragment sizes (0-2 mm and 6-12 mm). The top temperatures employed were 820ºC, 900/820ºC and 950ºC. The *'900/820ºC'* had a fusing cycled where the temperature was rising up and down between 900ºC and 820ºC in four stages, with a soak of 20 min on each stage. This was to encourage devitrification of the glass. The temperature 950ºC was fused as normal with 20 minutes hold time. No additives were introduced to the raw glass, and all glass samples were fully annealed.

The second set of experiments was to mix raw glass and frit. Each pair of frits was mixed in ratios 100/0, 95/5, 90/10, 85/15, 80/20, 75/25, and 50/50 and each mixture was mixed with the raw glass (ratio 1:10 for small grain size and 1:30 for large grain size) and fused. The mixture was placed in ceramic moulds and fused a variety of top temperatures, namely 860ºC, 880ºC, 900ºC, 950ºC and 980ºC and with a hold of 20 minutes on top temperature before annealing. Glass of fragment size 0-2 mm and 6-12 mm were used. The method of mixing frit with the larger grain size was to sprinkle the frit mixture on the bottom of the mould before the glass was laid on top. All samples used 35g raw glass.

For all temperatures, the boundaries of the glass fragments could be seen in the glass specimen, and a relatively low temperature of 820ºC gave a deeply-textured surface (Figure 3). For a temperature of 900ºC, the texture was completely flat (Figure 2). A temperature of 950ºC created more sticking behaviour with the mould material, especially for the smaller grain size. The temperature cycle 900/820ºC created a devitrified surface as desired. Some creeping of the edges was visible for the smaller grain sizes, especially for the higher temperatures, where the edges were curved. For larger grain size, the edges were more uneven and were rough with sharp points that needed to be ground off. This occurred more for the lower temperatures, but was still evident with the high temperature.

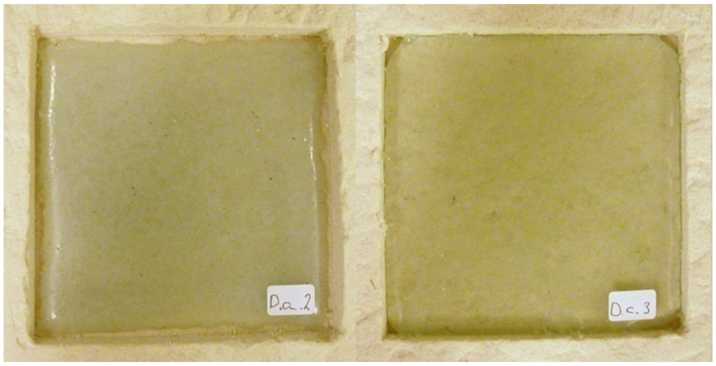

Figure 2, Texture after fusion at 900ºC

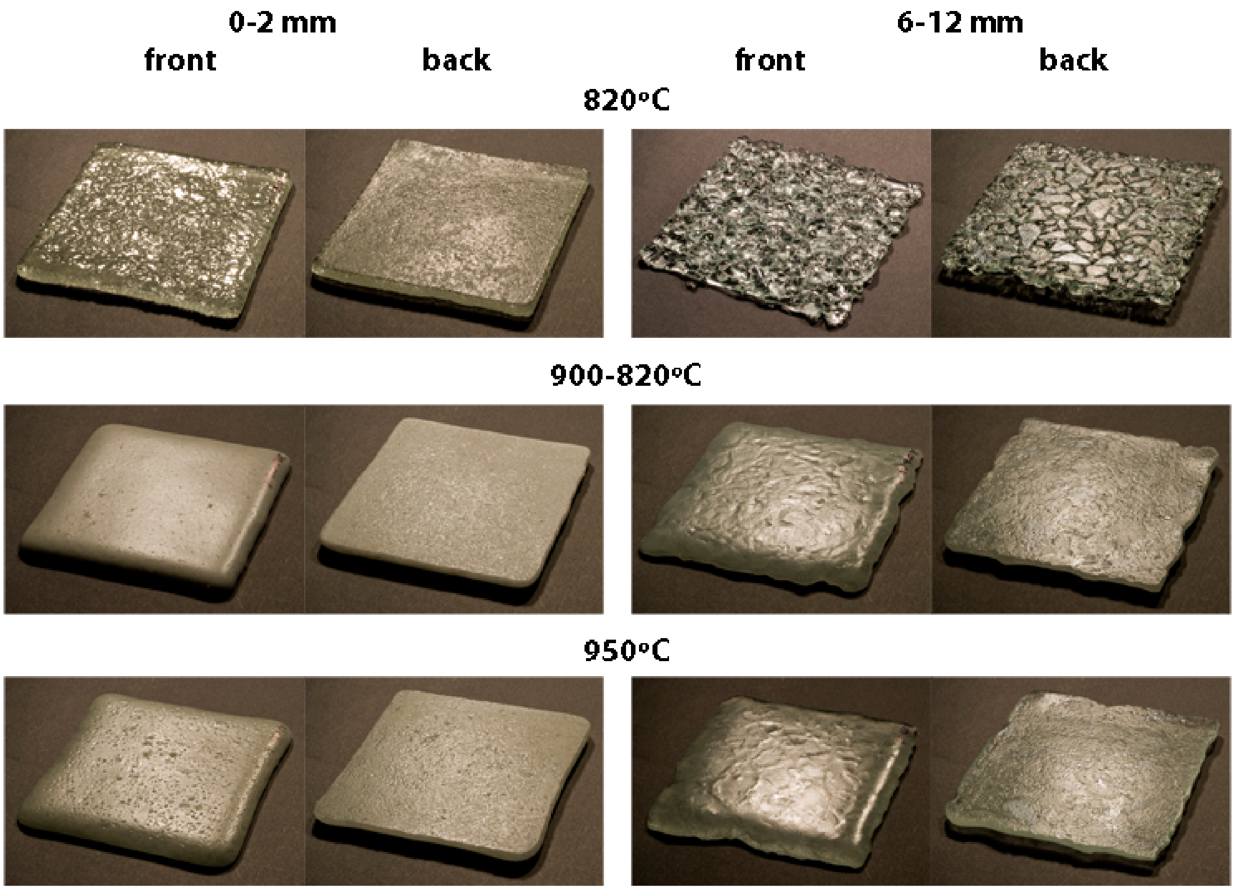

Figure 3, Texture after fusion, tiles seen front and back

As seen in figure 4 below, colours are made from three primary frits mixed with the raw glass. Fragment size 0-2 mm and 6-12 mm was used, combined with an increase of top temperature.

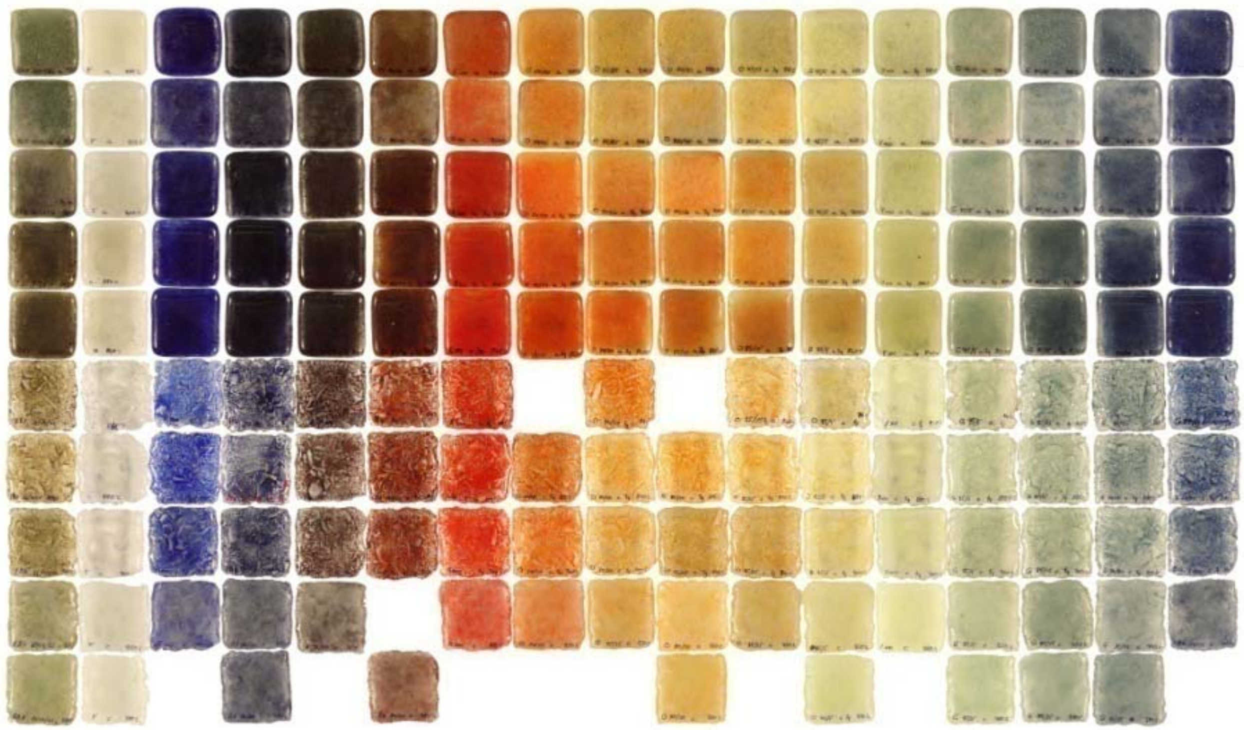

Figure 4, Frit and glass with temperature variations

Conclusion of creating texture and colours

Aesthetic properties of fused bottle glass were investigated in terms of texture, translucency and colour. Two factors were important. First, the actual quality of the texture and colour and, secondly, the ability to reproduce the same textures and colours. A wide range of textures are possible using various grain sizes, fused at various top temperatures. Three major conclusions were found:

- It is possible to produce a wide range of colours that is predictable and reproducible.
- Increasing top temperature flattened the texture and encouraged devitrification.
- Increasing grain size caused changes in texture, colour and translucency in a predictable manner.

Experimental work

Previous work (University of Washington, 1999) reported that the strength of fused recycled glass is high. However, that work does not reflect a systematic approach to the variables of fragment size, fusion temperature, frit addition and fusion time, some or all of which could affect the strength. Therefore, parametric studies of strength versus fragment size, fusion temperature, frit addition, and fusion time have been undertaken in order to investigate the possibility of producing a wider range of recycled materials. The results formed the basis for a case study where interior tiles were developed and produced to an architect's specification and installed in a show apartment.

To gain an insight into the strength of the recycled glass, the recommended four point loading method for testing the flexural strength was used, using a modified *'Hounsfield H20K-W'*, tensile tester (Figure 5). By this method, an increasing load is applied to the centre of the specimen, which is clamped between two bearing plates, upper and lower, see Figure 6. The bearing plates were manufactured in-house, and each glass sample was 'cushioned' with a suitable material. The choice of this material was extensively researched through practice in order to minimise the random variation (standard deviation) of the results.

Figure 5, Hounsfield H20K-W

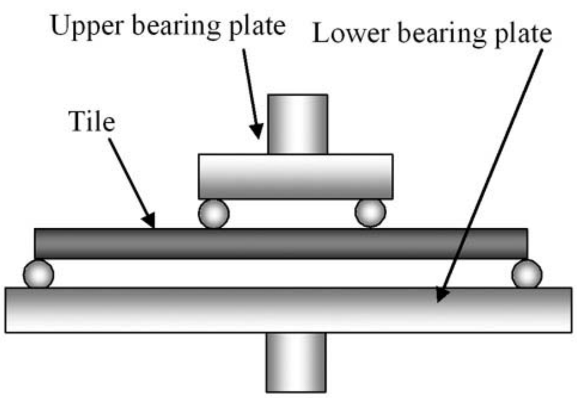

Figure 6, Upper and Lower Bearing Plate

The instrument automatically generates Force versus Displacement data. Hence, the energy and maximum force required to break the sample can be measured. The maximum break force allows the Modulus of Rupture (R) for the sample to be calculated for this experimental configuration. Four maximum temperatures were tested for the making of the specimens, namely 820ºC, 900ºC, 900/820ºC and 950ºC. The same annealing cycle was used for each maximum temperature test, and similar fragment sizes at each maximum fusing temperature. In addition, two colours of glass were prepared, ratio frit to glass as mentioned above. To test for repeatability of results, five tiles were made for each experiment. For example, five specimens fused at a maximum temperature of 820ºC with a grain size range of 0-2 mm and a red frit colour was prepared for one experiment. The glass was contained between four metal bars with the cushioning material.

The following conclusions have been drawn from this experiment:

- Glass made from smaller grain sizes was stronger than glass made from larger grain size.
- Larger grain sized material increased in strength with increasing top temperature, whereas small grain sized material did not show a significant change in strength with increasing top temperature.
- The strength was not affected with the range of concentrations of frit used.

An interesting consequence of the strength measurements was the observation of increased strength when crystallization was encouraged during the fusion process.

Case study

The case study has been undertaken where the aim was to explore the design factors identified by the professional architectural community and assess the validity of the recycled bottle glass material in terms of meeting commercial specifications. This case study was undertaken in partnership with the architects Phil Roberts and Elfed Roberts and marketing manager Joanna Margetts, at Grŵp Gwalia Cyf, Swansea, the largest housing association in Wales. The case study objective was to design and produce interior tiles for the bathroom and kitchen interiors of a show apartment, which was being used to promote low cost sustainable housing for a new development in Swansea. The proposition was that recycled glass tiles driven by the low-energy sustainable agenda could be sympathetic, to and resonate with, the sustainability objectives behind this innovative development which utilised only building materials that met strict low carbon and sustainability criteria. The case study was undertaken over the period January to June 2008, in Swansea's SA1 Maritime Quarter redevelopment of the old dock's area.

Glass tiles were produced through the following processes, with quality control checks as specified. Waste glass bottles were deliberately sourced locally, and separated according to colour. To minimize the presence of impurities, the bottles were cleaned carefully twice with hot water, and pre-crushed before the cullet was left to dry naturally as described. Small grain sizes of cullet were produced (0-2 mm).

For the architects to feel comfortable accepting the tiles, several design factors had to be satisfied. Already presented were the results from the four point bend test. However, the tiles needed to go through a set of qualitative tests to pass. A list of product specifications was provided, which the author had to meet. These were:

- *Durability*, i.e. impact resistance, resilience to cracking and shattering, scratch and abrasion resistance.
- *Maintenance*, with the concern of resistance to staining, ease of cleaning and resistance to abrasion from cleaning products.
- *Bonding*, if commonly available bonding products can be used.
- *Consistency of appearance*, with size, shape, texture/finish, and need a statement to explain aesthetic characteristics.
- *Availability*, with cost and budget, and the need to compare costs with a similar product at the higher end of the market.
- *Health and safety*, with the concern of sharp edges. Workability, in how to cut the tile etc.

- *Recycling/ Unique Selling Point*, with a need to explain aesthetic qualities, applications, environmental benefits, and provenance of materials.

It was noted that conformance to British Standards *'Resistance to Surface abrasion-glazed tiles EN ISO 10545-7'* and *'Impact resistance EN ISO 10545-5'* was not required for wall tiles, but only for floor tiles. The standards *'Resistance to staining on glazed tiles EN ISO 10545-14'* and *'Determination of resistance to surface abrasion for glazed tiles EN ISO 10545-7'* were required for wall tiles (British Standard, 2007). The tests were performed but are not described in detail in this paper. The standard *'Breaking strength and modulus of rupture, EN ISO 10545-4'* was also required for wall tiles. Data for the bending strength was already provided and accepted by the architects. It was interesting to note that the clear consensus of the architects for this project that was firmly based on sustainable and environmental factors was a clear preference for a matt tile finish (Roberts, 2008). A professional tiler provided comments regarding cutting the tiles for installations and suitable adhesives for the glass tiles. The tiler specified the use of a wet diamond saw to cut the tiles, cover the cut edges if exposed, use 2 mm of grout and possibly no spacer due to the curved edges of the tiles. The size of the tiles to be produced was agreed to be 100 x 100 mm.

The colour samples mentioned above were presented to the architects. The architect chose some samples which were then made to order. The fragment size was 0-2 mm and fused at two top temperatures, 860ºC and 900ºC. All samples were held for 20 minutes on top temperature. When presented with the colour samples the architect shortlisted four colours for the bathroom and four colours for the kitchen, but the precise choice of colour involved a series of iterations where subtle variations of colour were explored with the architects. The choice of tile texture was quickly resolved, where less *'glossy'* tiles were chosen as the preferred texture, and all tiles from this point were fired at 900ºC. The range of colour samples is shown in Figure 7. The final chosen colours were given names: *Broken White*, *Golden Sand*, *Sand* and *Olive*. For the bathroom tiles was called *White*, *Aqua*, *Dark Green* and *Light Grey*.

Figure 7, Colour samples provided for the architects

The case study was successfully completed. The interior wall tiles were produced from bottle glass to the architects' specifications both for the aesthetic and the physical features. In terms of the design factors listed in section above, the tiles were strong, durable, aesthetically pleasing, and scratch and stain resistant as well as reproducible. The architects confirmed their acceptance of the tiles by showing an interest in using them in other developments and the designer was re-commissioned for further work. Figure 8 below shows the tiles installed in the bathroom and Figure 9 and 10 show the kitchen interior. The tiles were installed in the show apartment during June 2008.

Figure 8, Recycled glass tiles installed in the bathroom

Figure 9, Recycled glass tiles installed in the kitchen

Figure 10, Recycled glass tiles installed in the kitchen

A request from the architects was also to design an artefact in order to further promote the recycled agenda in the apartment, for which the designer could choose any parameters of colour, texture and shape. A round bowl with a hint of amber colour, a shallow oval shaped plate and a square plate with a hint of blue colour were developed. The artefacts were highly textured using a lower energy approach (low fusion temperature 830ºC) keeping the glass in a transparent state. The bowl was 350 mm in diameter, 90 mm deep with 15 mm thick wall, the oval plate was 480 mm long 270 mm wide and 40 mm deep with similar thickness of the wall, and the square plate was 270 mm wide and 50 mm deep with a 10 mm thick wall. The amber colouring was created by amber coloured bottles and the blue colour derived from blue bottles, all locally sourced.

Due to its experimental nature a master mould was made from MDF to make the mould of plaster. The ring of plaster based on the desired shape acted as walls for the glass and which together with the kiln shelf, coated with separatore, acted as a hybrid mould to fuse the sheet of glass. Coloured glass of fragment size 0-0.5 mm was sprinkled in a thin layer on the bottom of the mould, before compatible glass with fragment size 6-12 mm or above 12 mm was positioned over the sprinkled coloured glass. The glass was fused to temperature 830ºC and held for 20 minutes. After fusion, edges were processed with basic polishing equipment to soften the sharp points. A shallow stainless steel mould was used for the shallow oval plate, and standard ceramic slumping moulds for the deep bowl and square plate. The kiln was taken slowly up to 760°C and held for 10 min before annealing and cooling to room temperature. Figure 11 below illustrates glass before first fusion, and Figure 12 shows the bowls and plates before slump. After last firing, the artefacts were ready to be exhibited (Figures 13 to 15).

Figure 11, Production of bowls and plates for the show apartment before first fusion

Figure 12, Production of bowls and plates for the show apartment before slump

Figure 13, Final design for oval plate

Figure 14, Final design for square plate

Figure 15, Final design for deep bowl

Design Factor analysis using questionnaire

This paper also includes the results of a questionnaire conducted where the aim was to measure opinion of Swansea's young professionals regarding recycled glass tiles. This questionnaire arose in communication with the architects that the recycled glass tiles were used for their attractiveness and to market low cost sustainable housing. It was decided that a questionnaire was to be conducted to measure people's attitude regarding the recycled nature of these glass tiles, using three design factors:

- Perception of aesthetic quality.
- Perception of mechanical integrity.
- Perception of value.

These are referred to as attractiveness, robustness and apparent value. There were two key elements to this experiment. The first was to investigate if recycled glass tiles could be favourable compared with commercial tiles based on the three design factors. The second was to measure if prior awareness about the recycled nature of the tiles influences people's attitude.

The study was conducted using a self completion questionnaire where the participants were systematically allocated into one experimental and one control group. The participants would rate the tiles on a five point Likert scale (Oppenheim, 1994). The advantage of using a standardized questionnaire is that it is relatively quick to collect information and the data are numerical and easily interpreted quantitatively. The data collected are ordinal, which have an inherent order or sequence using the median or mode for interpretation. Two-tailed hypotheses were posed for each of the three design factors. The null hypothesis is that there is no significant difference between the experimental group and control group for each design factor. If the experimental group scored significantly different from the control group, the alternative hypothesis was confirmed.

There were two issues investigated in this analysis:

- Query 1: Could the recycled tiles be favourably compared with commercial tiles against the three design factors?
- Query 2: does prior awareness of the recycled nature of the material influence people's attitude?

Population of interest in this study is British educated adults which have various emphases in their education. It was also decided to employ participants derived from three various educational backgrounds to avoid biased response based on *'subject-specific expert knowledge'*. The participants were students from Swansea Metropolitan University (SMU) with *'expert'* knowledge in aesthetics, sustainability or business. For pragmatic reasons the gender and age were not considered as significant factors. The samples were chosen from the School of Industrial Design, School of Built and Natural Environment and Swansea Business School. The purposive sampling was chosen to have equally amount of participants from each school (n=60) of which each group was divided one experimental and control group (n=30). (I.e. with prior knowledge of recycled material and the control group without prior knowledge).

Tiles

Five tiles were chosen with similar features including colour, size and suitability for the same interior location. Three tiles were commercially purchased and two were made from recycled glass. All tiles were interior wall tiles, in a white hue and 10 x 10 cm. Two tiles were made of ceramic with very similar aesthetic feature, where one was physical different being considerable thinner that the other, 10 mm and 6 mm thick. These ceramic tiles were referenced as *'ceramic thin' (c.thin)* and *'ceramic thick' (c.thick)*. One tile was made from stone, had a polished surface, 14 mm thick and referenced as *'stone'*, whilst two tiles were made from recycled glass. One tile representative for the case study with rounded edges, 7 mm thick and called *'gwalia'*, and the other tile was chosen to be representative of large grain sized devitrified glass, 10 mm thick and called large grain size glass, referenced as *'l.g.d.glass'*. Figure 11 below illustrates the tiles where *'A'* is stone, *'B'* is ceramic thin, *'C'* is ceramic thick, *'D'* is l.g.d.glass and *'E'* is taken from the final selection for the Gwalia-project.

Figure 16, Tiles to be tested: A=stone, B=c.thin, C=c.thick, D= l.g.d.glass and E=gwalia

The self completion questionnaire was used to assess the participants' perception of the five tiles in relations to attractiveness, robustness and value. For attractiveness and robustness participants were required to rate each tiles using a 5 point numerical rating scale (Uebersax, 2006). For perceived value, participants were required to rank the tiles in order of cost (e.g. tile A most expensive, tile D least expensive). All data has been analysed using a computer software package SPSS (Connolly, 2007). Parametric studies assume a normal distribution, and a simple test of frequency in SPSS, showed that the data did not have a normal distribution. Therefore, non-parametric tests have been used to analyse the data.

One clear observation from the questionnaire results is the high ranking of the large grain size devitrified tile. The tiles were ranked in the following order:

- For attractiveness: stone, l.g.d.glass and gwalia was equally ranked to be the most attractive, followed by ceramic thick and the least attractive tile to be ceramic thin.
- For robustness: stone was ranked to be the most robust followed by l.g.d.glass. Gwalia and ceramic thick was ranked equally at the third place of robustness and ceramic thin at the least robust tile.
- For perceived value: stone was ranked as the most expensive, followed by l.g.d.glass, gwalia, ceramic thick and the least expensive was ceramic thin.

Dividing the participants into a control and an experimental group testing if awareness of the recycled nature of the material altered the attitude of attractiveness, robustness and value showed the following statistically significant results:

- The l.g.d.glass tile was found more attractive with 99.2% confidence.
- No variations were seen in either robustness or value when awareness of the material was known. I.e. people's perception of robustness and value of the recycled tiles was not affected by prior knowledge of the material's provenance.

Conclusion

The colours and texture of the interior tiles were successfully developed to the client's wishes, and compliant with the technical specifications. The client marketed the apartments as a low cost sustainable housing for young professionals. The client defined the properties needed for the tiles, including texture, colour and strength. In terms of the design factors listed above, the tiles were strong, durable, aesthetically pleasing as well as reproducible. The architects confirmed their acceptance of the tiles by showing an interest in using them in other developments.

The questionnaire established that the two bespoke tiles were ranked as high as equal or the second most attractive tile compared to commercial tiles. This is a very positive result for this research project. Similarly, it is also encouraging that the tiles were not seen as less robust when the participants were aware of the recycled material. Regarding the perceived value, the participant did not perceive the recycled tile either more or less expensive due to the fact they were made of recycled glass, which suggested that recycled tiles can be competitive in the commercial market.

At the beginning of this project it was proposed that fused recycled bottle glass could be used as a design material if the physical and aesthetic properties could be controlled. As the case study has shown it is possible to control the physical and aesthetic properties of fused recycled bottle glass to meet the design specifications of an independent professional. In addition, the research has demonstrated the potential of a waste management model for product development that crucially uses locally sourced material, offering small enterprises in particular a broad range of novel product qualities with minimal / (low technology) equipment outlay. This is a significant contribution to the recycling agenda.

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