

An investigation into the effect upon flexural strength of different methods of cutting float glass and sintered recycled container glass

*Dr Shelley Doolan, Dr Tyra Oseng-Rees and *Dr Juan Ferriz-Papi
University of Wales Trinity Saint David, Swansea College of Art & *Faculty of
Architecture, Computing and Engineering*

Abstract

This paper outlines an investigation into the effect upon edge quality and flexural strength in 10mm float and sintered recycled container glass of different methods of cutting: hand diamond-scoring, diamond sawing and abrasive waterjet cutting. The research made use of a four-point-loading method to determine flexural strength and a surface roughness meter to assess the cut edge quality.

The paper discusses the results and presents areas for further research.

1. INTRODUCTION

1.1 Aim

The project aims to determine whether abrasive waterjet cutting (awj) adversely affects the flexural strength of glass in comparison with traditional cutting methods.

1.2 Rationale

The abrasive waterjet makes possible the cutting of intricate, complex shapes in hard brittle materials such as glass and ceramics that would otherwise be impossible with traditional cutting methods.

The ability to cut ceramics and glass in this way broadens the scope, scale and application of the material into increasingly complex artistic and architectural applications (1) (2). This research was prompted by questions from designers regarding the effect of water jet cutting upon the flexural strength of the material in comparison with traditional cutting processes.

2. EXPERIMENTAL SET UP AND PROCEDURE

2.1 Material selection and production

Two materials were selected for testing: 10mm thick Pilkington float glass and 10mm thick recycled container glass.

Float glass – *the* ubiquitous material in contemporary architecture – was selected because of its widespread use in design, art and architecture.

Its homogenous nature and consistency of production was a useful baseline for comparison with the second material to be tested: 10mm thick **sintered post-consumer recycled container glass sheet**.

There is an increased interest in the use of sustainable materials within architecture. This material makes use of a post-consumer waste product to create an aesthetically interesting 100% recycled glass sheet (3) (4).

The material is created using randomly collected cleaned container glass, crushed into a raw cullet prior to sieving into two ranges of mesh size. For the purposes of this experiment, only clear glass was used. Two ranges of cullet size were used: 0-2mm and 6-12mm.

The glass was packed into a large refractory mould and sintered at a temperature of 880°C to produce a flat sheet of material for cutting.



Figure 1

As Figure 1 demonstrates, although flat, the material differs from float glass in that it is not a transparent homogenous material but retains the positioning of the individual cullet pieces and has transformed into a crystalline material more akin to ceramic.

This is due to the nature of the cullet material and production process. The cullet is fused rather than fully melted, which results in a material with a non-homogenous granular structure. This means that the load is not uniformly distributed and the internal structure can concentrate stress in punctual parts of the specimen, becoming weaker.

To fully melt the glass (to produce a homogenous structure) rather than sinter, would require temperatures in excess of 1150°C. This exceeds the capability of a standard glass kiln and requires greater use of energy reducing the environmental sustainability of the material. Taking the glass to a full melt would create a different effect and not the aesthetic desired.

In practice the recycled material proved to be impossible to hand-score and was therefore excluded from the tests.

Table 1 illustrates the range of specimens created for testing. Ten samples of each specimen were prepared to dimensions of 160mm x 50mm, all 10mm thick. Ten specimens of each variable were tested for statistical relevance and to take account of any potential anomalous result.

Table 1

	Float	Recycled 0-2mm cullet	Recycled 6-12mm cullet
Waterjet cut	FGW	R-0-2-W	R-6-12-W
Diamond-saw cut	FGD	R-0-2-D	R-6-12-D
Diamond hand-scored	FGDS	N/A	N/A

2.2 Cutting Processes

Diamond-saw (water-cooled)

Model: Nuova Battipav (Figure 2)

Blade: 355.6mm diameter, 25mm bore, 120 mesh resin-bonded diamond saw blade.



Figure 2

Abrasive waterjet

Manufacturer: Water Jet Sweden. Type: NC 3015 E (Figure 3)

Abrasive: 120 mesh garnet

Pressure: 55,000 psi

Traverse rate: 435mm/minute

Abrasive flow rate: 255g/minute

Nozzle: 0.76mm diameter nozzle with a jewel orifice of 0.25mm diameter

Stand-off distance: 2mm

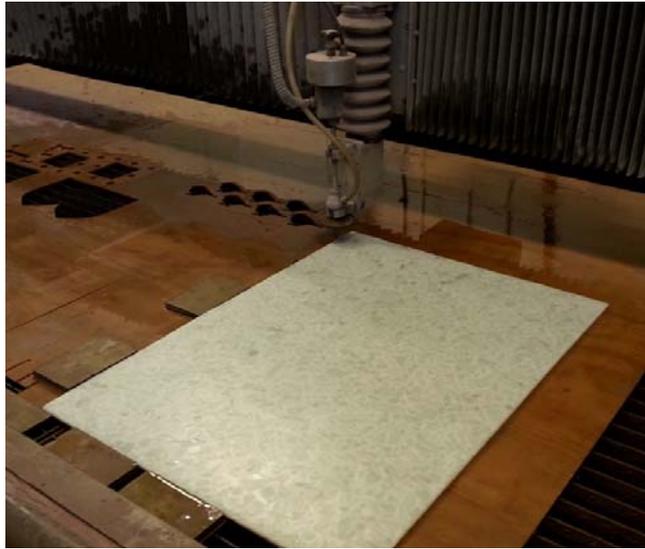


Figure 3

Hand diamond scoring

Oil-lubricated hand-held diamond scoring wheel, (Figure 4).

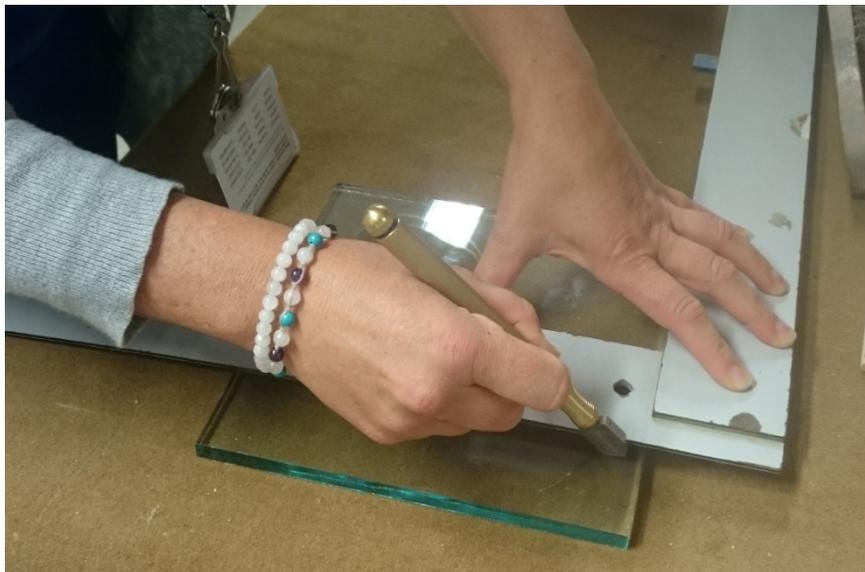


Figure 4

2.3 Surface roughness test

A Mitutoyo SJ 400 roughness tester was used to assess the cut edge surface quality of each material created by the different cutting methods.

The sample was secured in a vice with the probe positioned in the centre of the material (Figure 5). The sample was measured along the length of the material. This orientation was chosen to take account of the surface roughness created by the cutting kerf.



Figure 5

Measurement length: 4.2mm,
Increments: 0.006
Traverse rate: 1mm/second

2.4 Flexural strength test set-up

To test the flexural strength of the specimens, a Denison flexural tester (Universal testing machine, model WDW-100) was used (Figure 7).

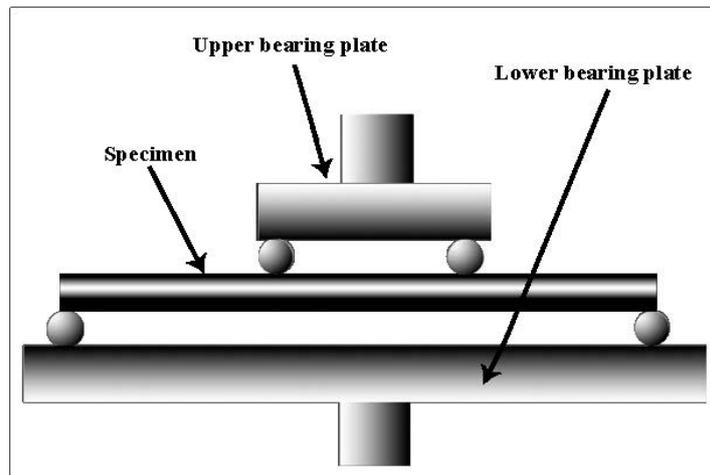


Figure 6

The test set-up was designed in accordance with the recommended four point loading method for flexural strength testing as shown in Figure 6 (5).

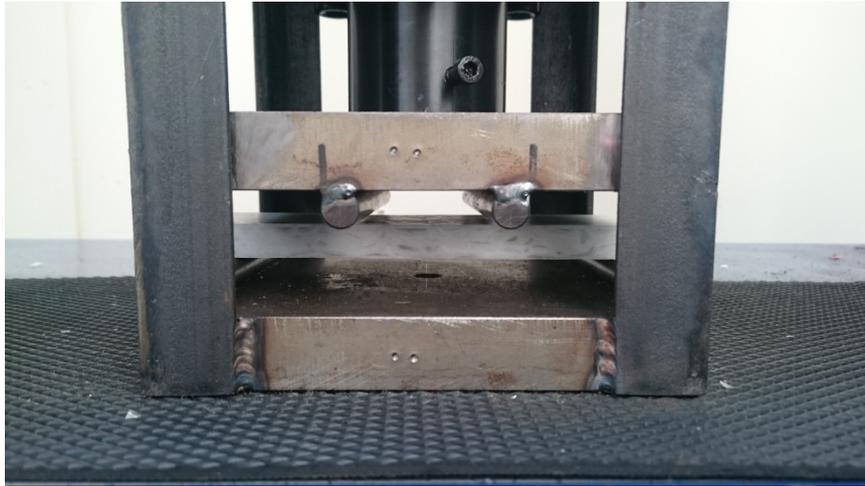


Figure 7

Drawing upon the research of Laredo dos Reis (6) the tests were performed at a displacement rate of 2mm/min. The outer span length was 150mm which corresponds to the recommended sample ratio dimensions of Carter and Norton (7).

The instrument automatically generated force versus displacement data. Hence, the energy and force required to break the sample could be measured. This value allowed the Modulus of Rupture (R) for the sample to be calculated for this experimental configuration, according to Equation (1) where P is maximum applied force, L is the span length between the outer supports of the lower bearing plate, b is sample width and d is sample depth. The Modulus of Rupture (R) was measured in this way for all subsequent samples. For a four point bend test where the loading span is one-third of the total supported span length, R is determined from equation 1.

$$R = \frac{PL}{bd^2}$$

Equation 1

3. RESULTS & ANALYSIS

3.1 Surface roughness measurements

The results as illustrated in Figure 8 demonstrate that waterjet cutting produced a significantly rougher surface than diamond sawing or diamond hand-scoring. It was noted that the roughness values, although greater, formed a consistent pattern.

The values for the diamond sawn sample were generally consistent but did include occasional values outside of the average range, with peaks and trough values at the extreme ends closer to the values for the waterjet cut surface.

As expected, the diamond hand-scored edge was smoothest, producing results with a consistent peak and trough value range. As illustrated in Figure 8, the nature of hand cutting produced samples that fractionally deviated from dimensional accuracy resulting

in a sample being slightly off horizontal ($<1\mu\text{m}$ across a distance of 4.2mm) on the test bed.

The roughness values reflect the characteristics of the cutting mechanisms. Where the glass is scored, a flaw is produced in the surface. The glass is then broken along this flaw line. The resulting break produces a visually clear edge finish. By contrast abrasive waterjet cutting and diamond sawing cut by erosion, resulting in an abraded edge surface.

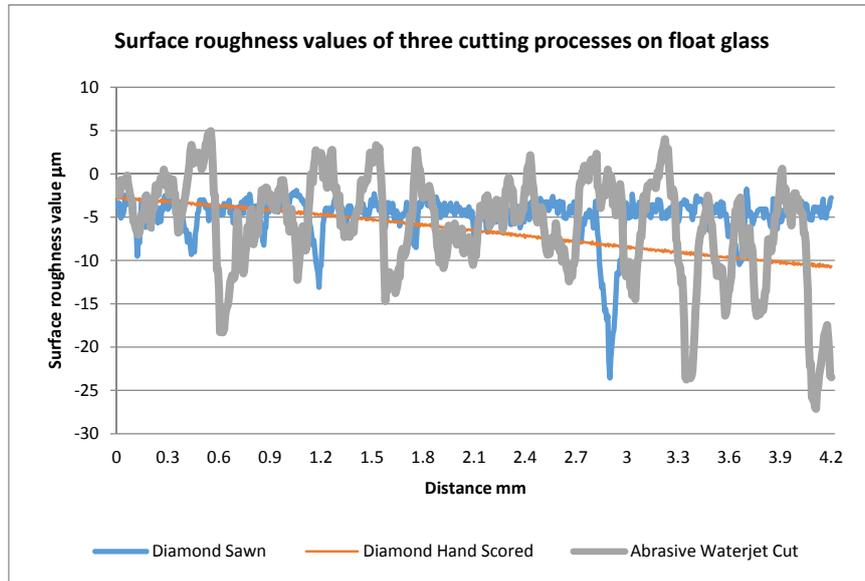


Figure 8

3.2 Flexural strength tests

3.2.1 Float glass

The average results (Figure 9) observed indicate diamond hand-scoring results in material with a higher flexural strength (avg. R 92.00) than either waterjet cut (avg. R 52.52) or diamond sawn glass (avg. R 53.00), both of which have a similar flexural strength. When taking account of the standard deviation of the results however, it should be noted that there was a significant range of values for modulus of rupture for hand-scored float glass (R 41.70 to 135.75) which equates to a standard deviation (STDEV) of 28.24. The results indicated that the STDEV for diamond sawn float glass (7.36) was higher than for waterjet cut float glass (6.15).

The results in terms of standard deviation reflect the nature of the process. For example the hand-scoring is a 'hand' cutting process and as such is subject to variations in pressure, speed of cut and hard to standardise. Similarly with diamond sawing, although a mechanical process, the saw is manually operated, with the operator manually feeding the material which determines the cutting speed. By contrast the abrasive waterjet cutting is a wholly CNC process.

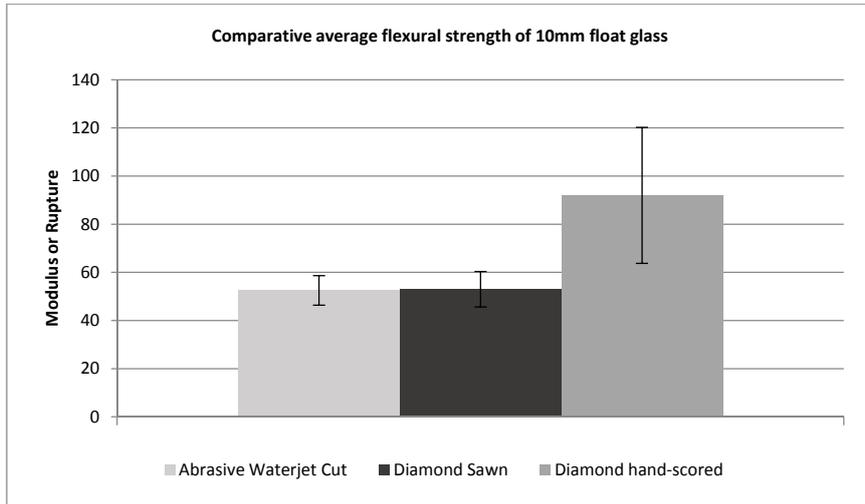


Figure 9

3.2.2 Recycled glass sheet

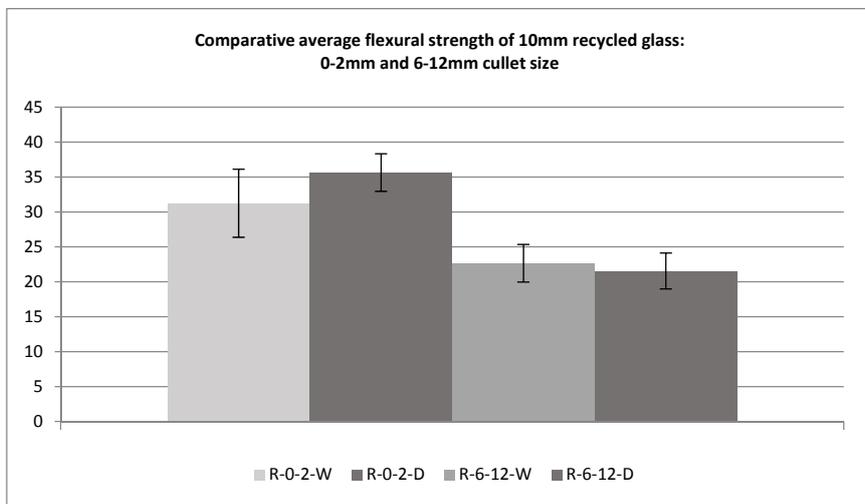


Figure 10

R-0-2-W = Recycled glass 0-2mm cullet. Abrasive waterjet cut

R-0-2-D = Recycled glass 0-2mm cullet. Diamond sawn

R-6-12-W = Recycled glass 6-12mm cullet. Abrasive waterjet cut

R-6-12-D = Recycled glass 6-12mm cullet. Diamond sawn

3.2.2.1 0-2mm cullet size

The average results observed (Figure 10) indicate that the waterjet cut material (avg. R 31.25) was weaker than the diamond sawn glass (avg. R 35.65). The STDEV was also marginally higher for the waterjet cut glass (4.87) than the diamond sawn glass (2.69).

3.2.2.2 6-12mm cullet size

The average results observed (Figure 10) indicate that there was minimal difference between the resultant flexural strength of the material cut using waterjet and diamond saw. The waterjet cut material (avg. R 22.67, STDEV 2.7) was marginally stronger than the diamond sawn glass (avg. R 21.56, STDEV 2.57).

3.2.2.3 Comparison of cullet size

The results indicate that the material created from 0-2mm cullet size is stronger than that made from 6-12mm for both waterjet cut and diamond saw cutting processes (Figure 10).

Previous research (8) also indicated that recycled glass material produced from 0-2mm grain size was stronger than that made by 6-12mm cullet size.

The samples in previous research were created by sintering cullet in individual refractory moulds (instead of cut from a large sheet). This production process created samples with irregular edges (Figure 11).

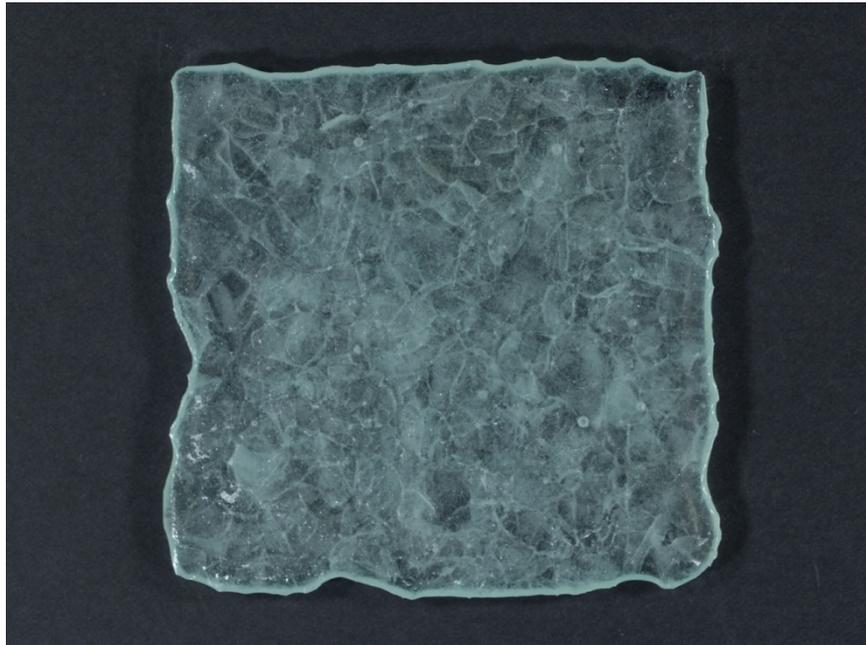


Figure 11

This was due to the nature of the cullet material and production process. As the glass was sintered at 880°C it did not fully melt to fill the mould and produce smooth edges.

Therefore the cullet grain size greatly affected the evenness of the edge. Using a smaller grain size enabled greater packing of the mould, resulting in smoother edges (Figure 12).



Figure 12

The previous research noted a high level of standard deviation in flexural strength of samples produced with larger grain size, corresponding with a lower average flexural strength. This raised the possibility that the edge quality and variable evenness could affect the flexural strength.

In order to address this question, the current research standardised the specimens by using the same cutting process to produce samples from sheets of each grain size, removing the additional variable of the edge evenness.

By removing the variable of the edge evenness, the current research indicates that the material made from smaller cullet particles (0-2mm) has a higher flexural strength than that produced using 6-12mm cullet size, confirming earlier research.

It was noted that the standard deviation in flexural strength of samples for both grain sizes was similar. This suggests that the unevenness in edge quality affects the standard deviation of flexural strength but that the material made using the smaller grain size has an higher flexural strength overall.

4. CONCLUSION

The tests indicate that diamond scoring using a hand held tool, which results in a break of the glass as opposed to erosion of material, creates an edge surface with a consistently low range of values for surface roughness. Glass cut in this way was found to have the highest level of flexural strength.

Abrasive waterjet cutting resulted in an edge surface that displayed the greatest degree of surface roughness. However, as shown in Figure 8, although the average range of

surface roughness of the diamond sawn glass was lower than that for the abrasive waterjet cut edge, the outlying values of peaks and troughs were close to those of the awj cut edge.

It is argued that this resulted in similar levels of flexural strength of the awj and diamond sawn glass, as evidenced in Figure 9 and Figure 10. This corresponds with Griffith's theory (9) which states that the flaws introduced into brittle materials by cutting – as indicated by the surface roughness value – will encourage fracture from the edge when subjected to an applied load. The edge roughness is therefore a critical element in the strength of brittle materials including glass.

The tests indicated that the recycled glass sheet produced using cullet in the range of 0-2mm had a higher flexural strength to that made using 6-12mm sized cullet.

4.1 Areas for further investigation

- Effect of post-processing to create an arised edge to diamond-scored glass
- Comparative impact tests
- Thermal resistance tests to assess how stress is distributed internally
- Optimising cutting and post-processing to improve flexural strength
- Investigation into reasons for higher flexural strength of recycled glass sheet created from smaller cullet size

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