Evaluation of the Use of TinGlass Construction Unit in Precast Concrete Elements

Vassilios Bugas

A thesis submitted in partial fulfilment of the requirements of the University of Brighton for the degree of Doctor of Philosophy

School of Environment and Technology

College of Life, Health and Physical Sciences

University of Brighton

December 2014

Abstract

The United Kingdom collects more container glass through its recycling program than can be returned to closed-loop recycling. This imbalance is particularly acute for pubglass (wine and beer bottles). Commingled glass (mixed clear, green and brown container glass) needs sorting by colour, and this limits its applicability. There is a need to find secondary uses for commingled waste glass on a large scale.

A novel material, TinGlass Concrete (TGC), is proposed for partial replacement of concrete by waste glass cullet of any colour, impurity and granules' size, by using the concept of Tin Glass Construction Unit (TGCU). The TGCU is an innovative product patented at the University of Brighton comprising mixed glass cullet fused in a tin-plated steel can. The steel can forms a permanent fused-on mould; it can be sourced from waste stream. It is proposed to use TGCUs in precast concrete by embedding them into concrete elements, cubes and beams, during casting. To establish how well TGC could reproduce properties of conventional concrete, a series of tests in compression and flexure have been performed.

The TGC products, TinGlass Concrete Cubes (TGCCs) and TinGlass Concrete Beams (TGCBs), were prepared in the same way as their counterparts (control elements), by using the same concrete mix and curing procedure (and steel reinforcement for the beams). For TGCC preparation, a TGCU has been embedded in concrete cube of 10 cm on the side at casting stage. This corresponds to the replacement of 25% concrete by waste materials comprising a TGCU. The compressive strength of TGCCs well reproduces (or even exceeds) that for the control cubes.

A modified methodology based on ASTM C 1260 standard has been developed for assessing ASR in concrete cubes. After the modified ASR test, the volume expansion in the TGCCs was 0.5% on average, and in the control cubes without TGCU it was 2%. The compressive strength of TGCCs after the modified ASR test was slightly higher than that for the control cubes after identical ASR test.

The flexural test used simply supported beams with single-point central load for the 15x15x71 cm^3 beams reinforced by three steel rods of 6 mm in diameter and length of 0.67 m in the tension part. The TGC beams were prepared as identical to the control beams but with a number of TGCUs embedded at casting stage (from 4 to 6 TGCUs in a beam). Comparison of flexural properties of TGC beams with the control beams has shown reasonable agreement. The environmental impact of the TGC was assessed regarding avoidance of pubglass landfilling and replacement of non-renewable materials in concrete production by waste materials. Estimates for embodied energy and embodied carbon dioxide (eCO2) for TGC are made on conservative basis.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DISCLAIMER

I hereby certify that the attached report is my own work except where otherwise indicated. I have identified my sources of information; in particular I have put in quotation marks any passages that have been quoted word-for-word, and identified their origins.

Signed:………………………………………………………………….

Date:…………………………………………………………………

ACKNOWLEDGEMENTS

I wish to extend my deepest gratitude and appreciation to my supervisors Dr Kassim Gidado, Dr Maria Diakoumi, Dr Elena Sazhina, and to Dr Elizabeth Manzanares and Dr Lyuba Mikhalovska as the consultants on the project, for their unstinting support and guidance throughout the project.

I also owe a deep debt of gratitude to Dr Kenneth Ip and Professor Andrew Miller for the expertise and guidance they provided on material selection throughout the initial stage of the project. The expertise and help of Dr David Pope, Dr David Pearce and Dr Patrick Palmer of School of Environment and Technology are gratefully acknowledged. Professor S. Dritsos of University of Patras, Greece is warmly thanked for his evaluation of the project ideas and consultations.

I am indebted to Professor Marie Harder and her colleagues at Waste and Energy Research group (University of Brighton) for their expertise and support of my research, and to Ms Zoe Osmond, Director of Green Growth Platform for developing the links to industry.

I am grateful to the Faculty of Science and Engineering technical team, in particular to Mr Tony Brown and Mr George Rowden, for their invaluable assistance in the mechanical engineering laboratory. Mr Peter Mathers and all the staff in Civil Technical laboratories deserve my warmest appreciation for their extensive help with the experimental programme.

I am indebted to my wife and sons for giving me the inspiration to carry through with this project, and for their love and patience throughout my study. I thank my father and mother, my sister and my uncle Othonas, for being my anchor.

I am grateful to my friends in Greece for their support and encouragement. The support of my UK friends, in particular Father Ierotheos Georgiou, Dr Yiannis Kypraios, Mr&Mrs Dimitris and Maria Mamouhas, Mrs Theodora Vandenbosch, Mrs Helen Atkins, Mr Mark Mitchell and Mr Denzal Cummings was invaluable to me and remain so.

I wish to thank the parishioners of the Greek Church in Brighton for their kind friendship and pastoral guidance, in particular Mrs Gloria Papachrysostomou.

I gratefully acknowledge the financial support of the Greek Government.

GLOSSARY OF TERMS

ASR	Alkai Silica Reaction
GBFS	Ground blast furnace slag
EE	Embodied Energy
ECO2	Embodied carbon dioxide
GHG	Greenhouse gas
HPC	High performance concrete
LPC	Low performance concrete
PFA	Pulverised fly ash
Pubglass	Mixed glass, mainly wine and beer bottles
SC	Standard (control) precast concrete cube
SB	Standard (control) precast concrete beam
SET	School of Environment and Technology, UoB
SoCEM	School of Computing, Engineering and Mathematics
Tin can	Tin-plated steel can (*e.g.* baked beans can)
TG	TinGlass produced by fusing glass cullet in tin can
TGC	TinGlass Concrete
	(precast concrete with embedded TGCUs)
TGCC	TinGlass Concrete Cube
TGCB	TinGlass Concrete Beam
TGCU	TinGlass Construction Unit
UoB	University of Brighton

CHAPTER 1
INTRODUCTION

1.0 Introduction

The United Nations policies on environment highlight the role of governments and individuals to commit to sustainable development so that the needs of the present generation can be met without compromising the ability of future generations to meet their own needs, as it is stated in Agenda 21 (Agenda 21, 2002). The Agenda 21 was worked out as an action plan with regards to sustainable development at the *Earth Summit*, the United Nations (UN) conference on Environment and Development held in Rio de Janeiro in 1992. The World Summit on Sustainable Development held in South Africa in 2002 focused on the implementation of Agenda 21 (Agenda 21, 2002). It has been followed by the UN conference on Sustainable Development in 2012 that is frequently called *Rio+20* as it was also held in Rio de Janeiro in 2012 (UN, 2012). This shows the growing concern for sustainability issues on international scale.

The UK Government and industry work together to meet sustainability targets in construction (Construction, 2025). A clear vision of where UK construction should be in 2025 is presented. The need for research effort in sustainable use of materials is highlighted in this document.

Sustainable policies aim to improve resource efficiency, and this implies a commitment to a better materials' recycling. For waste glass, it constitutes an urgent environmental problem (Jani and Hogland, 2014). The best solution to alleviate the environmental impact is to reuse container glass (soda-lime glass bottles and jars), or to remelt it under bottle-to-bottle approach, thus closing the glass recycling loop. However there are significant barriers to closing the loop (Butler and Hooper, 2005). Reusing glass containers requires collection and sorting, followed by transportation back to the original supplier for refilling them with beverages (wine, beer, soft drinks), jams and sauces. Remelting waste glass containers (bottle-to-bottle approach) faces the same labour-intensive collection, sorting and transportation to a specialised glass processing factory; also energy is needed for glass remelting.

This explains why a considerable proportion of mixed waste glass still goes into landfill. As recent estimates show (Richardson et al., 2009), in 2002 only 31% of the domestic and commercial glass waste was recycled in UK, whilst 69% went to landfill. When landfilled, waste glass occupies vast landfill space and for a very long time due to the non-biodegradable nature of glass.

Thus the need for large-scale applications of mixed waste glass is evident. Construction industry offers an attractive way to solve the environmental impact of the waste glass by using it for replacement of non-renewable raw materials going to concrete (Jani and Hogland, 2014).

The construction industry is the largest consumer of raw materials in Europe. Meyer (2009) states that the concrete industry is known to leave an enormous environmental footprint on our planet. The European Construction Technology Platform (ECTP, 2009) estimates that the total amount of construction materials required for construction purposes in Europe exceed 2 billion tonnes per year.

Faced with the challenge of using more sustainable building materials and the need to contribute to agreed targets for low carbon emissions, most European countries have now established National Technology Platforms (NTP, n.d.) to address the future needs of the built environment. Each country's NTP requires focus to be placed on the twin challenge of innovation and industry transformation of products used in the construction sector. Markets must now develop building materials which are made using recycled wastes and which have low carbon footprints and significantly reduced embodied energy.

The potential impact of this pan-European focus is indicated by the situation in the United Kingdom. Research undertaken by the UK Department for Environment, Food and Rural Affairs (DEFRA) has shown that the construction industry in the UK is not only the largest consumer of raw materials but it is also the largest industry. ‘’With the public sector responsible for 40% of EU construction activity and buildings responsible for 36% of EU CO_2 emissions, public sector construction needs to be sustainable and innovative.'' (DEFRA, 2011)

However, the surge towards effective NTP implementation contains almost as many threats as opportunities. Indeed, Soronis (1996) indicates that competitiveness in this new era depends on the ability to adapt to these new environmentally challenging circumstances. The innovative approaches to greening of the concrete industry are discussed by Meyer (2009). He suggests replacing, as much as possible, concrete, and especially Portland cement, by waste products.

Concrete is the most commonly used building material in construction today. Maier and Durham (2012) state that: "The production of Portland cement (PC) requires significant amounts of energy and produces significant amounts of carbon dioxide (CO_2). Carbon dioxide is a greenhouse gas, and is believed to be a main contributor to global warming. Most of the CO_2 produced comes from the high temperature kilns used in PC production plants. Of all the raw materials used in concrete today, PC is the largest contributor to greenhouse gases." The use of recycled materials to replace PC is common practice and has been for many years. Meyer (2009) reviews the uses of fly ash, recycled tires, post-consumer glass and other recycled materials, for this purpose.

Glass is potentially a very attractive additive to concrete as presented in Section 1.1. The similar densities of cement and glass mean that the replacement of one with the other will create very little weight deviation between products. The use of recycled waste glasses in Portland cement and concrete has attracted a lot of research interest (Shi and Zheng, 2007). In laboratory experiments, it has been shown that very fine glass powder undergoes beneficial pozzolanic reactions in the concrete and could replace up to 30% of cement (Shayan and Xu, 2004). The authors estimate that glass particles shall be finer than 38 microns for a good compressive strength of concrete. Although the use of fine particles is an effective solution for glass in concrete, the crushing and grinding of glass to a very fine size represents a significant cost.

Consequently, there are studies evaluating the use of coarse glass in concrete to overcome the cost associated with crushing glass to fine powders (Idir et al., 2010). A number of studies have been done by several researchers to study the influence of particle size, colour and percentage of glass used in concrete (Saccani and Bignozzi, 2010; Lee et al., 2011). In general, the limiting factor is the influence of alkali-silica reaction (ASR). The reaction products of alkali–silica-reaction (ASR) are expansive and lead to crack formation and deterioration of mechanical properties of the concrete (Ferraris, 1995). The concept of ASR is presented in Section 2.4.

An extensive review of properties of fresh and hardened concrete is done by Kovler and Roussel (2011). The authors review the influence of recycled aggregates on mechanical properties of hardened concrete. As it stated in the paper, 'mixed color waste recycled glass cannot be reused in glass industry' (Kovler and Roussel, 2011) and this calls for using recycled glass as an admixture to concrete. High percentage of coarse glass cullet would usually worsen concrete properties when directly added to concrete, and this sets motivation for current research.

1.1 Motivation

The requirements of future buildings are likely to be very demanding in terms of cost, environmental credibility and structural reliability. The first European Union Sustainable Development Strategy (EU SDS) was adopted by the European Council in Goteborg in 2001. The next EU SDS was ratified in 2006 by the Council of the European Union, and it incorporated the policy measures adopted by the European Council in Barcelona in 2002 and the main findings of the World Summit on Sustainable Development in Johannesburg, 2002. The latest report based on the new targets of the EU SDS was produced in 2009. The EU SDS upholds the principles of environmental protection, economic prosperity and the meeting of international responsibilities to ensure that the EU's internal and external policies are consistent with global sustainable development. A summary of the EU SDS Policy is given in 2009 Review of the EU Sustainable Development Strategy (EU SDS, 2009). The research conducted for the current thesis is based on the guidelines of the EU SDS. Specific emphasis is placed on:

- The EU SDS programme on the Conservation and Management of Resources which attempts to improve the management of natural resources and avoid their over-exploitation. This requires improving resource efficiency to reduce the overall use of non-renewable natural resources and the related environmental impacts of raw materials use.

- The EU SDS programme on Sustainable Consumption and Production which identifies the operational objectives and targets needed to promote sustainable consumption and production patterns. This requires member states to improve the environmental performance of products and processes, and encourages their uptake by business and consumers. The EU should try to find ways to increase its global market share in the field of environmental technologies and eco-innovations.

The focus of the present research on using coarse mixed waste glass via implementation of TinGlass Construction Unit (TGCU; the patent is shown in Appendix 1.1) into conventional precast concrete elements is entirely consistent with the EU programme on Conservation and Management of Resources.

Mixed container glass used in the research is traditionally deposited in landfill sites as a waste material. This is reinforcing the point that previously designated waste material can be used to improve environmental sustainability.

Furthermore, and entirely consistent with the programme on Sustainable Consumption and Production, this thesis evaluates the potential of the TGCU-based eco-innovative product as a replacement for an equivalent volume of concrete, thus saving non-renewable materials and energy for concrete production.

Glass is regarded by this thesis as an ideal waste stream for reuse as the source to produce a higher value product because there is simply so much of it. According to the DEFRA (2011), in the 10 year period from 1999 to 2009, UK packaging recycling rate has increased from 34% to 62%. Glass represents 25% of recycled packaging waste. The glass recycling target for 2012 is unchanged from 2011 at 81%. However, "Whilst the recycling figures for glass look really impressive, remelt have been declining in real terms since 2006" (DEFRA, 2011). The point being made is that more glass is recycled as waste material in open-loop processes than recycled back into new glass products (remelt) in closed-loop processes.

The DEFRA study adds that a tonne of glass sent for remelt saves 0.3 tonnes of CO_2 equivalent, while open-loop recycling such as for use in aggregates creates no carbon saving. Commingled glass collection (non-colour specific) favours open loop recycling. (Glass Recycling, 2012)

In the UK, the average total glass recycling rate is 61%. Out of it, only about 38% is being sent for remelt, 25% continues to be used for aggregates and the remaining bulk is destined for landfills if no market is found for mixed glass cullet. The price paid for mixed colour glass cullet has also been dropping and is affecting recycling rates. The UK glass bottle and jar recycling rate has decreased from 62% in 2009 to 60.7% in 2010 (Miltek, 2012). There have been recent proposals to create incentives for more material to be sent for remelt and thus increase the target for closed loop recycling. The reality is that more waste glass is produced every year with a consequent increase in the volume of glass entering the waste stream not only in the UK but internationally as well.

The major aim of environmental authorities is to reduce the disposal of postconsumer glass in landfill and to divert it to economically viable glass product streams. A new product using mixed colour glass such as TGCU is desirable and can potentially benefit several communities.

In Hong Kong, only 3% of waste glass is recovered and recycled. This is because Hong Kong does not have a local glass manufacturing industry to set a viable closed-loop recycling. It is essential to find a sustainable alternative to reuse and recycle of waste glass (Ling et al., 2011).

This research shall benefit UK local authorities that do not have many options for mixed glass recycling, especially in kerbside collection schemes.

It will also benefit developing countries that are still in the process of identifying waste management strategies. There is an excess of green and brown glass in countries like the UK and the US because of large volume of imported green glass containers (e.g., beer and wine bottles).

Hence, finding alternative outlets to absorb the rejected post-consumer waste glass is a major worldwide concern (Taha and Nounu, 2008).

In this regard, the use of waste recycled glass in construction will be potentially suitable. A reduction in the environmental impact of building construction is perhaps the most important operational issue for the construction industry in the UK. The selection of materials in the design process and the determination of their relative position in a construction project are some of the significant factors which need to be addressed.

Concrete is comprised of cement and aggregates (sand and gravel) as stated in Callister (2007). Reducing the amounts of cement and aggregates in precast concrete therefore leads to a corresponding reduction in the environmental impact of the building materials. The embedding of TGCU in precast construction element has the effect of reducing the net amount of concrete required in the construction as compared to a conventional practice, thereby serving the sustainability and environmental agendas.

The use of waste glass has long been the source of considerable research interest, due to the importance of recycling to sustainable development. However many previous research studies have highlighted a significant deterioration in the mechanical properties when waste glass cullet is added directly into the concrete mixture. This is due to the Alkaline Silicate Reaction (ASR), and Chapter 2 of this thesis will provide a review of developments related to this problem. Chapter 4 will present the results and analysis of original experiments carried out as part of this thesis for evaluating ASR in concrete cubes containing embedded TGCUs.

1.2 Mechanical properties of glass and concrete

Soda-lime glass is the most common commercial glass used for packaging containers such as bottles and for windows. The composition of soda lime glass is typically 60 – 75% silica (SiO_2), 12 – 18% soda (Na_2O), and 5-12% lime (CaO). Some other materials in low percentages can be added for specific properties (CES, 2011). Glass is potentially a very attractive additive to concrete. A comparison of the physical and mechanical properties of concrete and soda-lime glass is detailed in the following Table 1.1

Mechanical Property	Units	Concrete	Soda-lime Glass
Density	kg/m^3	2450	2465
Tensile strength	MPa	1 - 1.5	31 - 35
Young's modulus	GPa	15 - 25	68 - 72
Yield strength (elastic limit)	MPa	1 - 3	30 - 35

Table 1.1 Comparison of physical and mechanical characteristics of concrete and soda-lime glass CES (2011)

Concrete is a mixture of cement, fine aggregate (sand) and coarse aggregate (gravel) (Callister, 2007); it becomes a hardened concrete due to the chemical reaction when water is added in certain proportion, and subsequent curing in water for 28 days. The similar densities of concrete and glass mean that the replacement of one with the other creates very little weight deviation between products. The Table 1.1 also highlights that glass is superior to concrete in its mechanical properties such as strength.

1.3 Environmental evaluation of materials

Various sustainability tools are available for the environmental evaluation of materials, such as in the UK, the Building Research Establishment's Environmental Assessment Method (BREEAM, n.d.), the Leadership in Energy and Environmental Design (LEED) and the Environmental impact and whole life cost analysis for buildings (Envest2, n.d.). In the US, the Building for Environmental and Economic Sustainability (BEES, n.d.) and the Comprehensive Assessment System for Built Environment Efficiency addressing issues and problem pertinent to Japan and Asia (CASBEE, n.d.). The types of environmental evaluation include material resources, embodied energy invested, and transportation.

CES Edupack (CES, 2011), is a software for materials selection. The software package allows for eco-auditing of products and processes including energy input, manufacturing, transport and disposal. What becomes evident as an outcome of any eco-audit evaluation is that re-using and recycling materials can reduce embodied energy (EE) and relative

emissions. The EE associated with mining and extraction, processing and transportation is reduced by recycling or re-using materials or products.
Similarly, the EE for manufacturing of a product is less when it is made from a recycled material rather than from a raw material.

Most EU countries have established re-use and recycling targets that range from 50% to 90% of their construction and demolition waste material. Recycling also costs less than sending recyclable materials for disposal in landfill sites. Placing more and more waste in landfill sites is unsustainable, because doing so simply fuels the demand to find increasing numbers of landfill sites, and such sites are not in infinite supply. Unsurprising, the revenue accrued from landfill tax is increasing every year.

Landfill Tax is a tax on the disposal of waste. It aims to encourage waste producers to produce less waste and to obtain greater value and utility from waste. The tax is charged by weight. In the UK, there are two rates: a standard rate and a lower rate. Inert or inactive waste is subject to the lower rate. The lower rate is charged at £2.50 per tonne and introduced in April 2008. It applies to those inactive (or inert) wastes listed in Schedule 2 of the Landfill Tax (Qualifying Material) Order 1996. This category includes segregated waste such as glass and construction waste such as blocks. A standard rate applies to all other taxable wastes and this includes unclassified municipal and commercial waste. From April 2013 the standard landfill tax rate is £72 per tonne (HMRC, 2012). The lower rate is unchanged.

TGCU is a recyclable product. It could be recycled in a closed-loop in construction recycling scheme. An eco-audit of TGC is presented in Chapter 7.

1.4 Gap in knowledge and aims and objectives

From the review above, it becomes apparent that there are significant advantages in the use of mixed waste glass in concrete. However, previous research studies have highlighted an important issue when coarse waste glass cullet is added directly into the concrete mixture. This is due to the Alkaline Silica Reaction (ASR) that takes place in this case and can lead to a significant deterioration of the mechanical properties of the concrete. This is further explained in Chapter 2. Unless this problem is mitigated the disadvantages of the ASR may outweigh the advantages of using waste glass in the concrete mix.

The gap in knowledge is whether TGCU can be used as an insert in precast concrete elements without compromising the mechanical properties whilst meeting the environmental aims of reduction of waste glass landfilling, and saving of non-renewable materials, energy and emissions associated with concrete production.

This research project integrates knowledge from the fields of sustainability, construction and engineering to assess and develop a new construction material, TGC based on the concept of TGCU embedded in precast concrete element. This has the benefit of allowing a volume of traditional non-renewable materials comprising concrete, to be replaced by the same volume of material from two waste streams.

The proposal to implement the new precast concrete material, TGC, into the construction industry is justified by multiple criteria, not least of which is the fact noted earlier that the construction industry is the largest industrial sector in the UK. This industrial sector continues to be encouraged to reduce its dependence on prime materials and to incorporate more recycled content into its construction projects.

This study searches for a method of turning coarse mixed waste glass into a viable and valuable resource for precast concrete industry. As coarse glass cullet mixed in with concrete has been shown to be susceptible to ASR (Lee et al., 2011), this thesis provides a solution that glass is introduced into concrete in a manner that it is shielded by another material to prevent ASR. Therefore the basis for this research is to investigate the effects of using a glass core contained within a metal shell. The metal shell shields the glass and therefore prevents the development of ASR in concrete.

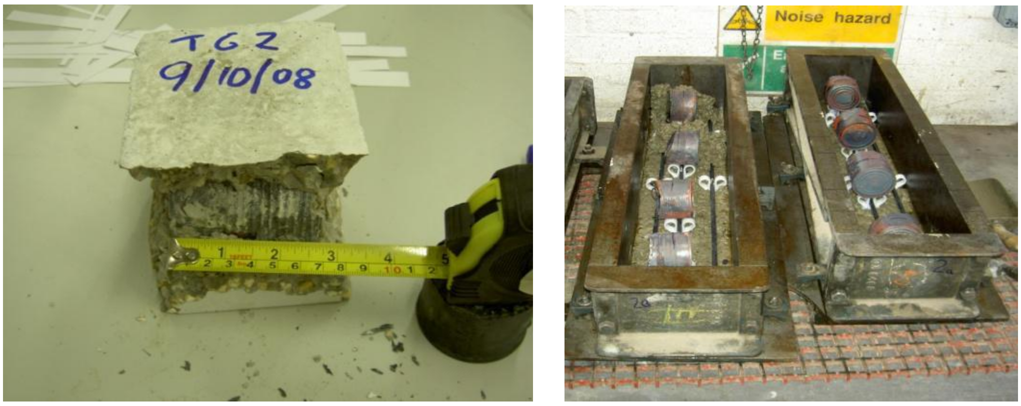
The fused glass core contained within a metal shell is called the Tin Glass Construction Unit (TGCU). TGCU is an eco-innovative product developed by researchers at the University of Brighton, as listed in Appendix 1.1 (PCT Patent No 0708603.6). It is produced by fusing waste glass cullet that is placed in a recycled tin-plated steel can (such as a baked bean tin).

Consequently, two waste streams are processed together, resulting in a construction unit with attractive mechanical properties (Appendix 1.1). Examples of TGCU are shown in Figure 1.1; the dimension of TGCU is about 7 cm in diameter and 7 cm in height. Due to its size it is too big to be classified as aggregate in concrete.

In this thesis, TGCU has been embedded in concrete to make precast concrete cube (TGCC) and beam (TGCB) elements. The preparation procedure and mechanical properties of the precast products have been investigated.

Figure 1.1 The TinGlass Construction Unit (TGCU)

Embedding TGCU in concrete to produce Tin Glass Concrete (TGC) has the potential of using coarse recycled glass for precast elements. Glass granules' size is irrelevant in this case. A TGCU is produced by fusing waste glass cullet (without any preference for colour and size of the glass granules) within a metal shell (waste steel can) that will serve as a barrier between glass and cement when embedded in precast concrete.
Figure 1.2 shows how this study has used recycled glass in concrete.



(a) *(b)*

Figure 1.2 TGCU embedded in precast concrete *(a)* cube and *(b)* beams

The aim of the research is to develop a novel and sustainable technique of producing precast concrete elements by partially replacing concrete with waste materials (including mixed coarse waste glass) without compromising the mechanical properties of the final product.

This technique makes use of the TGCU unit which comprises of waste glass cullet encapsulated in a metal (waste steel) shell and has been developed in previous studies carried out at the University of Brighton. Due to the dimensions of the TGCU unit its application is considered more suited to precast concrete elements

To achieve the above aim, the research focuses on the following objectives:

- To determine a viable and easily repeatable configuration for the embedment of the TGCU units into precast concrete elements that meets industry standards.

- To determine the compressive strength of concrete with embedded TGCU units and compare it to conventional concrete. Sample preparation and testing to be carried out in accordance with current codes of practice (British Standards).

- To determine the flexural strength of reinforced concrete beams with embedded TGCU units and compare it to conventional reinforced concrete beams. Sample preparation and testing to be carried out in accordance with current codes of practice (British Standards).

- To assess the effect of the Alkali Silica Reaction (ASR) on the concrete elements with embedded TGCU units in accordance with current codes of practice (ASTM).

- To assess the environmental benefits of partially replacing concrete with waste materials by embedding TGCU units into precast concrete elements.

To achieve the research aim and objectives, the following methodology is proposed:

1. Design and preparation of TGC cubes (TGCC) and TGC beams (TGCB).

2. Design of the experiment for assessment of the alkali-silica reaction (ASR) in TGC. This addresses the fact that the TGCU is not a gravel aggregate as stipulated in the standard ASR test (ASTM C 1260) but a macro-component.

3. Characterisation of TGCC performance in compression tests. This includes the comparison between TGCCs, and control precast concrete cubes, when both were subjected to alkali immersion for prolonged period at elevated temperature, and then tested in compression.

4. Characterisation of TGCB performance in flexural bending tests, on the basis of alignment and number of TGCUs embedded in a precast beam.

5. Environmental evaluation of the TGC precast elements. This involves assessing embodied energy, carbon footprint, and life cycle assessment of the new product, and discussion on eco-accounting methodology for it.

The motivation for this research will be extensively discussed in the next section. Here it can be briefly summarized as following:

- to recycle coarse mixed glass in concrete products in response to government and industry directives supporting the use of recycled materials in construction as a means of landfill avoidance;

- to decrease the depletion of non-renewable materials going into concrete production.

This is the first study of TGC involving TGCC and TGCB as the new products. The target is to gather relevant data that will contribute towards finding an appropriate application for TGC as a new material for construction industry.

This research aims to surmount a knowledge gap by providing reliable experimental data on TGC, and analysing its viability for using coarse mixed waste glass in precast concrete elements.

- The research study introduces the concept of adding a macro-component constituent (TGCU) to concrete. Contrary to other studies, it is not used as a replacement for individual components of concrete (sand, cement, gravel). Instead, the TGCU is used to replace an equivalent volume of the whole concrete.

- The performance of the new material is investigated according to the methods recommended by the relevant ASTM and British Standards.

- As an illustration of the modification of standards relevant to TGCU embedded in precast concrete, this thesis has developed a modified ASR test (ASTM C 1260) as discussed in Chapter 4. It specifically addresses the fact that the replacement material is a macro-component in precast concrete.

- Furthermore, this study shall encourage research in life cycle analysis for waste glass. It creates the window of opportunity for excess of mixed waste glass to be recycled instead of being landfilled. This kind of new research can have an impact onto new government policies and legislation.

1.5 Layout of Thesis

The present thesis is organized into eight chapters. After introduction in Chapter 1, the review of existing knowledge in the area is the subject of the Chapter 2.

The methodology for design of production processes for the TGC cubes and beams are described in detail in Chapter 3. The TGC cubes and beams used in this research are prepared by embedding TGCUs into liquid concrete mixture at casting stage. Testing in compression and flexure is performed to the existing British and European standards.

Chapter 4 describes the design of modified ASR test for TGC based on existing ASTM standards. The obtained experimental results on TGCCs against SCs (standard precast concrete cubes) are analysed.

Chapter 5 details and compares the compressive strength tests on TGC cubes (with embedded TGCUs) vs. control (conventional) concrete cubes. Analysis of the results, discussion and areas of further investigation are presented.

Chapter 6 provides a comparison between the flexural strength of SBs (standard concrete beams) and TGCBs (concrete beams with embedded TGCUs). The conventional steel rod reinforcement is the same both for TGCBs and SBs. Analysis of the results, discussion and areas of further investigation are also presented.

Chapter 7 designs an approach for environmental evaluation of the TGC based on the embodied energy (EE) of the TGCU and the EE of the concrete replaced by the glass. An assessment of the energy efficiency shall take into account that the EE for TGCU under laboratory conditions is bound to be much higher than under future industrial implementation of TGCU production.

Chapter 8 is the discussion-and-conclusions chapter. It addresses the results of the mechanical properties testing of TGC against control precast concrete elements from the perspective of the research hypothesis, and indicates the degree and nature of its applicability. A summary of the whole research programme including why this research was conducted, how the objectives were achieved, and the results and conclusions of the work undertaken, is presented. Finally, some recommendations for future work are suggested to carry the outcomes of this work forward.

Various information is included in the Appendices to supplement the main text within this Thesis.

CHAPTER 2

REVIEW OF LITERATURE

2.0 Introduction

The motivation for this research is seen in the need to recycle mixed waste glass in large quantities in concrete products. This is in response to the government and industry directives supporting the use of recycled materials in construction as a means of landfill avoidance, and decreasing the depletion of virgin raw materials.

This research project has investigated the production requirements and mechanical properties of concrete structures containing embedded TinGlass Construction Units (TGCUs) in precast cubes (TGCC) and beams (TGCB). TGCU is produced by fusing waste glass cullet that is placed in a recycled steel can. The use of TGCU reduces the amount of concrete needed for the precast structure.

The aim of this thesis has been to characterise two innovative precast concrete products TGCC and TGCB in terms of their production benefits or limitations, and in terms of their mechanical properties, in order to identify a suitable application.

Precast concrete is produced by casting concrete in a mould which is then cured under controlled conditions. Precast concrete products are predominantly sourced from within the UK. There are over 800 precast factories across the country. Moulds can be designed to be customized and precast concrete has the potential to be made in any shape. Therefore, precast concrete has many applications and manufactured to be fit for purpose and compliant with British Standard requirements (Precast Concrete, 2008).

Furthermore, precast products have reduced the environmental impact of other industries by using their by-products. Precast products can safely incorporate materials such as blast furnace slag (from the iron and steel industry) and fuel ash (from coal-fired power stations). There is intensive literature in this area (Ozkan, 2008).

The research project has integrated knowledge from the fields of sustainability, construction and engineering, and this chapter aims to review the state-of-art with the emphasis on the use of waste glass in concrete. Section 2.1 presents a literature review of the construction industry and its environmental impact. Section 2.2 considers the issues and challenges raised by recycling of waste glass and Section 2.3 presents a small-scale study in Brighton, England, that pinpoints the practical issues of implementing a waste glass recycling system. Section 2.4 discusses in detail the Alkali-Silica reaction (ASR). In Section 2.5, current developments in using waste glass as an additive to concrete mixture are reviewed, with emphasis on the influence of alkali-silica reaction. In Section 2.6, the underlying principles and standards for mechanical testing of precast concrete elements are covered. In Sections 2.7 and 2.8, research studies on TGCU initiatives undertaken by other students at the University of Brighton that predate this study are reviewed with the emphasis placed on their relevance to the present study.

2.1 The construction industry and its environmental impact

Buildings are responsible for almost half of the UK's carbon emissions, about one third of landfill waste and a quarter of all raw materials used in the economy (SSC, 2008). The current scope of sustainable development in the construction industry is focused on (SSC, 2008):

- The reduction of greenhouse gas (GHG's) emissions associated with the manufacture of construction materials and their transport (DTI, 2012)
- The reduction of construction, demolition and excavation (CD&E) waste placed in landfill sites.

There is an imperative need to change current unsustainable patterns of consumption by implementing production prototypes made of materials that are appropriate for reuse, recycling and recovery and which also promote and develop manufacturing processes that reduce the demands on energy and decrease greenhouse gas (CO_2) emissions.

The total UK waste generation by sector is shown in Fig. 2.1. In 2008 (Waste Data Overview, 2011), the largest contributing sector was construction and demolition (101mt), followed by mining and quarrying (86mt), commercial (67.3mt) and household sources (31.5mt).

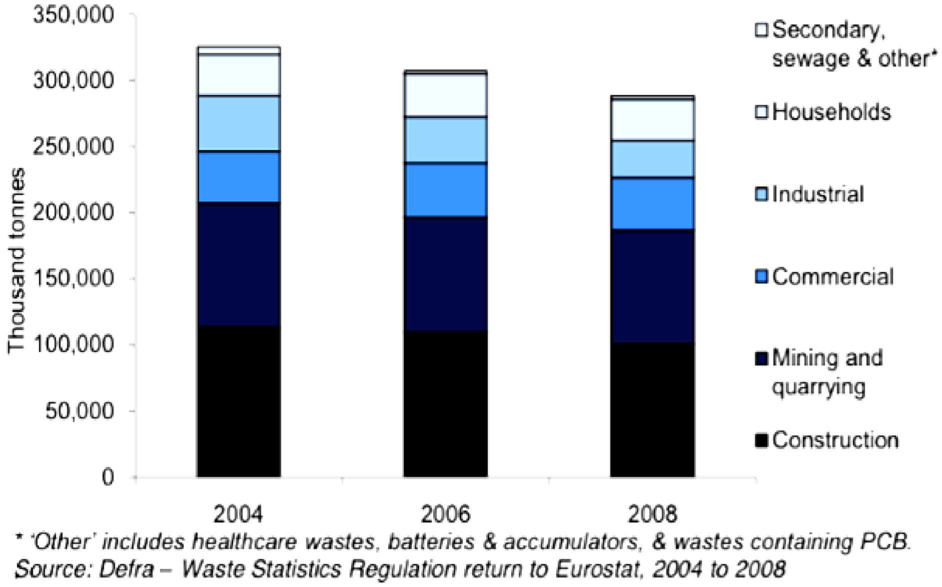


Figure 2.1. UK waste generation by sector, 2004 to 2008 (Waste Data Overview, 2011).

The EU Waste Framework Directive 2004/12/EC (EU, 2004/12/EC) contains a target for the reuse, recycling and recovery of 70% of construction and demolition waste by 2020:

- Governments are encouraged to put in place the aggregates' levy that promotes the use of recycled materials to replace virgin aggregates.
- Regarding the construction industry, a target is set to halve the amount of construction, demolition and excavation waste going into landfill sites by 2012.

Construction, Demolition and Excavation (CD&E) waste constitutes a significant part of what specialists call the environmental impact of construction activities. Re-use and recycling of CD&E waste suitable for reprocessing into aggregates (particularly demolition and earthworks) has increased. Fig. 2.2 shows the DEFRA statistics for the construction industry and cites the following observations (DEFRA, 2012b):

- In 2008, 53 million tonnes were recycled and a further 11 million tones were spread on exempt sites (usually land reclamation, agricultural improvement or infrastructure projects). The remaining 22 million tonnes were sent to landfill as waste.
- Between 1999 and 2008 the proportion of construction and demolition waste recycled by crushers and screeners has increase from 35% to 61%. The

proportion of construction waste sent to landfill has decreased from 37% to 22% and the amount of waste going to exempt sites has fallen from 27% to 13%.

The 2008 Strategy for Sustainable Construction has a target of reducing CD&E waste to landfill by 50% by 2012 compared to 2008 (SSC, 2008; CD&E Waste, 2010). There has been a slowdown in the building section since 2008 and construction waste is not expected to rise above the 2008 level. The target for construction waste sent to landfill for 2012 is around 11%.

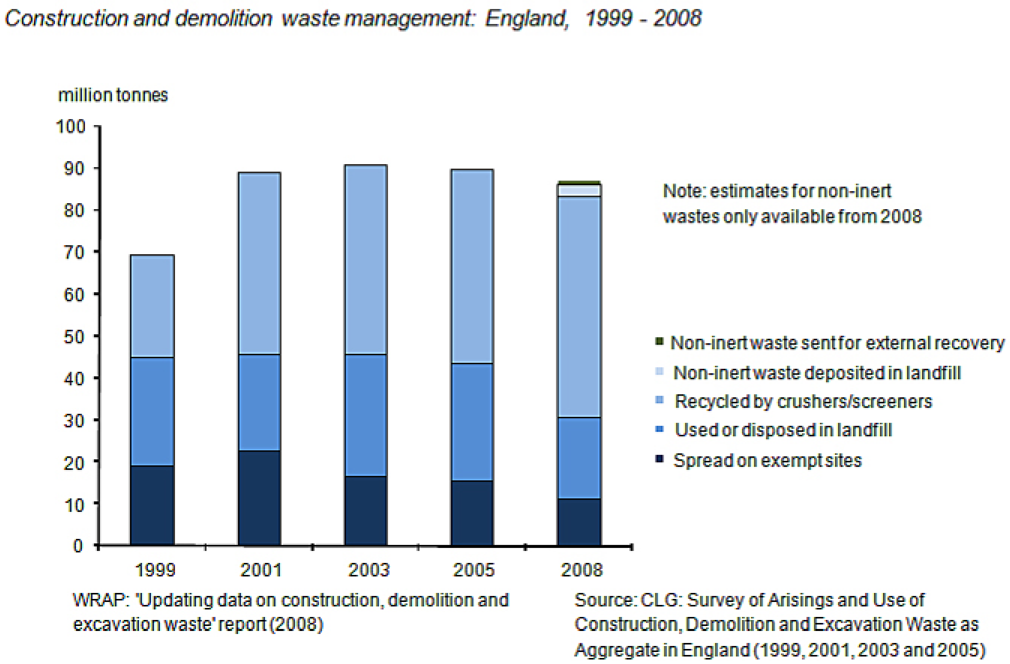


Figure 2.2. Quantities designated for disposal in landfill, recycling, (DEFRA, 2012d)

An understanding of the nature of the issues facing the UK in relation to its European and national policy agendas on recycling can be facilitated by providing a brief snapshot of the situation regarding material production in the construction industry. In the precast concrete sector, around 800 factories are responsible for producing over 36 million tonnes of precast concrete products (worth over £2.3 billion) every year in the UK (Precast Concrete, 2008).

Many precast concrete products incorporate a high recyclable content with end-product performance compliant with British Standards. According to a report produced by the Supply Chain Resource Efficiency Sector (Precast Concrete, 2008) for every tonne of precast concrete produced in 2006:

- 28% of cementitious materials used were secondary materials e.g. pulverised fuel ash (PFA) or ground granulated blast furnace slag (GGBS).
- 16% of the aggregates used were recycled or secondary aggregates. Producers of block pavers and precast elements routinely use recycled materials derived from their own concrete production waste as an aggregate.
- 3kg of packaging materials were used, of which 82% was timber and 17% plastic.
- 32kg of waste was produced, of which 29% was recycled onsite, 57% recycled offsite and 14% was landfilled.

Precast products have the characteristic of sharing the service life of the structure on which they are used. When used for recycling, precast concrete products can be crushed to form a recycled aggregate which can be used in a number of applications when the end of their service life is reached. It is estimated (Precast Concrete, 2008) that 90% of concrete products are currently either reused or recycled. The precast concrete industry is expected to meet the 2012 target of waste sent to landfill.

2.2 Waste glass: issues and challenges regarding re-use and recycling

European and UK government policies encourage the diversion of waste material away from landfill sites, by systematic approach to reusing and recycling initiatives that minimise the quantity of waste material designated for disposal. This strategy is represented by a hierarchy triangle shown schematically in Fig. 2.3.

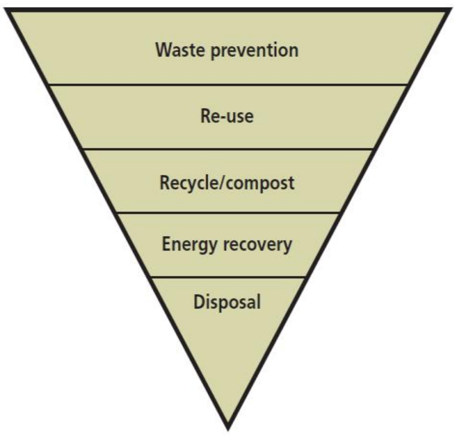


Figure 2.3 Waste reduction hierarchy triangle (DEFRA, 2012b)

Reflecting the European perspective, Government waste strategy (DEFRA, 2012c) makes explicit mention of two EU directives in this policy area:

- The EU Landfill Directive which sets targets for recycling and recovery for household and municipal waste.
- The EU Packaging and Waste Directive that places recycling and recovery obligations upon all businesses in the packaging supply chain.

DEFRA's strategy promotes the development of an increased number of initiatives that aim to divert waste material away from landfill sites and which support research initiatives that are needed to improve the recycling of waste material.

A broad consensus is reached on the conclusion that research into sustainable development must contain inquiry into 'decision support projects', including what some researchers call 'visionary concepts'. It is generally accepted that research of this type is instrumental to any credible attempt to tackle problems which are of both a global and a regional nature. The draft Strategy for Sustainable Construction (SSC, 2008) indicates a possible approach to decision support projects: referring, as it does, to a need to promote inter-disciplinary and trans-disciplinary initiatives that involve social and natural sciences and which attempt to bridge the gap between science, policy-making and implementation.

Drawing on SSC's recommendation, the present research can be placed squarely in the category of 'visionary concepts'. It is a response to the need to divert waste from landfill sites by investigating the potential of a new prototype product for the construction industry. The proposed product, TGC, will use only materials drawn from household and municipal waste streams; it can be reused and recycled at the end of its usual life.

Figures from DEFRA (DEFRA, 2012b) reveal that 290 million tonnes of annual waste are produced in the UK from its households, commerce and industry. Suitable landfill sites are diminishing which means that the ongoing quantity of waste material that needs to be addressed by policy makers represents a major environmental challenge. This challenge is set to increase. DEFRA estimates that the rate of growth in the total quantity of household waste will double in twenty years – household waste accounts for around 32 million tonnes of the overall total of national waste but household waste is growing at a rate between 3-4% a year.

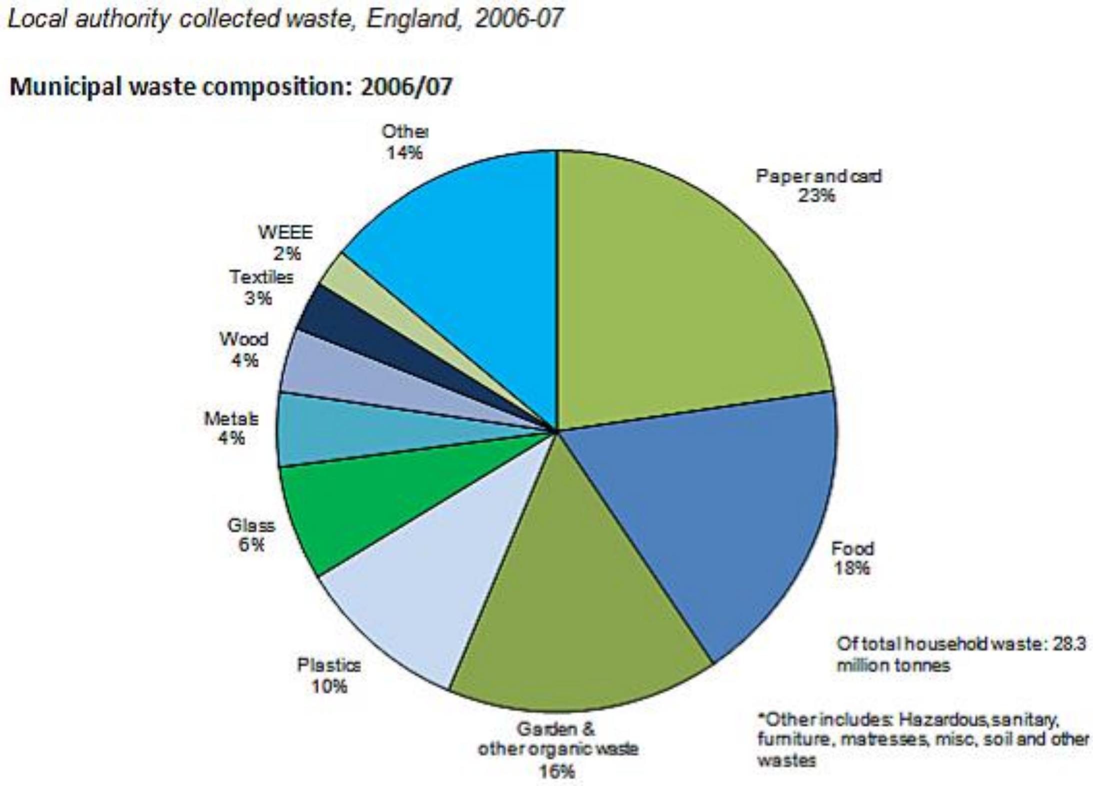


Figure 2.4 UK Household waste composition England 2006-07 (DEFRA, 2012b).

Figure 2.4 shows the composition of household waste in England in 2006-07. Around 6% of household waste material is glass. Only a fraction of this waste material is recycled. In the UK, around 2 million tonnes of container glass will enter the waste stream every year. When these figures are compared to most other European countries, the UK's recycling rate is relatively poor, several European countries are able to achieve a recycling rate of over 80% (DEFRA, 2012b).

The use of recycled glass as a material component in the manufacture of new glass results in a consequent reduction in CO_2 emissions. Current glass recycling initiatives display a total saving of approximately 186,000 tonnes of CO_2 emissions when recycled glass is used (ENVIROS, 2003). It is evident that great environmental benefit results from using increased amounts of recycled glass as a feed material in the manufacture of new glass. Also, glass fibre sector absorbs around 15,000 tonnes of recycled glass each year (ENVIROS, 2003).

The problem for environmentalists and policy makers is that UK manufacturers produce mainly clear glass; however, it is mainly green and brown glass (pub glass) which is collected. Large-scale application for mixed granulated glass include road aggregate, filtration and pressure blasting (Greenblast, n. d.).The report (ENVIROS, 2003) reveals, however, that the use of recycled glass in aggregate or filtration applications would result in a net increase in CO_2 emissions. Such applications, from a global climate change perspective, cannot be encouraged. Ultimately, the best environmental option would be for surplus recycled glass to be exported to foreign glass manufacturers, but this strategy would impact on transportation issues and labour-intensive sorting.

Any researcher or policymaker attempting to address the issue of using recycled glass to reduce environmental damage and improve sustainability must deal with the challenges and contradictions presented by the use of recycled glass. Helpfully, for this research project, ENVIROS (2003) lists the available end of life options of glass. These options are:

1. Glass is manufactured from virgin raw materials and waste containers are disposed to landfill at the end of their life i.e. a base case of no glass recycling
2. Glass is recycled and used as a feedstock for the manufacture of new glass containers.
3. Glass is recycled and used as a feedstock for the manufacture of glass fibre insulation.
4. Glass is recycled and used as an aggregate substituting quarried materials.
5. Glass is recycled and used as a filtration media substituting quarried sand or gravel.
6. Glass is recycled and used as a shot blast abrasive.
7. Glass is recycled and used as an additive in clay brick manufacture.

Utilizing the ‘visionary concept’, this present work would like to propose another option, No 8, related to the number 4 above:

8. Glass is recycled and used in precast concrete as Tin Glass construction Unit, TGCU (Appendix 1)

TGCU is not a conventional concrete aggregate (gravel). It is granulated glass re-melted in a tin-plated steel can. TGCU has the potential of using the excess of mixed waste glass that cannot be absorbed by UK glass manufacturers. As TGCU replaces an equal volume of concrete when embedded to make precast blocks or beams, there is an additional beneficial environmental impact of producing less concrete.

2.3 Waste glass recycling challenges – an example

As this research has previously noted, there are a number of issues affecting glass recycling. Some of these are aggravated by the rapid production and increased levels of consumption of glass, which can then lead to its increased wastage. An illustrative example for purposes of analysis is the experience of wine consumption in the UK. Wine is mostly imported and bottled in green glass but UK glass manufacturers need clear glass for producing glass packaging for UK products like jams, sauces and similar foodstuffs.

The number of bottles of wine drunk per head of the population per year has considerably grown. The option of returning wine bottles to their source of origin for refilling is not widely applied even for European wine producers, and it is even more costly for far destinations as Australia and Latin America. The costs of preparation and transportation that are required to return bottles for refilling overseas may have caused landfilling the bottles rather than recycling them.

It needs to be stressed by the present research study that issues of glass wastage and low levels of recycling are problems not limited to developed countries like the United Kingdom. These issues are global problems. For example, Hong Kong generates approximately 33 tonnes of waste glass every day. 98% of this waste glass is deposited in landfill sites because the territory's glass recycling rate is exceptionally low due to its lack of a glass manufacturing industry (Ling et al, 2011). Even countries and regions with adequate recycling and collection procedures in place may have only a few glass manufactures or wine producers in existence. In such cases, recycling measures would require waste glass to be transported over very long distances, which would leave a considerable carbon footprint on the eco-system.

Research undertaken in collaboration with Magpie Coop, (Jones, 2008) a social enterprise company in Brighton, England, reveals the practical problems of integrating waste glass recycling into the sustainability agenda. Magpie Coop, which has an established glass collection service, has been collecting waste material from a network of pubs and restaurants in Brighton since 1990. The study on the company's collection activities reveals that whilst clear glass can readily be re-used and recycled in the UK, there is no real market for pub glass, green and brown glass, such as from beer and wine bottles. A second issue uncovered by the study was the scale of the distances Magpie Coop's glass collection had to be transported before the process of granulation. The pub glass collected in Brighton, on the English coast, first of all had to be transported by van to Crawley where it was then reloaded onto a truck bound for Scotland (or even overseas) from where it was eventually granulated (Jones-Mantle, 2008)

There is clearly the need to create a range of feasible applications for waste glass products. Hence the current study's investigation of visionary uses of waste glass in the construction industry. Using glass cullet as replacement for aggregates in concrete is hindered by a known challenge of alkali-silica reaction that is reviewed in next section.

2.4 Alkali-Silica Reaction

The Alkali-Silica Reaction (ASR) is a chemical reaction between the silica present in the aggregates and the hydroxide ions (OH) present in the pore water of concrete as noted by Ferraris (1995).

Cement itself is made by roasting together crushed chalk (calcium carbonate) and clay slurry in giant steel kilns to a temperature of 1,450°C (Winter, 2012). During this process water and carbon dioxide escape, and the dry residue is crushed to form cement powder. This powder is mainly a mixture of calcium and aluminium silicates:

$$3CaCO_{3(s)} + Al_4Si_4O_{10}(OH)_{8(s)} \rightarrow Ca_3SiO_{5(s)} + Al_4Si_3O_{12} + 4H_2O_{(g)} + 3CO_{2(g)}$$

During the roasting process, some calcium carbonate decomposes to form calcium oxide, but does not then become neutralised by the clay; so the cement, and the subsequent concrete, contain unreacted calcium oxide, a strong base:

$$CaCO_{3(s)} \rightarrow CaO_{(s)} + CO_{2(g)}$$

Concrete is quite a porous material and, as rain water soaks through it, the calcium oxide dissolves to form calcium hydroxide solution (limewater):

$CaO_{(s)} + H_2O_{(l)} \rightarrow Ca(OH)_{2(aq)}$

Calcium hydroxide is also alkaline. The level of alkali in the powder determines the levels of additives to combine to make viable concrete.

Silica, SiO_2, being the oxide of a non-metallic element, is acidic and, in the presence of water, reacts with the alkali in the cement in the previously mentioned 'Alkali-Silica Reaction' (ASR) - sometimes called the 'Alkali-Aggregate Reaction' (AAR). It is believed that the hydroxyl ions penetrate the surface of the aggregate and breakdown the silicon-oxygen bonds (Ferraris, 1995).

The reaction results in cracks opening in star formation, a process commonly called ‘concrete cancer’. Within these gaps a calcium alkali silicate gel can accumulate, which expands on absorbing water thereby increasing the size of the crack. In wintertime, in cool temperate and in cold climates, the deterioration is accelerated due to freeze-thawing of the water within the cracks. Ferraris (1995) observes that this phenomenon is not new, being first discovered in the 1940s by civil engineers in the USA.

The conditions that lead to the deleterious expansion and cracking associated with ASR are:

- Reactive forms of silica minerals that are present in some aggregate sources,
- A sufficiently high concentration of soluble alkalis, sodium and potassium,
- Exposure of the concrete member to moisture

A mechanism for ASR is thus summarised accordingly: a gel is formed that swells as it draws water from the surrounding cement paste.

Alkali hydroxide + reactive silica gel → reaction product (alkali-silica gel)

The amount of gel formed in the concrete depends on the amount and type of silica and alkali hydroxide concentration.

When absorbing water, these gels expand, thus inducing pressure and subsequent cracking of the aggregate and surrounding paste:

Gel reaction product + moisture → expansion

Very often, the cracks appear in a star formation. Once this has occurred, water is able to penetrate the concrete to a deeper level.

When glass cullet is used in concrete mixes, ASR-related mechanical deterioration is suspected. Many research studies have indicated that ASR can be reduced by the addition of chemical substances and using an appropriate size of glass powder (Lee et al., 2011; Ozkan and Yuksel, 2008; Shi and Zheng, 2007; Shayan and Xu, 2004), but the ASR problem is far from being fully resolved. An overview of using waste glass cullet for aggregate or cement replacement in concrete is presented in the next section.

2.5 Current state-of-art of using waste glass as an additive to concrete

The ASR reactivity of glass cullet added to concrete has been extensively studied to assess the effects of:

- particle size
- glass colour
- chemical additives as ASR suppressants
- cement composition

A good review for precast concrete with added glass cullet has been presented in recent literature (Lee et al., 2011; Shi and Zheng, 2007; Shayan and Xu, 2004; Ling et al., 2011). The particle size of glass aggregate has a major influence on ASR expansion since the rate of reaction depends mainly on the surface areas of reactive silica aggregate. Furthermore, it is also expected that the ASR expansion increases with increasing glass aggregate content in concrete (Lee, 2011). Hence these are intrinsic uncertainties when adding glass cullet directly into concrete mixture.

Most of the ASR studies utilized the accelerated mortar bar test in accordance with ASTM C1260 (80°C, 1 N NaOH solution) (ASTM C 1260) According to this standard, ASR-related expansions less than 0.10% at 16 days after casting are indicative of innocuous behaviour, while those between 0.10% and 0.20% at the same period of time are indicative of both innocuous and deleterious behaviour. The expansions more than 0.20% at 16 days after casting are indicative of potentially deleterious expansion.

2.5.1 Use of fine glass powders

There is general agreement that fine glass powders have beneficial pozzolanic reactions in the concrete (Shi et al., 2005; Karamberi and Moutsatsou, 2005; Shayan and Xu , 2004 ; Shao, 2000). This means that very fine glass particles behave like cement in the mix. It has been indicated that micro-scale glass powders undergo pozzolanic reactions with cement hydrates, forming secondary calcium silicate hydrate (C-S-H) (Dyar and Dhir, 2001).

The study by Shayan and Xu (2004) showed that fine glass granules of size <10 μm incorporated into the concrete could replace up to 30% of cement in some concrete mixes with satisfactory compressive strength.

Work by Karamberi and Moutsatsou (2005) focused on the use of three different types of glass such as flint cullet, green and amber glass as a component of cementitious materials or as aggregates. They found that the use of glass powder of < 90 μm in size led to a decrease in ASR expansion.

The UK Waste and Resources Action Programme (WRAP) sponsored project ConGlassCrete II (2004) carried out a study of pozzolanic reaction of ground glass. The most important results from this work are that glass reactivity in cementous systems is more related to fineness than waste glass source or degree of contamination.
The source includes the influence of glass colour, and contamination refers to the presence for example of Cr_2O_3 and PbO in sampled glasses. To utilise the pozzolanic property of glass, glass cullets must be ground to a fine size; the costs of glass grinding is quite high as it can be seen from Appendix 2.1 (CES, 2011).

2.5.2 Use of coarse glass particles

Unlike fine glass powder, it has been shown that the use of coarse glass particles are usually deleterious to concrete due to alkali–silica reaction (ASR) and therefore limits their use as aggregate. In general, the ASR expansion increases with increasing particle size of glass aggregate (Lee et al., 2011: 2611).

Lee et al. (2011) investigated the influence of using different particle sizes of recycled glass, casting methods and pozzolanic materials in reducing the expansion due to ASR of concrete blocks prepared with the use of crushed glass as fine aggregate. They found that ASR expansion increases with increasing particle sizes of glass, in particular for glass size more than 600 µm. They also observed a reduction in flexural strength following exposure to alkali environment. Some of their results are reproduced here.

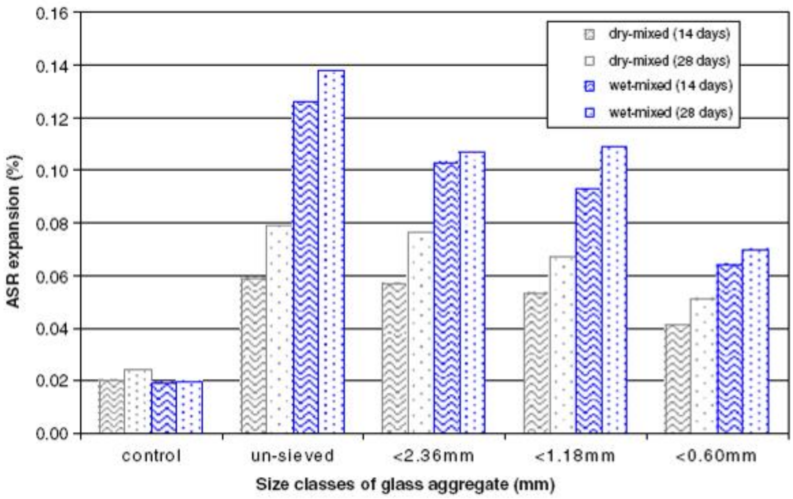
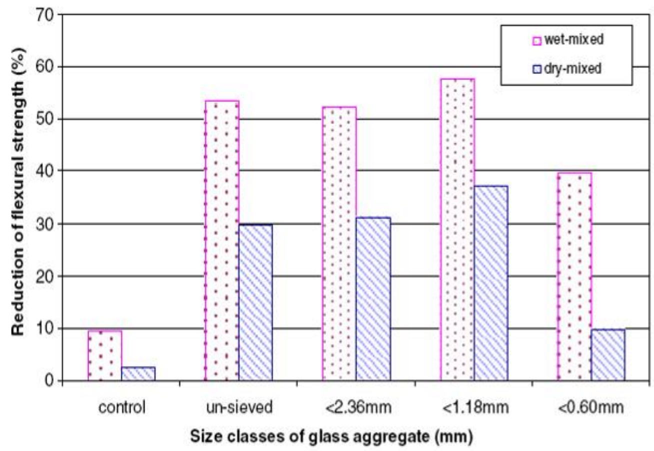


Fig. 2. Effect of different particles size of glass on ASR expansion at 14 and 28 days.

Figure 2.5a Reproduction of Fig.2 from Lee (2011): Effect of particle size of glass on ASR expansion at 14 and 28 days



Effect of wet-mixed and dry-mixed on the reduction of flexural strength after exposed to rapid environment (1N NaOH at 80 °C) for 14 days.

Figure 2.5b Reproduction of Fig.5 from Lee (2011): Reduction of flexural strength after exposure to NaOH environment

The effect of green glass cullet as an aggregate replacement was investigated by Sangha et al. (2004). The work involved aggregate replacement by cullet identically matched with the particle size distribution of the 10 mm all-in flint natural aggregate. The cullet was produced by an implosion process and their SEM studies showed better bonding was achieved between the glass aggregate and its surrounding cement matrix. Concretes made with cullet replacement were found to be stronger throughout the replacement range (10–60%) studied. Strength gains between 28 days and two years for concrete with 60% cullet replacement were 100% greater than for the control concrete, for both compressive and tensile strengths. Sangha et al. (2004) also observed that the performance of glass cullet was equally good with either Portland cement or cement containing ground granulated blast furnace slag. The authors did not carry out ASR studies.

2.5.3 Use of ASR suppressors

The problem of ASR is not restricted to glass aggregate in concrete. The ASTM C1260 has been developed to assess the potential of ASR expansion and reactivity of various aggregate additives in concrete. Mladenovic (2004) studied ASR when lightweight aggregates (LWAs) are used in concrete. Four LWAs - expanded vermiculite, expanded clay, expanded glass and perlite - were studied using the accelerated mortar bar test, ASTM C 1260 and the combined scanning electron microscopy–energy dispersive X-ray technique (SEM–EDX). The results showed that neither the expanded vermiculite nor the expanded clay exhibited any potential ASR. On the other hand, in the case of the aggregates containing a glassy phase (expanded glass and perlite), the results of SEM–EDX analysis showed serious decomposition of aggregate texture due to ASR, although no deleterious expansion was observed in the accelerated mortar bar test, emphasizing the need for better test criteria.

Lam (2007) studied the use of waste glass cullet as an aggregate in construction materials. He reported a negligible ASR expansion for 25% or less of waste glass cullet. For mixes with higher glass content, the incorporation of mineral admixtures such as pulverized fuel ash (PFA) and metakaolin was able to suppress the ASR

Supplementary cementitious materials (SCM) have been used to replace cement in concrete for many years. Common cement replacements used today are fly ash, silica fume and ground granulated blast furnace slag (GGBFS). GGBFS, also referred to as slag cement, is a by-product of the iron manufacturing industry. Research shows that SCM can be added as ASR suppressors in cement containing waste glass. Ozkan (2008) investigated the properties of mortars produced with cement containing waste glass, fly ash (FA) and granulated blast furnace slag (GBFS). In their work mortars made with Portland cement were studied. Waste glass powder, FA and GBFS replaced cement in the specimen samples. In general, compressive strength decreased as replacement levels increased. The ASR test results using ASTM C 1260 showed that the colour of the glass, clear, green and brown, had no significant effect on ASR expansion. Combination of waste glass with FA or GBFS is more effective than the usage of waste glass alone, as it was concluded in the paper by Ozkan (2008).

Topcu (2008) conducted a similar study. In his study, mortar bars were produced by using three different colours of glass in four different quantities as fine aggregate by weight, and the effects of these glass aggregates on ASR were investigated, according to ASTM C 1260. Additionally, in order to reduce the expansions of mortars, 10% and 20% fly ash (FA) as mineral admixture and 1% and 2% Li_2CO_3 as chemical admixture were incorporated by weight in the cement and their effects on expansion were examined. It was observed that among white, green and brown glass aggregates, white aggregate caused the greatest expansion. In addition, expansion increased with an increase in the amount of glass. According to the test results, it is seen that high FA and Li_2CO_3 replacement levels are required to produce mortars resilient to ASR.

The above examples relating to use of ASR suppressors is consistent with the recommendations from BRE (2004) regarding the detail guidance for new constructions. BRE suggests the use of Silica fume or Metakaolin or Lithium salts in the concrete mix. 'Silica fume is a by-product of the manufacture of silica metal or Ferro-silicon alloys.' 'Metakaolin is a material produced by the calcining of purified kaolinite clay'. 'Lithium salts are: lithium hydroxide or lithium nitrate', (BRE, 2004)

Recent studies have shown that fine glass powder can also be used as ASR suppressor. Earlier work by Shayan and Xu (2004) showed that addition of glass has a potential to replace traditional pozzolans such as fly ash and silica fume.

Taha and Nounu (2008 a,b) had proposed that the addition of lithium nitrate and pozzolanic glass powder, which are used in concrete as cement replacements, can contribute to ASR suppression. Nassar and Soroushian (2011) carried out field pavement construction projects investigating the use of concrete containing milled waste glass. Several test results indicated that concrete containing WG offered excellent strength and durability attributes when compared with normal concrete. In another study, Nassar and Soroushian (2012) investigated the use of two waste materials, i.e., waste glass and demolished concrete (as recycled aggregate). The recycled aggregate replaced 100% crushed limestone virgin aggregate and in addition fine milled glass powder of average particle size of 13 µm (20% by weight of cement) was added.

The use of milled glass powder as partial replacement for cement effectively overcame the limitation of using recycled concrete aggregate (higher water absorption) without detrimental ASR expansion (Ismail and Al-Hashimi, 2009). This work is viewed to facilitate broad-based use of recycled aggregate and diversion of large quantities of landfilled-bound construction concrete waste, and waste mixed-coloured glass.

However, where waste glass (WG) is concerned, the most interesting results to date relate to the findings by several researchers that the combination of fine glass powders and coarse glass aggregates have positive consequences in concrete as the pozzolinic activity of fine glass powder can function as an effective suppressor to reduce ASR expansion of concrete mixtures containing coarse glass (Idir et al., 2010).

Although the use of fine particles is an effective solution for glass in concrete, the crushing of glass represents a significant cost to obtain an efficient fineness of glass (almost equivalent to cement). Idir et al. (2010) studied the combination of fine glass powder and coarse glass particles. Mortar bars containing 20% of different glass particle sizes showed that particle sizes under 1 mm were not deleterious in terms of alkali–silica reaction (ASR). Effects of fine-grinded glass on expansion of mortar bars containing mixes containing 20% coarse glass and various amounts of fine glass led to the reduction of mortar expansion due to coarse particles; moreover, fine fraction increased the compressive strength of mortars.

In addition to studies focusing on waste glass, there are also studies relating to the concrete or cement. ConGlassCrete II (2004) found that cement alkali content of the concrete made with WG affects ASR dramatically, the larger the alkali content of the cement, the more pronounced the ASR expansion. Lee et al. (2011) investigated the influence of using different particle sizes of recycled glass, casting methods and pozzolanic materials in reducing the expansion due to ASR of concrete cubes prepared with the use of crushed glass as fine aggregate. They found that i) ASR expansion reduced with reducing particle sizes of glass, in particular for glass size less than 600 µm and ii) The dry-mixed method for preparation of concrete was very efficient in reducing the ASR expansion especially for larger particle size (highly reactive) glass aggregate. For a given mix proportion, the reduction of expansion is up to about 44% as compared with the wet-mixed method. It was understood by the mortar bars made by dry-mixed method had higher porosity which was able to accommodate more gel produced due to ASR resulting in lower expansion and cracks.

2.5.4 Summary

Summarizing the above studies covered by this review, incorporation of very fine glass powder into concrete tends to stop the ASR tendency and improves mechanical properties of the concrete. Fine glass powder has been tested to BS EN 450 standards and found to be a comparable pozzolan to fly ash.

Using coarse glass as a replacement aggregate increased ASR. However, in admixtures with PFA, GBFS, lithium salts, metakaolin, and fine glass powder, ASR expansion can be suppressed. Although in some studies no deleterious expansion was observed in the accelerated mortar bar test, electron microscopy investigation can show serious decomposition of aggregate texture or high porosity, emphasizing the need for better test criteria.

2.6 Underlying principles and standards for testing of precast concrete

Concrete is a particle-reinforced composite with Portland cement as typical binding matrix; the dispersed phase is fine aggregate (sand) and coarse aggregate (gravel). Both matrix and dispersed phase are ceramic materials, and this explains mechanical properties of concrete: it is a brittle material susceptible to failure by crack propagation. Its tensile strength is approximately 10 to 15 times smaller than its compressive strength (Callister, 2007).

Compression remains the most popular method of testing concrete due to the difficulty in applying uniaxial tension to a concrete element. The tensile properties are assessed by indirect methods, in flexure and under split-cylinder test. The measured properties are, respectively, flexural strength and splitting tensile strength, and they are widely used in design of concrete structures. In particular, tensile properties of concrete are important for the design of non-reinforced concrete structures such as dams, especially under earthquake conditions. The standard for determining splitting tensile strength is set by ASTM C496 / C496M – 11. The split-cylinder test is applied to a cylindrical specimen placed horizontally between the loading surfaces of a compression testing machine. The horizontal tensile stress is estimated based on diameter and length of the cylinder, and the applied compression load (Neville, 1995). The load is increased until the cylinder is split into two halves along the vertical plane, and the compression load at failure is recorded.

Some of the references in Section 2.5 used this test for tensile strength analysis (Sangha et al., 2004; Shi and Zheng, 2007; Taha and Nounu, 2008). The Split-Cylinder test has not been used in this present study but should be considered for future work. It shall be noted that STS correlates with compressive strength as shown by Zain et al. (2002) and

Khayat et al. (1995), and hence the compression testing of this work can give some indication of tensile properties when using these correlations.

(a) (b)

Figure 2.6. Test rigs used in this work: (a) compression test rig and (b) central loading flexural test rig

In this thesis, the TGC has been tested under compression (as TGCC) and in flexure (as TGCB) as shown in Fig.2.6. A brief overview of principles and standards of these two methods of mechanical testing is presented below.

2.6.1 Compression testing

Under compression test, a cubic or cylindrical specimen of concrete is placed under platens of compression testing rig. The contact area of the specimen with the platens must be smooth to avoid stress concentrations. It is well-known that concrete is a brittle material and it is susceptible to failure by crack propagation. A considerable effort goes into increasing toughness of concrete, in particular by addding macro-synthetic fibres for reinforcing concrete (TR65, 2007). This is a recent development on the top of traditional reinforcements by steel rods. It is important to use a standard method to compare the compressive strength of the TGCC and control precast concrete cubes. The methodology followed in this thesis is in agreement with the European Standard BS EN 12390-3:2009. According to it, the compressive strength of hardened concrete is obtained by testing the compressive strength of concrete cubes with dimensions 10x10x10 cm^3. For compression testing, Fig.2.7 and Fig.2.8 illustrate compliance. The tests in accordance to BS EN 12390-3:2009 are considered satisfactory when all the cracked faces of the cube are similar to Fig. 2.7, that is, faces are cracked with almost equal symmetry and with little damage to the faces in contact with the platens of the machine.

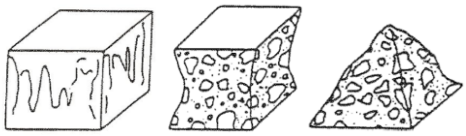


Figure 2.7 Satisfactory failures of cube specimens: All four faces cracked equally are considered to be a satisfactory failure of cube specimens [BS EN 12390-3:2009]

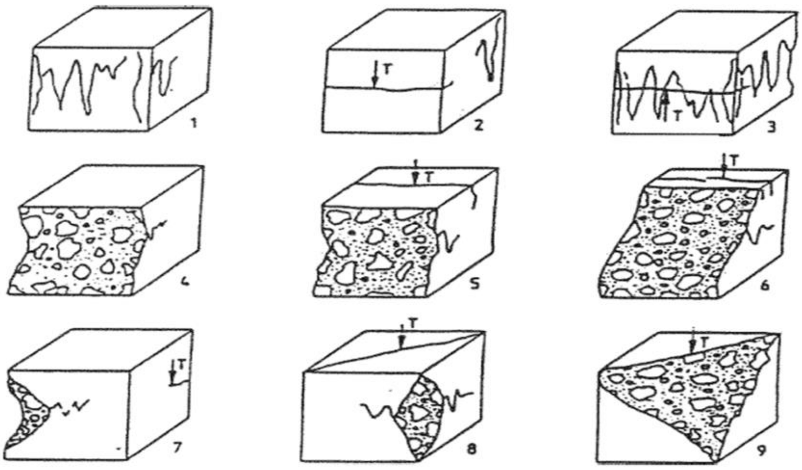


Figure 2.8 Unsatisfactory failures of cube specimens BS EN 12390-3 2009

2.6.2 Flexural testing

The test in bending is an established method for the evaluation of the behaviour of solid bodies, which have been subjected to various types of load. This has been historically studied by great scientists such as Leonardo da Vinci (1452-1519) and Galileo Galilei (1564-1642) who performed experiments in order to determine the strength of bars, beams and wires, as referred to by Gere and Goodno (2012).

Moving on forward to recent research in this field, a test in bending for a simply supported beam with a central load (three-point beam) for measuring the flexural properties of the beams is proposed for brittle materials in many textbooks including Callister and Rethwisch (2011) and Bhatt et al. (2006). As is stated by Bhatt et al.

(2006), “Simply supported beams ... are an important element in pre-cast concrete construction”.

Brittle materials testing and fracture mechanics: Because concrete is a brittle material, it is prone to failure under tension. A test in uniaxial tension for brittle materials is difficult to set up for the following reasons:

- It is difficult to manufacture specimens having the required geometry
- It is difficult to grip a brittle specimen without fracturing them
- The tensile test strength of a brittle material is much lower than strength under compression or bending, because of the crack propagation mechanism. The results may be not reproducible because of the random nature of crack distribution (Callister and Rethwisch, 2011).

Brittle materials are tested in bending rather than in tensile test (Callister and Rethwisch, 2011). The cracks are initiated in the bottom part of a simply supported beam under vertical load, where bending stresses are tensile. Further crack propagation is arrested by the compression part of the beam.

A schematic of the experiment for measuring the load–deflection of a three-point beam is shown in Fig. 2.9. The bending moment and bending stresses for such a beam reach the maximal value at the point of load application (Gere and Goodno, 2011).

There is a variation of deflection along the beam. Deflections reach maximum in the mid-span of the beam as schematically shown in Fig. 2.10. Solid line shows the unloaded beam, whilst dashed line shows the beam under load.

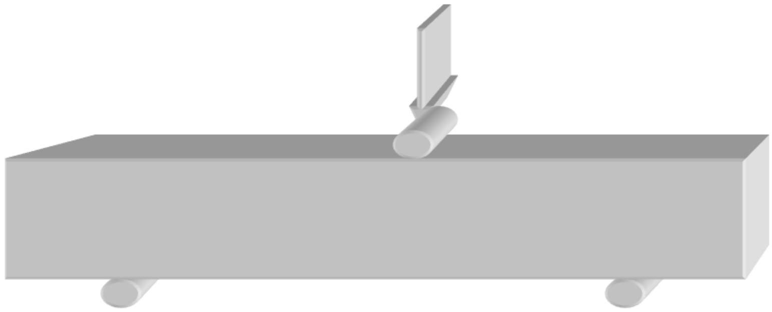


Figure 2.9. Schematic of a three-point beam under central load

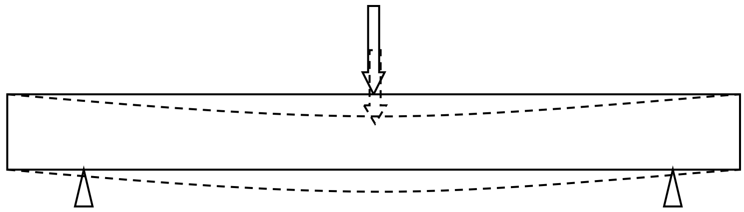


Figure 2.10. Schematic of the deflection of three-point beam under central load (out of scale)

Flexural tresses in elastic regime: For a homogeneous prismatic beam under elastic regime, bending stresses σ are given by (Gere and Goodno, 2011)

$$\sigma = y\frac{M}{I} \qquad \text{(Equation 2.1)}$$

where M is the bending moment, I is the second moment of area for the beam, and y is the distance from neutral axis. The second moment of area for the beam in Fig 2.9 – 2.11 is given by $I = \frac{bh^3}{12}$.

The bending moment M reaches maximal value at the mid-span of three-point beam. From static equilibrium, it follows that it is equal to quarter of the load multiplied by the beam span L (Gere and Goodno, 2011), $M = \frac{FL}{4}$.

The neutral axis is the location of zero bending stresses. Neutral axis under elastic regime is marked by dashed line on the diagram in Fig 2.11, for a beam with rectangular cross-section of height h and width b**:**

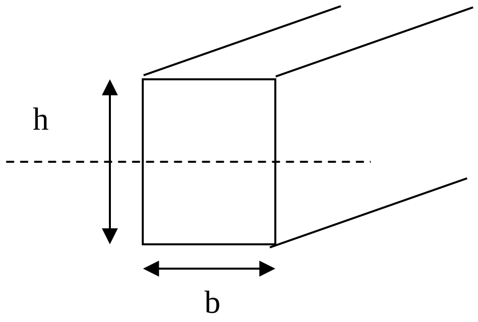


Figure 2.11 Location of neutral axis for a homogeneous beam with a rectangular cross-section of height *h* and width *b*

Hence maximal value of distance from neutral axis is $y = h/2$.

This gives the flexural strength of three-point beam as:

$$\sigma = \frac{3FL}{2bh^2} \qquad \text{(Equation 2.2)}$$

where *F* is the load in Newtons, and all dimensions (*b, h, L*) are in meters.

Shear stress in homogeneous beams reaches maximum value on the neutral axis and it is given by $\tau = \frac{V}{bh}$ where *V* is the shear force. For a load *F* applied to the three-point beam, the shear force is $V = \frac{F}{2}$. The normal stresses are zero at neutral axis whilst shear stresses reach maximum value.

For a long beam, the normal stresses are dominant as being proportional to the bending moment. For a short beam, shear stress becomes important, and this might cause crack orientation at 45° and 135° to the beam axis. This is because normal stresses are zero at neutral axis whilst shear stresses reach maximum value there. Hence the condition of pure shear exists at neutral axis. This result in normal stresses of magnitude of shear stress oriented at 45° and 135° to the beam axis. The resulting diagonal tension can lead to cracking of concrete.

Deflections in a simple beam under central load: The rigorous definition of the deflection: it is the distance between original neutral axis in the unloaded beam, and the neutral axis under load (Gere and Goodno, 2012).
In the experiment, the displacement of the bottom edge of the beam was measured and it was accepted as the deflection of the neutral axis of the beam under load.

The maximal deflection of three-point beam **in elastic regime** is given by (Gere and Goodno, 2011):

$$\delta = \frac{FL^3}{48EI} \qquad \text{(Equation 2.3)}$$

where F is the load in Newtons, δ is the deflection in meters, L is the length (meters) of the beam between the supports, and E (Pascals) is the Young's modulus of the beam material.
As it can be seen, the deflection is proportional to applied load F, and it is inversely proportional to flexural stiffness EI. Thus the slope of load-deflection curve in the elastic regime is determined by the beam's flexural stiffness.

Reinforced beams: Flexural properties of beams can be greatly enhanced with steel rods reinforcement in tension part of the beam. The investigation of the flexural behaviour of reinforced concrete beams in elastic and plastic range is a complex issue, and this is a subject of vast research, in particular by Bhatt et al. (2006); the influence of corrosion on reinforcement properties is assessed by Graef et al. (2008).

Figure 4.4 of Bhatt et al. (2006) shows a typical load-deflection curve illustrating the desirable mode of beam failure, with a large plastic regime. This mode gives an ample warning before failure.
.

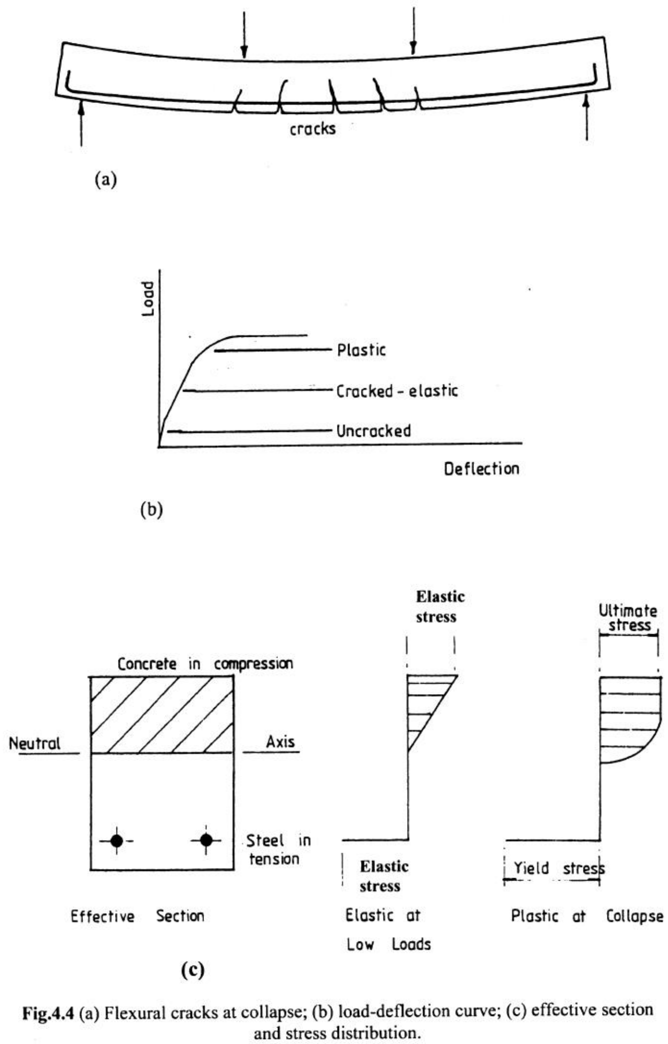


Figure 2.12 Typical cracking pattern, load-deflection curve and stress distribution for singly reinforced concrete beams in flexure (reproduced from Bhatt et al., 2006)

Typical points on the curve show the uncracked, elastic and plastic regimes. In the uncracked regime, the concrete beam behaves as a monolithic beam, with normal bending stresses linearly increasing with the distance from neutral axis. After the onset of first crack, the steel reinforcing rods hold the beam together. This is why the rods are placed in the lower part of the beam under tension. The compression strength of concrete is much higher than its tensile strength. The concrete in compression zone behaves elastically under moderate loads. Finally, the plastic regime starts in compression part of the beam.

A schematic of load-deflection curve for a concrete reinforced beam is given in Fig. 2.13 as reproduced from Concrete Society report TR64 (2007). Linear part of the curve under elastic regime stops with the onset of cracking of concrete, and the non-linear behaviour persists until failure of reinforcing rods.

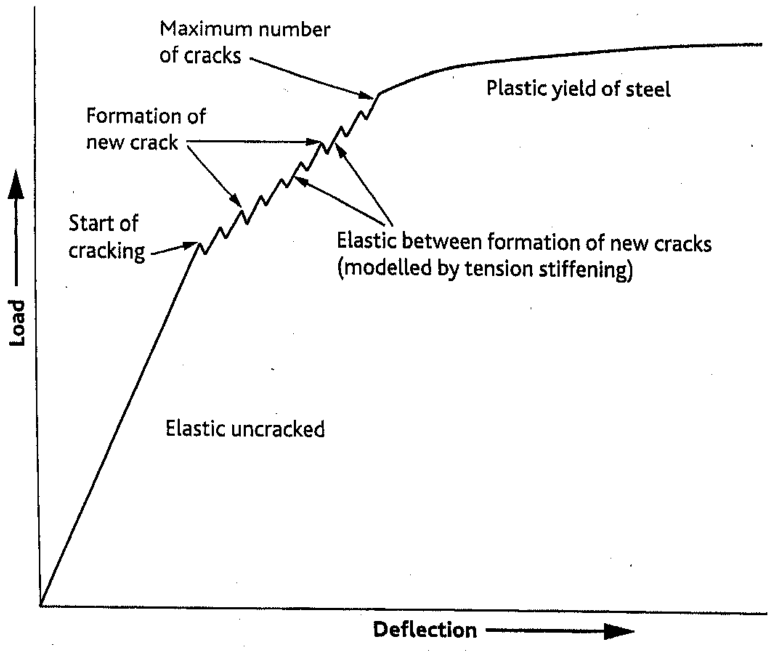


Figure 2.13. Typical load-deflection curve for reinforced concrete slabs
(Reproduced from TR64, 2007)

The area under the curve correlates with the energy absorbed to failure (toughness), and this is an important characteristic in dynamic regime (Callister and Rethwisch, 2011). Toughness of a material is particularly important under seismic conditions and for blast resistance. An initial investigation of TGCBs in dynamic regime was performed under the guidance of Dr D Pearce of University of Brighton. The scope of a vibration test is the evaluation of the dynamic response of a structure. In particular it will give any resonance zone, where large deflection is activated from a small quantity of energy. The frequency spectra of mobility function for three beams were quite close. This means that no new resonances (that is, structural weaknesses) are emerging for novel beams when compared with conventional concrete beams. The results are early findings and no further work was carried out. For reference, the information is given in Appendix 6.1.

The area under the load-deflection curve correlates with the energy absorbed by a beam to failure. This is a key property called flexural toughness and it is widely used in construction industry, especially for fibre-reinforced concrete (Jiabiao et al., 2004; Alani and Beckett, 2013). The equivalent flexural strength is determined from flexural stress – deflection curve (Fig 2.14) on the basis of area under the curve. According to ASTM C 1609 standard, it is determined on a beam of cross-section 150mm x 150mm and at least 500mm for the length of the beam with span of 450mm. The area under the curve up to the beam deflection of 3mm is measured and converted into equivalent flexural stress. The ratio of the equivalent flexural stress to the maximal flexural stress gives the strength ratio Re3. The value of Re3 gives an indication of ductility of concrete composite (Alani and Beckett 2013).

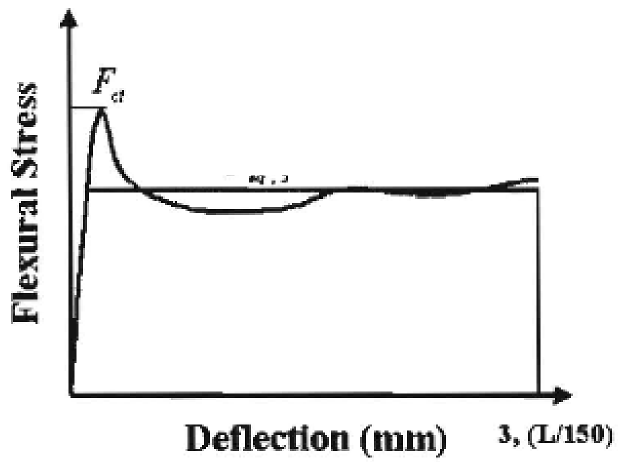
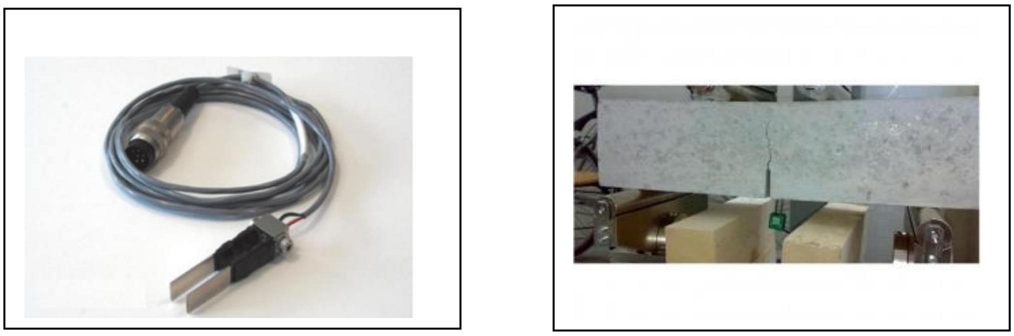


Figure 4 Equivalent flexural strength

Figure 2.14. Equivalent flexural strength for a concrete beam in flexure (Jiabiao et al., 2004)

The crack propagation process can be monitored for a notched beam using the concept of Crack Mouth Opening Displacement (CMOD). A plot of *load – CMOD* can give an important information for fracture mechanics analysis of concrete beam (Zhang and Ansari, 2005). A displacement transducer for measurement of crack opening is essential for the test setup as shown in Fig 2.15.



(a) (b)

Figure 2.15. (a) Displacement transducer for measurement of crack opening; (b) The transducer mounted on the bottom of a notched concrete beam (Controls Group, n.d.)

Whilst the measurements of CMOD and Re3 were beyond the scope of current work due to experimental limitations, it can be recommended for future research

2.7 Current state of research, dissemination and feedback from industry

The background studies for this research were initiated using the facilities in the Glass Workshop Studio (GWS) at the University of Brighton. The GWS was set up around 2006 and it is used by students and staff across University of Brighton. The motivation is to encourage waste glass valorisation and reduce excessive diversion to landfill sites.

The TGCU concept was patented at the University of Brighton in 2007 under the title of 'Construction Unit' (as listed in the Appendix 1.1). The patent abstract states 'A construction unit includes a metal shell in the form of an open-topped waste steel can having a glass core. The glass core is a solid glass core provided by a quantity of waste glass cullet which has been heated in the can to fuse the cullet, before allowing to cool in the can. The construction unit may also provide environmental advantages through the reuse of glass and metal materials.'

TGCU has been the subject of many student projects. A work by Ojomo (2010) went in parallel with the work on this thesis and it represents an example of knowledge dissemination. The research areas were clearly differentiated and intellectual property rights were carefully observed.

Ojomo (2010) reported results of compressive strength tests on cubic concrete blocks with embedded TGCUs which are consistent with the results presented in this study as discussed in a later section (Chapter 5). X-ray diffraction analysis of the interface between the TinGlass and concrete was also conducted by Ojomo (2010) and revealed that there was no significant variation in mineral composition across the interface. Relevant part of her work is reviewed in Section 2.8.

There were several opportunities during the term of this project to meet with industry representatives and solicit their opinion regarding the potential or drawbacks of introducing the TGCU product to the construction market.

Zoe Osmond (2007) of the University of Brighton Business Services had prepared a datasheet about TGCU and its potential applications. It had been distributed to several companies and a list of potential contacts had been drawn. Consultations with some of the contacts raised the issues regarding:

- Alkali-silica reaction
- Energy required to produce TGCU
- Embedding TGCU in concrete under industrial conditions

These issues are discussed in detail below.

Alkali-silica reaction: A meeting with Tarmac representatives (Tarmac, 2008) raised the concern with ASR. Hence this precipitated the investigation of ASR. A methodology for carrying out accelerated ASR for TGCU in precast elements has been developed as presented in Chapter 4.

Another contact was with Remade South East (Remade, 2009) who have questioned the impact of ASR and TGCU integrity if the metal shell is corroded or mechanically pierced and the glass comes into contact with the concrete.

Filippatos (2011) has investigated the effect of corroding TGCU in sea water. He has exposed samples of TGCU to sea water for several days. The study showed that when the sea water corroded the metal shell, the Charpy impact energy of the TGCU was diminished and reverted to that of a solid glass block produced by melting the glass cullet without the metal shell; this indicated that the metal shell contributes significantly to the compressive strength of the TGCU.

Embedding TGCU in concrete under industrial conditions was discussed with Tarmac Building Products, a major UK supplier of concrete products (Tarmac, 2008). The

discussion with Tarmac highlighted that the present mass production scheme for producing precast blocks and beams is not ideal for the incorporation of the TGCU because it would involve an additional step of embedding the TGCU into the concrete mixture.
However, there are encouraging news from another segment of the building industry that is developing new robo-builders. In the USA, Bryson et al. (2005) and Maynard (2005) have designed a robot for paving operation. It involves a robot that incorporates each task-specific piece of machinery used in the concrete paving process into one fully autonomous process.

In Germany, Pritschow et al. (nd) presented a paper on the prototype realisation of a mobile bricklaying robot designed for use on the construction site. It is possible to replace traditional brick laying with computer controlled robotic nozzles which will pipe quick-drying gypsum or concrete to form walls, floors and roofs (Times, 2007).

It has also been reported that the Gantenbein Winery in Switzerland (Robot bricklayer, 2009a) was built using robot bricklayers. The same contractors also built an infinite loop weaving structure in New York using some 7000 bricks to demonstrate the capability of the robot bricklayer (Robot bricklayer, 2009b).

In this scenario, it can be envisioned that the development of more automatic procedures in the construction sector could enable the accurate embedment of TGCUs into concrete elements without the need for additional manual labour.

In addition, the author and colleagues have attended several dissemination opportunities. The author presented the first part of this work in *SB08MED* conference (Bugas et al, 2008) International Conference, Athens. The also presented in the Early-Stage Researchers in Science, Engineering and Technology (SET for Britain) held at the House of Commons in 2009 (SET, 2009).

In addition, there were several participations in Eco-events such as the EcoBuild (2008), London Technology Network (LTN) event in March 2009, the Greenwave Eco-festival in 2008 (Preston Park, Brighton) and the international conference EPPM2012 (Bugas et al., 2012). These are summarized in Appendices 2.2 - 2.4.

2.8 TGCU in precast concrete

A work by Ojomo (2010) was a direct extension of the subject of this thesis and represents on-going knowledge dissemination during current research. It is reviewed in this chapter before the original work is described in Chapter 3 and onwards.

Characterisation of TGCU: Since its development, the procedure for producing TGCU as described in this thesis has been used by other students. Ojomo (2010) prepared several TGCUs and carried out an extensive experimental review of properties of TGCU. This is important for estimating the average values, and standard deviation of physical properties of TGCU, such as its density. Her visual observations and measurement of volume and dimensions of typical TGCUs are summarised below.

Ojomo (2010) has prepared TGCUs as designed by this author, and described in Chapter 3. Table 2.1 shows the visual observations made by Ojomo of TGCUs before embedding these into concrete for compression testing. Table 2.2 shows the TGCU dimensions. The data illustrates some of the difficulty in achieving uniformity in TGCU samples.

Tin Glass number	**Visual Observations**
 Tin Glass 1	A few holes around the side wall of the TGCU
 Tin Glass 2	On the lid and side wall of TGCU, small sections are eroded away The lid does not fully seal the glass
 Tin Glass 3	The lid does not fully seal the glass
 Tin Glass 6	The lid fully seals the glass
 Tin Glass 7	A slight hole on the lid exposing fused glass core A few patches of exposed fused glass on side walls
 Tin Glass 4	The lid does not fully seal the glass
 Tin Glass 10	A hole on the lid exposing fused glass core The lid does not fully seal the glass. A patch of exposed fused glass on the side wall
 Tin Glass 11	Large variation in max-min height The lid does not fully seal the glass, and it is fused to glass core in the inclined position

Table 2.1 Visual inspection of TGCUs before embedding into concrete for a compression test (Ojomo, 2010)

TG No	Max height (mm)	Min height (mm)	Diameter (mm)	Dry weight (g)
1	69.54	67.07	65.80	531
2	84.33	73.14	73.94	716
3	67.16	60.14	73.62	562
4	72.50	69.20	66.80	549
6	62.66	55.84	73.98	593
7	76.19	65.87	72.95	668
10	78.91	71.80	66.38	537
11	84.54	59.35	66.34	535

Table 2.2 Measurements of dimensions and weights of TGCUs listed in Table 2.1 (Ojomo, 2010)

Ojomo (2010) measured the volume of five of the samples using the displacement method described below and reported the density using the dry weight and measured volume. The results are given in Table 2.3.

Measurement of TGCU density: The displacement method for determination of density was used. To get accurate measurements of the TGCU volume, a water displacement method was used where the TGCU was placed in a water-filled immersion container with a spout (as shown in Figure 2.13). The amount of water displaced from the spout after the insertion of a TGCU was measured by means of a measuring cylinder and taken as the TGCU volume.

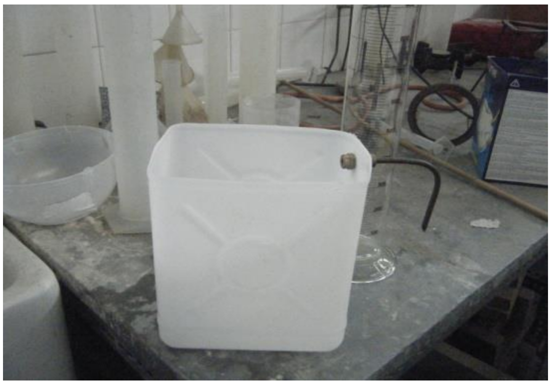


Figure 2.16 Water - filled immersion container for density measurement of TGCUs

The results of density measurement using the immersion technique, for the five TGCU samples from Table 2.2 are recorded in Table 2.3 below.

TGCU No	**Volume**	**Dry weight**	**Wet weight**	**Absorbed water weight**	**Density of dry TGCU**
	cm^3	g	g	g	kg/m^3
1	210.0	531.0	535.0	4.0	2528.6
6	262.0	593.0	595.0	2.0	2263.4
4	211.0	549.0	553.0	4.0	2601.9
2	309.0	716.0	720.0	4.0	2317.2
11	250.0	535.0	538.0	3.0	2140.0
Average	248	585	588	3.4	2370.2
St_Dev	41	77	77	0.9	191

Table 2.3 Experimental estimation of the absorbed water weight and density of TGCUs (Ojomo, 2010)

As can be seen from Table 2.3, the average density is 2370 kg/m^3; the standard deviation is rather high, 191 kg/m^3. This means that with realistic accuracy, the density is about (2400±200) kg/m^3. This is close to density of concrete and thus the weight of a TGC element shall be close to that of an element with the same dimensions but made of conventional precast concrete.

This is important for ergonomic properties, making substitution simple such that embedding TGCU in concrete to make precast element is tantamount to replacing an equal volume of concrete with TGCU.

The volume of absorbed water is about 3cm^3 (this is given by 3g of absorbed water weight divided by water density of 1g/cm^3). This is quite small, about 1.2% (as the ratio of 3 cm^3 by average TGCU volume of 248 cm^3). This shows that TGCUs do not absorb much moisture even when fully immersed into water, and this is an attractive property for moisture resistance.

Further, using the immersion technique, Ojomo measured the density of TGC by embedding TGCU in precast concrete cubes. She reported the density of the concrete cube with TGCU (TGCC) as 2340$\pm$50 kg/m^3 . The density for an identical concrete cube without TGCU (control cube) is estimated as 2300$\pm$10 kg/m^3. This agrees with expectations since the density of TGCU (2400$\pm$200 kg/m^3) is slightly higher than that for the control concrete.

The crystallinity of fused glass in TGCU has been explored by Ojomo (2010) by using PANalytical X-pert PRO X-ray diffractometer at University of Brighton (Appendix 2.5). A much higher degree of crystallinity is observed for the fused glass than that for the original glass cullet before fusing. This indicates that the TGCU glass core is a glass-ceramics with beneficial mechanical properties such as high strength (Callister, 2007).

The bond of TGCU with concrete has been also explored by Ojomo (2010). A concrete cube with embedded TGCU has been sawn in two halves. Visual inspection has revealed a robust bonding between TGCU and concrete.

Powder samples of concrete were drilled at the distances of 1cm, 2 cm and 4cm from the interface of TGCU – concrete for investigation by X-ray diffraction methods by using PANalytical X-pert PRO X-ray diffractometer at University of Brighton. A good encapsulation of TGCU material has been observed: the chemical composition of concrete remained the same for all distances from the interface. For comparison, there was a significant change in chemical composition for a fused glass brick embedded into concrete. There was no protective barrier between glass brick and concrete whilst it is provided by oxidised tin-plated steel can for the TGCU (Appendix 2.5). The good encapsulation of glass core within TGCU is seen as beneficial for preventing the ASR between silica in glass and alkali in cement. The presence of TGCU in a precast element will not interfere with the chemistry of concrete, whilst embedding of glass brick shows the interference.

An electron microscopy investigation of TGCU interface has been performed by Dr M.V. Trenikhin of Institute of Hydrocarbons Processing, Russian Academy of Sciences under FP7 IRSES grant ENSOR project with University of Brighton. The SEM images show good bonding, and the results for chemical composition agree with expectations are shown in Appendix 2.6.

CHAPTER 3

METHODOLOGY OF EXPERIMENTAL PROCEDURES

3.0 Introduction

This chapter introduces the new concept of TinGlass Concrete (TGC). This is a conventional concrete with embedded TinGlass Construction Units (TGCUs). It has been designed by the author to achieve partial replacement of concrete by waste materials in precast structural elements. The innovative precast concrete products are TinGlass Concrete Cube (TGCC) and TinGlass Concrete Beam (TGCB) with TGCUs embedded to make precast concrete cube and beam, respectively.

The manufacture of TGCUs does not require any virgin materials. These are prepared from waste materials, by fusing granulated mixed waste glass in a tin-plated steel can that serves as a permanent fused-on mould. Their production is seen as labour-efficient because sorting of waste glass by colour and chemical composition is not needed. By comparison, a meticulous sorting of waste glass by colour is an essential requirement for conventional remelting of waste glass to make bottles in a closed-loop recycling; production of recycled glass tiles requires both an accurate control over chemical composition and long annealing times, in order to avoid cracks caused by thermal stresses.

The aim of this thesis is to characterise TGCC and TGCB in terms of their production benefits or limitations and in terms of their mechanical properties in order to identify a suitable application. This chapter describes the methodologies applied in this work.

In terms of methodology, the author has made original contribution towards:

- Modification to the production of TGCU from the original patent
- Modification to the standard Accelerated Mortar Bar Test for ASR
- Design of the optimal placement and number of TGCUs in precast concrete elements

The concept of TGCUs is described in the patent (Appendix 1.1). The method of manufacturing TGCUs as set in the patent by Bataineh et al. (2007) has been modified for the preparation of TGCUs suitable for embedding into precast concrete. The TGC production requires TGCUs with the glass core fully enclosed within the metal shell for prevention of ASR.

This has been achieved by the author by placing a metal lid on the top of glass cullet before fusing process, and weighing it down by steel weights. The latter was done to achieve a good bond between the lid and top surface of glass cullet in the tin-plated steel can. The height of glass cullet in the can was steadily decreasing during fusing process, the voids between granules being filled in by melting glass. The weights pressed the lid down for a good contact with the receding surface of glass cullet. This modification represents original work by the author (Bugas et al, 2012).

The Accelerated Mortar Bar Test, ASTM C1260 Standard Test Method for Potential Alkali Reactivity of Aggregates, is a widely used test to detect alkali-silica reactive aggregates. Mortar bars of Portland cement and aggregates under investigation, are placed in 1N NaOH solution at 80°C. The expansion at 16 days after casting is taken as an indication of potential reactivity. This methodology is used to detect the potential for deleterious alkali-silica reactions of aggregate in mortar bars based on monitoring the increase in length of long, thin bars and the increase their volume (Kozlova et al., 2004).

Modifications to the standard ASR test are necessary due to the inability to embed TGCU into the mortar bars specified by the conventional ASTM C1260 methodology. A TGCU has dimensions of diameter of 70 mm and at least 70 mm tall, whist the concrete prismatic bar required by ASTM C1260 has dimensions of 75x75x250 mm. Therefore, for this study, concrete cubes of 100 mm on the side have been used instead of mortar bars, and changes in volume rather than length were monitored.

The Modified ASR Test for testing the occurrence of ASR in precast cubes containing TGCU used in this study is described below. The ASR testing methodology should be applicable to other entities of dimensions much larger than aggregates that are embedded in concrete. This modification represents original work by the author.

The design and preparation of TGC precast elements by embedding TGCUs into liquid concrete mixture at the casting stage constitutes original research by the author. The design of the optimal placement of TGCU in the precast element (cube or beam), and establishing the number of TGCUs in a precast beam, will be described in this chapter.

The roadmap of this part of the research is schematically represented below.

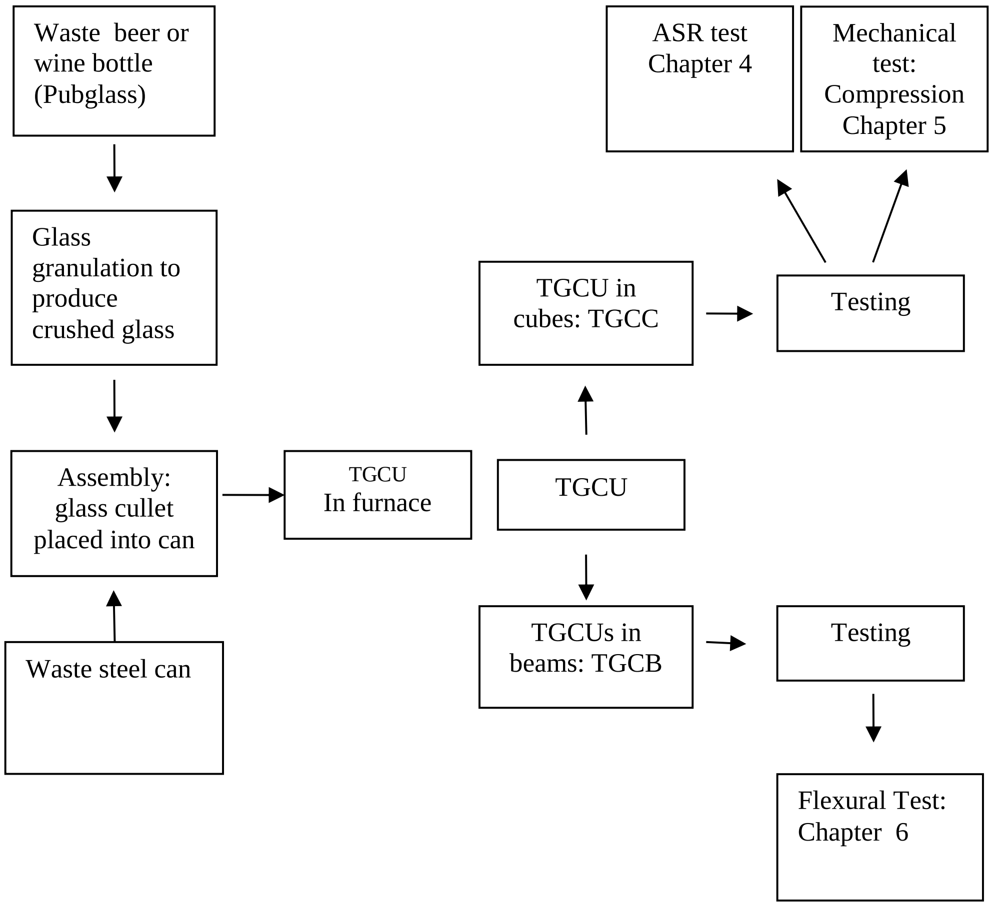


Figure 3.1 A schematic representation of the layout of the research on TGC

This chapter is comprised of Sections 1 – 4 relating to sample preparations. The TGCC specimens were prepared for compression tests (including ASR investigation). The TGCB specimens were prepared for flexural testing. The testing methodology is described in Sections 5 – 7 of this Chapter.

The scope of this chapter is:

- Procedures for the manufacture of the TGCU with typical dimensions of 70 mm in diameter and 70 mm in height.
- Procedures for the preparation of the concrete mix. The ratio of water : cement : sand : aggregate in the mixture is 0.6 :1 :2 :4 conforming to BS1881-125:2005.
- Measurement of density using the water displacement (immersion) method.
- Preparation of the concrete cubes of 100 mm on the side
- Preparation of concrete beams of dimensions 150 x 150 x 710 mm^3.
- Operational procedures for modified ASR Test.
- Operational procedures for compression test.
- Operational procedures for flexural test.

3.1 Preparation of TinGlass Construction Unit (TGCU)

Two waste streams, namely waste green and brown glass (pubglass), and tin-plated steel cans (*e.g.* baked beans cans) are used for TGCU production as shown in Fig. 3.2. Thus all the required materials are sourced from general waste of low economic value.

The required equipment is

- An imploder for granulating waste bottles into glass cullet
- A furnace for glass fusing; furnace should be able to reach 1000°C.

Figure 3.2 Mixed colour glass cullet and tin-plated steel cans for TGCU production

Feasibility studies for TGCU applications have been developed by the author in two directions: (a) precast concrete elements and (b) finishing materials for mortar structures. It has been decided to focus the in-depth research on (a) whilst the results of feasibility studies of TGCUs as finishing materials (such as an eco-alternative to flint walls) were disseminated to the project students of University of Brighton, as it is described in Appendix 8.1.

Novelty of current research for preparation of TGCU: The main problem of the TG preparation as proposed in the TGCU patent (Appendix 1.1) is that it left the top glass surface uncapped exposing the top surface of the solid core. The exposed upper surface of TG is an area of concern due to ASR susceptibility between silica in glass and alkali in cement as discussed in Chapters 2 and 4.

A method of production of TGCU without the exposed upper surface has been developed by the author, using the steel lid of the waste steel can to cap the glass cullet. This is also an effective use of the waste steel can. The lid from the can is placed over the glass granules in the can before putting the assembly for fusing in the furnace (Bugas et al, 2012).

The initial trials have revealed a major difficulty with this otherwise simple idea. The fusing process is gravity-dominated. Molten glass starts to fill in the voids between glass granules, and glass core sags down under the influence of gravity. It fuses intimately with the bottom and side walls of the can but the lid on the can does not fuse well with the glass as a gap is created between the glass and the lid (Bugas et al, 2012).

Following a series of laboratory tests, it has been observed that when the glass granules soften with increasing temperature, most of the gaps between granules get filled resulting in height compaction by approximately 30%, from 110 mm to 70 mm in height. Figure 3.3 shows the resulting glass and tin can after melting in the oven.

Figure 3.3 The height compaction is approximately 30%, from 110 mm to 70 mm

The next stage is the essential and critical modification in the preparation of TGCU. It involves the design and manufacture of a set of specially designated steel weights to be placed on the top of the assembly before the fusing process to help provide a good fused bond between the lid and the glass core of a TGCU. A specially manufactured steel cylinder of 150g weight is placed on the steel lid and it is sufficient for weighing it down during the fusing process, thus providing good bonding with the receding glass cullet.

Figure 3.4 The steel weight for TGCU production designed by the author

A further refinement of the TGCU preparation procedure is designed by the author. The glass granules are sieved following granulation. The finer granules of glass are placed on the top before placing the steel lid, and this result in a very good bonding between the lid and solid glass core. The TGCU with fused lid on the top has been designed to reduce susceptibility to ASR when TGCU is embedded in concrete to prepare precast cubes and beams.

The working steps:

Preparation of the glass: Waste glass was supplied by Magpie Recycling Cooperative (Magpie Coop, n. d.) a social enterprise with an established glass collection service from a network of pubs and restaurants in the Brighton area. The beer and wine bottles were soaked in large containers filled with tap water to remove most of the labels and organic residues. They were taken straight from the container without a thorough cleaning and granulated in the imploder GP1 supplied by Krysteline Ltd (n.d.).

It shall be observed that the soaking step can be omitted under industrial condition for crushing glass bottles. The TGCU preparation is very forgiving for any organic impurities and heterogeneity of glass cullet. TGCU will take any mixture of waste glass cullets with varying chemical compositions and granule sizes.

Preparation of the tin-plated steel cans: Waste tin-plated steel cans were also sourced from Magpie Coop. A typical can (*e.g.* a baked beans tin) was about of 70 mm in diameter and 110 mm in height. Its height reduced after glass cullet fusing to approximately 70 mm. Figure 3.5 shows a typical TGCU sample.

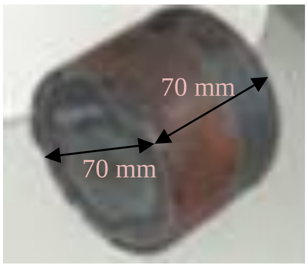


Figure 3.5 A typical TGCU sample

It is noted that aluminium cans (such as sardines' can) are not suitable for TGCU production. An aluminium can will melt before glass is fused. However, as is demonstrated by the author, fusing glass cullet in a sardines' can produces a fused glass brick with a silvery aluminium lining. This can be of relevance for decorative purposes, as shown in Appendix 8.1.

Manufacture of TGCU: The steel can was filled to the top with granulated glass, with the metal lid from the can placed on the top and weighed down by the 150g steel weight. The assembly was placed inside a furnace at room temperature. The furnace used was a 3kW desktop furnace as shown in Figure 3.6. The temperature was ramped up to 950°C for 40 min with the fastest rate allowed by the heating elements of the furnace. Then the temperature was kept constant at 950°C (soaking time). As it is established in the experiment, it takes from 40 minutes to 1 hour at temperature of 950°C to melt the glass. Then the temperature was ramped down with the fastest rate allowed by the heating elements of the furnace.
All these operations were performed without opening the furnace door until it cooled down to room temperature. This made the processing safe and straightforward. This process allowed molten glass to crystallize into glass ceramic of opaque appearance.

Figure 3.6 Photo of Townson Mercer furnace

Characterisation of TGCU: Since its development, the procedure for producing TGCU as described above has been used by collaborators including Ojomo (2010) who has prepared a separate batch of TGCUs and assessed their average density and standard deviation by immersion method. This has been reviewed in Chapter 2.

Measurement of TGCU density: The immersion method for determination of density was used by the author and students. To get accurate measurements of the TGCU volume, a water displacement method was used. A TGCU was placed in a water-filled immersion container with a spout. The amount of water displaced from the spout after the insertion of a TGCU was estimated by using measuring cylinder, and it was taken as the TGCU volume. The results of density measurement using the immersion technique have been given in Chapter 2.

Figure 3.7 The TGCU volume was measured using water displacement

3.2 Preparation of Concrete

The concrete was prepared in the concrete laboratory of School of Environment and Technology, University of Brighton. The concrete mixture has been prepared according to standard specifications (BS 1881-125:2013) adopted by the construction industry.
The concrete was tested using the slump test in accordance with BS EN 12350-2-2009 before casting in the moulds.

3.2.1 Materials

The concrete mixture comprised of water, cement, sand and aggregate. The type of cement used was Portland cement and the sand was composed of grain sizes given in Table 3.1 and Figure 3.8. The coarse aggregates were local crushed aggregates (gravel from a river bed) with a maximum diameter of 10 mm and a semi-rounded shape.

	Quantity of sand (grams)	
Sieve size [mm]	**Sample 1 Weight = 1049 g**	**Sample 2 Weight =1040 g**
2.36	174	168
2.00	25	25
1.18	54	54
0.71	44	45
0.60	15	15
0.30	161	173
0.25	140	132
0.15	431	424
other	5	6

Table 3.1 Sieved sand size by weight

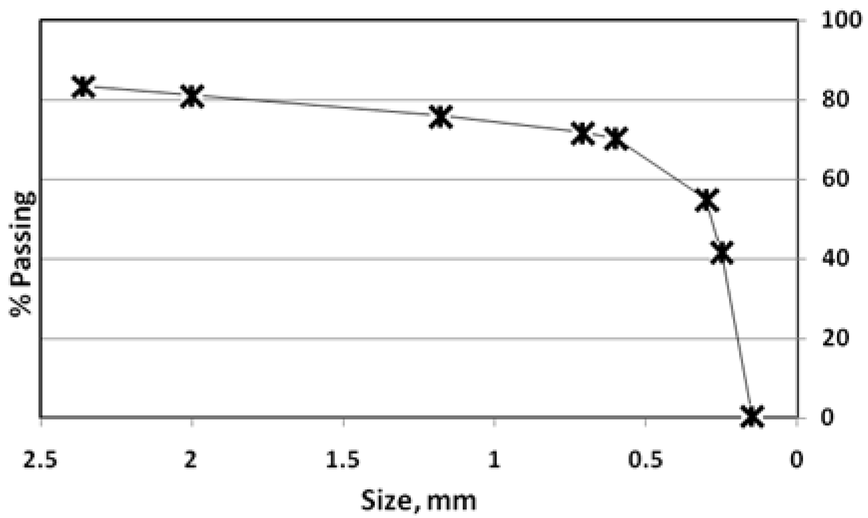


Figure 3.8 Representative sand distribution in terms of % passing

The composition of the concrete mixture used in this work is given in Table 3.2. The ratio of **water : cement : sand : aggregate** used in the mixture was **0.6 : 1 : 2 : 4** conforming to BS 1881-125:2013.The accuracy of the water weight measurement was approximately 0.5%, and for the aggregates it was 1%. The equipment used in the laboratory was a rotary mixer drum with a scoop and a calibrated balance to weigh out the materials.

Material	**Type**	**Weight Ratio**
Water	Tap water	0.6
Cement	Portland	1
Sand	As in Table 3.4	2
Aggregate	Maximum diameter is 10 mm	4

Table 3.2 Composition of concrete mixture

3.2.2 Process of mixing

The rotary drum was cleaned and left to dry before commencing the mixing. Half the quantity of aggregate and sand was placed in the mixer and the drum was allowed to rotate for thirty seconds. Subsequently, half of the water quantity was added. After a total of three minutes the mixer was stopped and its contents were covered. Then the cement was added in the mixer. The mixer was started again and the remaining quantities of water, sand and aggregate were added, and mixed for about four minutes until the mixture became homogeneous. It was ensured that there was not any dry sand or cement at the bottom of the drum after the mixing. The mixing process complied with BS 1881-125:2013.

3.2.3 Slump testing of concrete

The slump test of concrete measures the workability of the concrete mixtures. The slump test followed the guide lines as stipulated in BS EN 12350-2-2009. The equipment used was a hollow frustum cone with a base diameter of 200 mm, a top diameter of 100 mm, and a height of 300 mm. A compacting rod of 16mm in diameter and a base steel plate were also used. The damp cone was placed on the steel plate and held firmly. The cone was filled in three layers; the thickness of each layer was equal to one third of the cone height. Each layer was compacted by twenty five strokes of the compacting rod. The mould was then removed and the slump was measured as shown in Figs. 3.9 – 3.10. The entire operation of filling the cone till its removal had a total duration of about 150 seconds. The height *h* was recorded.

All concrete mixes prepared in the experiment, had roughly similar *h* values in the range of *h = 2 - 5 cm* which is in the acceptable range. Figure 3.9 illustrates the condition for an acceptable slump test according to BS EN12350-2-2009. Figure 3.10 shows the slump test performed for this work in the concrete laboratory of University of Brighton.

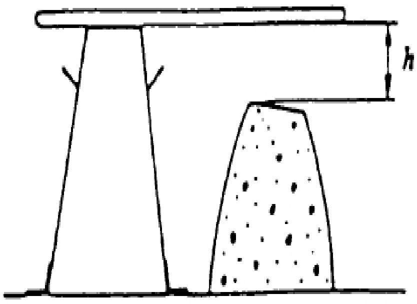


Figure 3.9. Concept of height *h* in the slump test (BS EN12350-2-2009)

Figure 3.10 Slump test in the concrete laboratory of University of Brighton

3.3 Preparation of cubes

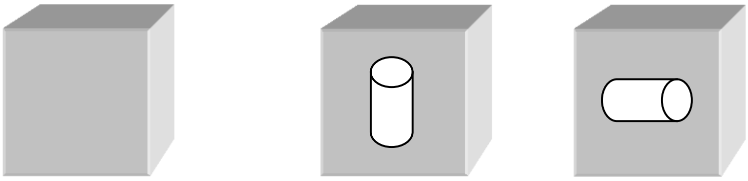
Concrete cubes were prepared for the series of experiments on alkali-silica reaction discussed in Chapter 4 and for compression testing discussed in Chapter 5. The dimensions, tolerances and moulds used for casting of the cubes are specified by the following reference, BS EN 12390-1:2009. The internal dimensions of each mould were 10 x 10 x 10 cm^3. Calibrated moulds were used. The moulds were made from cast iron and the tolerances of the sides of cube with reference to the base were less than 0.5mm. The working steps were as follows:

1. Clean the moulds and remove any loose grit.
2. Put release oil to ensure easy removal of the moulds after 24 hours from casting.
3. Mark the level of the inside of the mould at 1.5 cm, 3.5cm, 5.5cm, 7.5cm from the bottom according to the prescribed preparation in BS EN 12390-2-2009. Place a layer of concrete 1.5 cm thick at the bottom of all moulds.
4. Vibrate the first layer until it creates a homogeneous material.
5. Place a TGCU, if making TGCU cubes, in the middle of each cube in such a way that the distance of the TGCU from the edge of all faces of the moulds is about 1.5cm.
6. Fill with concrete until the marked heights, both for the control and the TGCU containing cubes, whilst vibrating at every layer to create a uniform mixture with no appearance of air bubbles coming out on the surface of the concrete.
7. For the last layer, vibrate until the surface becomes smooth with a glazed appearance.
8. Mark the moulds to identify the standard (control) cubes, and the TGCU-containing cubes.

The specimens were marked following a naming convention. A Standard Cube is abbreviated as SC whilst TGCC stands for TinGlass Concrete Cube. Each concrete cube is given an ID which denotes the type of cube (control cube, or a cube containing TGCU) and the batch number of the concrete mix. Different batch numbers indicated that the concrete were prepared on different days. To identify the ID of a cube, the following nomenclature was used:

- TGCC.n.m is a TinGlass cube with number *n*, and it was made using concrete batch *m*.
- SC.n.m refers to the standard cube with number *n* and concrete batch *m*.

Within a batch, both SCs (standard or control cubes) and TGCCs (cubes with embedded TGCU) were made from the same concrete mixture, processed at the same time as given by the working steps and cured for the same number of days. Two selected orientations of the TGCU were explored regarding the top surface of the concrete mixture in the mould as shown in the Fig.3.11. This is relevant for compression testing. The sides of the mould shall produce smooth contact faces for the platens of compression rig to avoid stress concentrations. The influence of TGCU orientation in TGCC on compressive strength of TGC needs to be assessed.



(a) (b) (c)

Figure 3.11 Schematic of a standard cube SC (a), and TGCCs (b, c) containing TGCU in different orientations regarding the top surface of the concrete mixture in the mould

Figure 3.12 Casting concrete mixture with embedded TGCUs

After steps 1 – 8 as above, the cubes were further prepared as follows:

9. Allow the cubes to set in the mould for one day at room temperature.

10. Extract them from the moulds and cure the cubes in water for 28 days. The water temperature was in the range of 15-20ºC.

For compression testing, four batches of concrete with the numbers no. 3, 6, 7, have been prepared and cast as the cubes of sides 100 mm, as summarised in Table 3.3.
Batch no. 6 has been used for ASR testing, and the working step 10 has been replaced by curing for 1 day in water at 70^{o}C (accelerated curing), then curing for 19 days in alkali solution at 70^{o}C as will be described in detail in Chapter 4.

	Batch no. 3	**Batch no. 6**	**Batch no.7**
Number of control cubes	2	4	1
Number of cubes with TGCU	2	4	1
Average weight of TGCU embedded in each cube (g)	670	595	670
Average volume of each TGCU (cm^3)	270	240	270
Ratio of Volume of TGCU to the volume of the mould	27%	24%	27%
Slump test, *h* in (cm)	2.0	2.7	5.0
Cube reference number	SC.1.3 SC.2.3 TGCC.1.3 TGCC.2.3	SC.1.6 SC.2.6 SC.3.6 SC.4.6 TGCC.1.6 TGCC.2.6 TGCC.3.6 TGCC.4.6	SC.1.7 TGC.1.7
Concrete composition ratio of water, cement, sand, aggregate in the mixture	0.6/1/2/4	0.6/1/2/4	0.6/1/2/4
Curing time	28 days	1 day at 70^{o}C 19 days in solution of 1N of NaOH at 70^{o}C	97 days

Table 3.3 Precast concrete cubes of 10x10x10cm^3 tested in compression for this study.

The TGCUs in all the batches have been prepared from identical tin-plated steel cans (as baked beans can) with mixed coloured waste glass cullet. Compressive strength of the resulting TGCC has been assessed as discussed in Chapters 4 - 5.

3.4 Preparation of beams

Precast beams were prepared for flexural testing that will be described in detail in Chapter 6. Various numbers of TGCUs were embedded in concrete beams and in different orientations along beam axis (marked as A and B) as shown in Fig. 3.13.

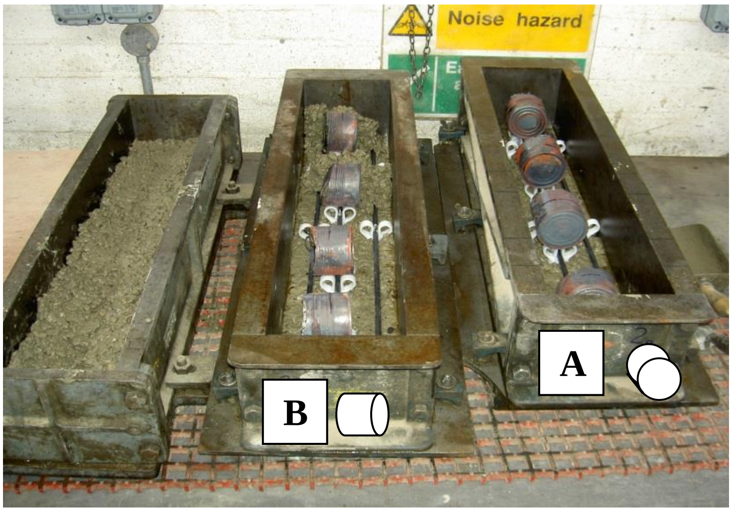


Figure 3.13 Embedding TGCU units in concrete beams at casting stage.

A series of TGCBs, concrete beams with embedded TGCUs, have been designed by the author and produced by him in the concrete laboratory. The TGCU-containing beams, TGCBs, were produced by placing the TGCUs in the core part of the beam, that is, around the neutral axis of a beam. The concept of a neutral axis is defined here as the location of zero bending stresses in a beam. The neutral axis passes through the centroid of a cross-section, and the bending stresses in concrete are develop linearly with distance (Gere and Goodno,2011) in elastic regime. This is a realistic assumption for the elastic analysis of the beam before the appearance of any cracks. After that, the reinforcing rods in the tensile part of the beam hold the concrete together. The neutral-axis region in a TGCB was favoured by the author for the placement of TGCU to avoid excessive stresses in a beam around TGCU.

For bending test, the beams of 15 x15 x71 cm^3 were cast out of the batches of concrete with the numbers 3 and 7 (as listed in the Table 3.3). The beams were produced according to the guidelines given by BS EN 12390-5:2009. The operational procedure is detailed below,

Standard (control) beam (SB): The procedure for the preparation of a standard precast concrete beam without TGCUs is described below:

1. Prepare the mould of dimension 15x15x71 cm^3.
2. Clean the moulds, remove any loose grit and put release oil to ensure easy removal of the moulds after casting and setting.

3. Use three steel rods, 6 mm in diameter and length of 0.67 m, for reinforcement of each beam. Use three plastic spacers to support each rod; hence, a total of 9 plastic spacers for the 3 rods.
4. Position the rods in the lower part of the beam, at the height of 20 mm from the bottom of the beam. There was no need to anchor the rods.
5. In each mould, place one layer of concrete at a time. The first is placed until the level of 3.0cm height from the bottom of the mould is reached. This ensures that there is sufficient compacting by the application of the vibration on the vibrating table. Inspect that the surface of the concrete looks homogeneous and there are no appearance of air bubbles. The other layers are added at 6.0 cm and 11 cm from the bottom of the mould. The last layer is to fill up the beam. The vibration procedure is repeated for each layer.

TGCU-containing beam TGCB: The procedure for preparing the TGCBs is similar to that of the SBs but there is an addition to the step 4 above. For TGCBs, it shall read (the new part is highlighted in bold):

4. Position the rods in the lower part of the beam, at the height of 20 mm from the bottom of the beam. There was no need to anchor the rods. **A required number of TGCUs shall be positioned above the steel rods, using additional plastic spacers to support them. They will be placed after the first layer of concrete has been filled in and vibrated.**

Two plastic spacers are used for positioning each TGCU. For a TGCU beam with five embedded TGCUs, the number of spacers is equal to:

$$6 \text{ (for the rods)} + 2 \cdot 5 \text{ (for TGCUs)} = 16.$$

It shall be observed that the increased number of plastic spacers in a TGCB, might worsen the flexural characteristics of TGCB when compared with SB. This may happen due to additional areas of stress concentrations associated with the spacers. Thus the described laboratory experiment on TGCBs *vs* SBs is seen as being set on conservative side (as a worst-case scenario for TGCBs).

The layering procedure is similar to that described above: the layers of concrete are placed one at a time. After the first layer is vibrated, the TGCUs are placed on the prepared spacers in the mould. Subsequently, a second layer of concrete is placed in the mould, and the thickness is 6cm. The concrete covers the lower part of TGCUs in the mould. After the layer is vibrated, a third layer is then placed, with top surface at 11cm from the bottom of the beam. It just covers the top part of TGCUs in the mould. After vibration, the last layer is placed to fill up the beam. After the final vibration the surface of concrete becomes smooth with a glazed appearance, and without excessive segregation.

The homogeneity of the concrete is important because it influences the strength of the concrete. Concrete with bubbles may be produced due to inadequate vibration. Hence a detailed procedure for vibration compacting of concrete was developed. All the beams for a given batch of concrete mix were vibrated at the same time and on the same vibrating table.

For example, if three beams were being prepared: one standard beam (SB) and two TGCBs (beams with TGCUs), then the first layer of concrete was poured into all three moulds and then all of them were vibrated simultaneously on the same vibrating table. Then the second layer was added to all the moulds, and vibrated simultaneously on the same vibrating table. This was repeated until the last layer.

After casting, the moulds are left in the laboratory at room temperature and after 24 hours, the moulds are released and the beams are cured in water.

Two orientations of TGCUs, with respect to the beam axis, were prepared for analysis. The orientation is labelled A and B in Fig. 3.13. The detailed technical drawings (Appendix 6.2) show the position of the steel rods and the plastic spacers that support the rods and embedded TGCUs. An example is shown in Fig. 3.14.

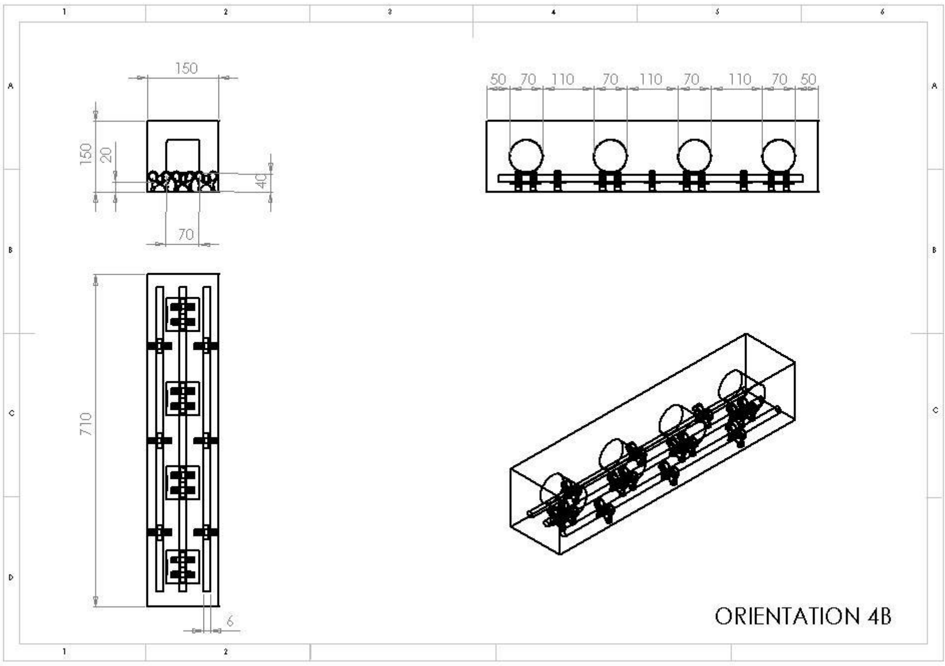


Figure 3.14. Technical drawing for a beam; the Orientation 4B stands for four TGCUs embedded into the beam at orientation B as in Fig. 3.13.

The following notation for beam ID has been used: TGCB.4B standing for 4 TGCUs in type B orientation.

3.5 Modified ASR Test

The modifications to the ASR test are necessary due to the inability to embed a TinGlass unit into the mortar-bars specified by the conventional ASTM C1260 methodology. A TGCU has dimensions of diameter of 70 mm and at least 70 mm tall, whilst the concrete prismatic beam required by ASTM C1260 has the dimensions of 75x75x250 mm.

Therefore the decision has been taken to use concrete cubes of dimension 100x100x100 mm in current work, and to monitor the changes in volume of the cubes (rather than change in length of the ASTM C1260 bars). The methodology for the modified ASR test in precast concrete cubes is described below. The methodology should be applicable for ASR testing for other entities of dimensions much larger than aggregates that are embedded rather than mixed into concrete. The preparation of TGCU has been described in Section 3.1. Special attention and preparation have been devised to minimize the amount of glass at the top surface of the TGCU that may come in contact with concrete. The preparation of the concrete and concrete cubes has been described in Sections 3.2 and 3.3.

The details of the operational procedure for the modified ASR test were as follows:

1. Eight precast concrete cubes were prepared from the same batch of concrete according to the methodology described in 3.3. The dimensions of the each cube were 100x100x100 mm^3.
2. Four of the cubes (SCs) contained no TGCU (control set). The other four (TGCCs) contained TGCU, and they were called the specimen set. The control cubes were labelled as SC1, SC2, SC3, SC4. The specimen set were labelled as TGCC1, TGCC2, TGCC3 and TGCC4.
3. The volume of each cube was measured by the water displacement method.
4. Four identical plastic containers were used, as shown in Fig.3.15. Each plastic container could accommodate two cubes.
5. Two water baths were used. Each water bath could accommodate two plastic containers.
6. The water bath is shown in Fig 3.15. The water baths were filled with distilled water and it was kept at a constant temperature of 70^{o}C.
7. Two control cubes were placed in a container; two specimen cubes were placed in another container. The two plastic containers with cubes in place were filled with 2 litres of 1 N NaOH solution. Each container was sealed with a watertight lid.
8. The plastic containers were then placed in the water bath and the water bath topped up to a marked level.
9. After one hour the NaOH solution reached the temperature of the water bath.
10. The second water bath with two more plastic containers was prepared similarly, steps 6 – 9 above.
11. The cubes stayed soaked in NaOH solution at 70^{o}C for 19 days.
12. At the end of the incubation, the containers were removed from the water bath and the cubes were removed from the containers. The initial volume of NaOH solution in each container was 2 litres. The volume of the NaOH solution

remaining in the container after incubation was recorded. Any reduction in solution volume is due to absorption.

13. The volumes of the NaOH-treated cubes were measured by the water displacement method and compared to the initial volumes of step 3.

This modified ASR test also made the following changes to the ASTM standard. The 1N NaOH was at 70°C instead of 80°C, a limitation of the water bath equipment, and a soaking time of 19 days instead of 16 days, a longer time to compensate for the lower temperature.

There were further checks to the procedure, as itemized below.

- The water level of the baths was marked on each container and checked every 12 hours. If evaporation occurred, distilled water was added to the bath.
- Each container was shaken daily to ensure the NaOH solution was kept in equilibrium.
- During incubation (soaking), condensation of the NaOH solution was observed on the inside surface of the container lid. The lids was watertight; the condensed NaOH did not escape the container, but was returned to the main body of the solution.
- The temperature of water in the baths was regulated by the thermostat of the bath. It was daily checked by using a portable thermometer.

(a) (b)

Figure 3.15 (a) Each plastic container could accommodate two concrete cubes; (b) Each water bath could accommodate two plastic containers.

3.6 Compression Test

According to BS EN 12390-3:2009, the compressive strength of hardened concrete is obtained by testing concrete cubes with dimensions 10x10x10 cm^3. For the compression testing in this work, a calibrated Avery 7227 machine was used, with a maximum load capacity of 2000kN. The specifications for this testing machine conform to BS EN 12390-4:2009. The load was applied to the specimen in incremental steps until the failure is reached. The loading rate used for the tests was 180kN/min.

The manner of the failure was monitored for the compliance with BS EN 12390-3:2009 as described by Fig 2.7 – 2.8. This is illustrated in Fig 3.16; the fractured concrete cube shows that its side faces are cracked equally. Little damage has been observed to the cube faces in contact with the platens of the machine.

Figure 3.16. A typical fracture of precast concrete cube observed in this work

The following inputs to the compression rig were specified: the weight of a cube, the date when it was produced, the dimensions of the cube, the reference number and the age of the cube. A new parameter is important for TGCC, namely the orientation of the embedded TGCU relative to the direction of the applied load. The orientation of the TGCU and the load *F* applied in all the tests is shown schematically in the Fig.3.17.

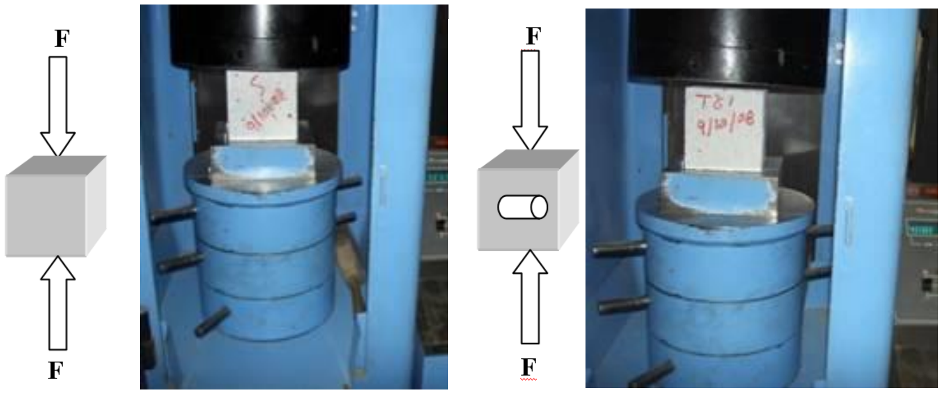


Figure 3.17 Compression test for SC and TGCC samples

There were three sets of compressive testing experiments performed corresponding to three batches of concrete mix, with reference numbers 3,6,7 as listed in Table 3.3.

Batch 3 was used to compare compression strength between SC and TGCC cubes after standard curing in water for 28 days. Batch 6 compared the strength between SC and TGCC cubes following accelerated alkali exposure. Batch 7 compared the strength between SC and TGCC cubes subjected to prolonged curing time.

3.7 Flexural Bending Test

Under flexural tests of this work, the dimensions of precast concrete beams were fixed with the height of 15 mm, width of 15 mm and length of 710 mm. Each beam was tested as a simply supported beam with central load (three-point beam). The aim of the tests was to compare flexural performance of TGCBs (precast concrete beams with embedded TGCUs) with that of standard beams (SBs). The deflections at midspan were measured for recorded applied load, and the load-deflection curves were plotted and analysed. All beams were tested to fracture.

A theory for flexural bending for a simply supported beam with a central load (three-point beam) has been reviewed in Section 2.5. There is a variation of deflection along the beam. Deflections reach maximum in the midspan of the beam. In the experiment, the displacement of the bottom edge of the beam was measured and it was accepted as the deflection of the neutral axis of the beam under load. A schematic of the experiment for measuring the load–deflection of a three-point beam is shown in Fig. 2.10.

The testing was performed in Civil Engineering laboratories at School of Environment and Technology (SET) of University of Brighton, using the machine Avery 7IN42.

The beam is supported on two lower rollers, and the load is applied via the third, upper roller. The centre-point loading method was used (BS EN 12390-5:2009). The configuration for the test is schematically shown in the Fig 3.18 below. For all the beams used in the tests,

- the beam dimensions were 71cm x 15cm x 15cm;
- As described in Section 3.4, the reinforcement of each beam was provided by three steel rods of 6 mm diameter placed in the lower part of the beam, at the height of 15mm from the bottom of the beam. This will be the tension part of the beam below neutral axis. The length of each rod is 0.67 m.
- Three plastic spacers (supports) were used for each rod. Due to the small dimension of the beam, no anchorage had been applied .
- The position of the supports is as shown in Fig 3.18; both rods and beam overhang the supports, by 10 cm and 12 cm respectively.

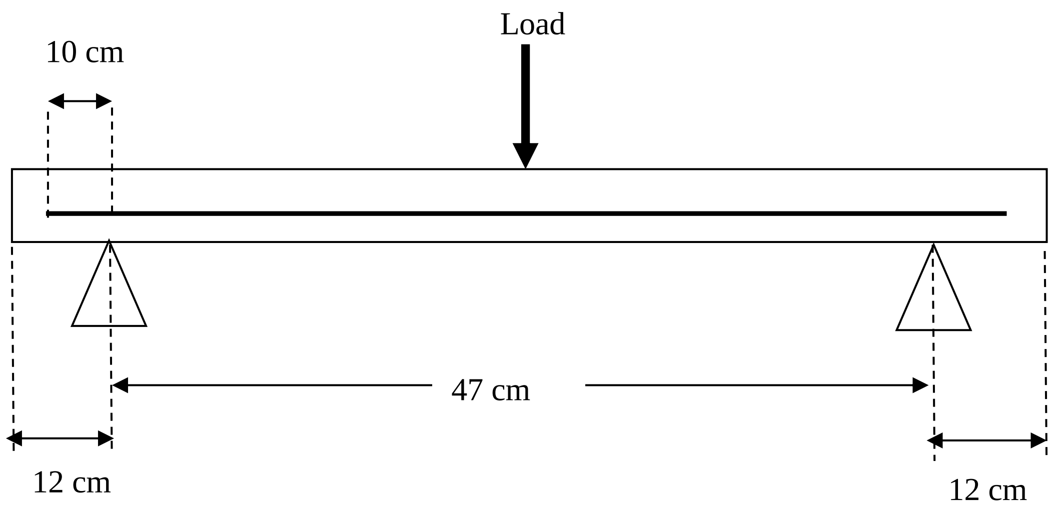


Figure 3.18 Three-point beam diagram for the flexural test setup; the vertical position of the reinforcing rod is out of scale

3.7.1 Data acquisition methods

Manual method: The deflections of the beam are measured by a micrometer placed under the beam at central point. The researcher reads the deflection measurements from the micrometer dial. As an additional verification, a video of the micrometer dial was simultaneously filmed by an assistant on a camcorder. The load can be read from the dial of the Avery machine. The manual method requires two persons: the operator of the Avery rig loudly reads out the load and the researcher notes it down along with the deflection at this moment of time.

Data acquisition by data logger. A calibrated transducer is placed beneath the middle part of the beam for measuring the deflection of the beam. The deflection data are transferred to a data logger, with a time resolution of 5 seconds.

Two calibrated load cells are positioned between the rollers and the bottom of the beam at the supports. The load cells monitor the load applied; the data are taken every 5 seconds and transferred to a data logger. A computer connected to the data logger stores all the measurements, The output files can be converted into Excel spreadsheet.

CHAPTER 4
ALKALI SILICA REACTION

4.0 Introduction

The concept of Alkali-Silica Reaction (ASR) has been presented in Section 2.4. A review of literature relevant to ASR in concrete with additives, in particular coarse glass cullet, has been presented in Section 2.5. This thesis suggests a radically new approach for combating the ASR by the use of a protective barrier between the concrete and the glass cullet. This barrier is provided by the metal shell of the TGCU, the TinGlass unit (Appendix 1.1).

TGCU is not an aggregate but an entity embedded in precast concrete. A modified version of the ASTM C1260 test was devised by the author and is described Section 3.5. It is consistent with continuing development of ASR testing as described by Kozlova et al. (2004).

Therefore the objective of the ASR test is to determine if the incorporation of TGCU in precast construction elements will affect the occurrences of ASR within the concrete.
This was achieved by a comparison of the results of ASR testing between control set of concrete cubes without TGCU (SCs) and specimen set of cubes containing TGCU (TGCCs).

In this chapter the comparison of the influence of ASR will be based on

- volume expansion under modified ASR test
- compression test of TGCCs and SCs after the alkali exposure.

Whilst 1) follows the traditional approach for assessing the extent of ASR by measuring expansion of specimen, the method 2) is seen as a novelty. It is proposed following critical analysis of literature in Section 2.4. In some studies no deleterious expansion was observed in the accelerated mortar bar test, however, the results of SEM–EDX analysis showed serious decomposition of aggregate texture due to ASR (Mladenovic, 2004).

Lee et al. (2011) has observed that the dry-mixed method for preparation of concrete was very efficient in reducing the ASR expansion especially for larger particle size (highly reactive) glass aggregate because mortar bars made by dry-mixed method had higher porosity which was able to accommodate more gel produced due to ASR, thus resulting in lower expansion and cracks.

These studies reveal that ASR test on the basis of expansion alone is not sufficient to discount ASR presence and that there is the need for better test criteria. Several of the studies mentioned in Section 2.4 not only tested for ASR using ASTM C1260 but also tested the mortars for concrete compressive strength. A combination of low expansion and good strength are the desired outcomes, as it is stated by Shayan and Xu (2004).

For this work, in addition to testing for volume expansion using the modified ASR methodology, the TGCCs and SCs have also been tested for strength under compression.

4.1 Volume expansion under modified ASR Test

Four TGCC samples and four SCs samples were assessed as is described in Section 3.5. The results are given in Table 4.1 using the notations of Section 3.3. The Table summarizes the results of volume expansion measured after the modified ASR test.

Bath Number	Plastic Container Number	ID of the precast cubes	Initial volume of cubes (ml)	Final volume of cubes (ml)	Volume Change (ml)	% Change
Water Bath 1	1	TGCC.1.6 TGCC.2.6	2040	2050	+ 10	0.5%
	2	SC.1.6 SC.2.6	2020	2060	+ 40	2%
Water Bath 2	3	TGCC.3.6 TGCC.4.6	2020	2030	+ 10	0.5%
	4	SC.3.6 SC.4.6	2070	2110	+ 40	2%

Table 4.1 Volume expansion after modified ASR test by water displacement method

The control set, SCs, has expanded more than the TGCCs. The SCs expanded by 2% compared to 0.5% for the TGCCs. The results for both water baths were similar and this shows consistency and reproducibility of the experiment.

Table 4.2 shows the amount of NaOH solution absorbed by the concrete cubes. The control SC samples absorbed 50 ml of NaOH solution compared to 40 ml for the TGCC samples.

On visual examination of the cubes after completion of the ASR test, brown spots were observed on the surface of both the TGCCs and SCs, but no cracks were identified, as shown in Fig.4.1. There were more spots observed on the SC samples than on the TGCC samples

Plastic Container	Samples in the container	Initial volume of NaOH solution (ml)	Final volume of NaOH solution (ml)	Absorbed NaOH solution (ml)
1	TGCC.1.6 TGCC.2.6	2000	1960	40
3	TGCC.3.6 TGCC.4.6	2000	1960	40
	Average			40
2	SC.1.6 SC.2.6	2000	1950	50
4	SC.3.6 SC.4.6	2000	1950	50
	Average			50

Table 4.2 Volume of NaOH solution absorbed by cubes.

Figure 4.1 Observations of brown spots on the surface of the cubes following ASR testing

4.2 Compression Test Following Alkali Exposure

As it has been described in Section 3.5, four SCs and four TGCCs were placed in a solution of 1N of NaOH at 70^{o}C for 19 days under the modified ASR test. After volume expansion measurements as described in Section 4.1, they were dried for 12 days before being tested in compression. The results are presented in Table 4.3, the first column following the notations introduced in Section 3.3.

Precast Concrete Cube ID	Compressive strength (MPa)	Weight of cube (kg)
TGCC.1.6	69.2	2.4
TGCC.2.6	67.4	2.3
TGCC.3.6	56.9	2.3
TGCC.4.6	52.6	2.3
SC.1.6	55.1	2.4
SC.2.6	56.5	2.3
SC.3.6	52.8	2.4
SC.4.6	56.8	2.3

Table 4.3 Results of the compression test after curing in the alkali solution

It can be observed from Table 4.3 that compressive strength for TGCCs tends to be higher than that for SCs. A statistical analysis and discussion of the results are performed in the next section.

4.3 Analysis of ASR test results

Compression testing: As it was calculated from Table 4.3, the compressive strength of the TGCC samples is (61±8) MPa and for the SC samples it is (55±2) MPa. The TGCC average compressive strength (61MPa) is 11% higher than that for the SC samples (55MPa). It was observed however that the scatter in data (standard deviation) is much higher for TGCCs (8MPa) than for SCs (2MPa) based on Table 4.3. The reasons for higher standard deviation of TGCCs were investigated by examining the scatter in the volume of TinGlass Construction Units (TGCUs) embedded into the TGCCs in the test.

The TGCUs were showing variation in volume and shape as it can be seen in Figure 4.4 and Figure 4.5.

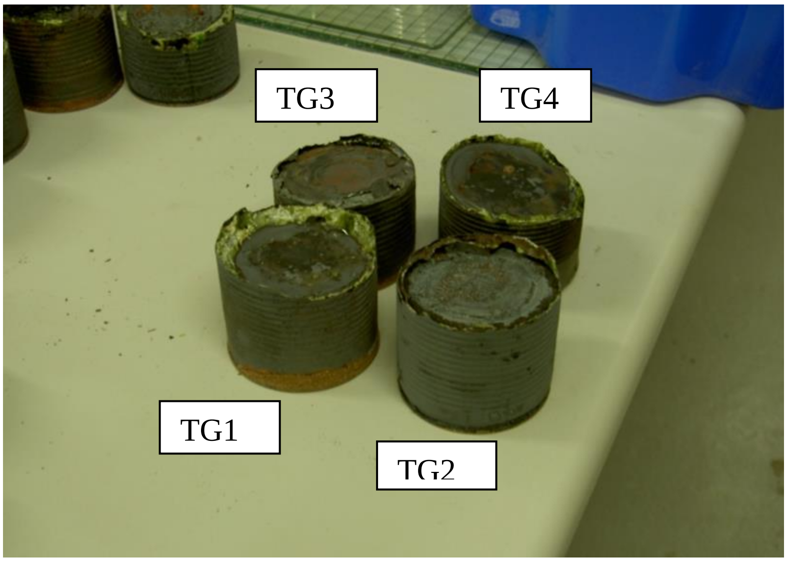


Figure 4.2 Visual inspection of TGCUs before embedding them into the TGC cubes under ASR test: TG3 (TGCC.3.6) and TG4 (TGCC.4.6) are smaller than TG1 (TGCC.1.6) and TG2 (TGCC.2.6)

It was established that

- TGCUs with ID labels TGCU.1 and TGCU.2 had a height of 6.5 cm and an equivalent volume of 250.1 cm^3; whereas the TGCU.3 and TGCU.4 had a height of 6.0 cm and an equivalent volume of 230.8 cm^3. The equivalent volume was calculated for the cylinder of height and diameter as measured for TGCU.
- It was observed that the lids on TGCU.1 and TGCU.2 were flat and horizontal but this was not the case for TGCU.3 and TGCU.4 (the lids were sloped). The lids on all the TGCUs were well bonded to fused glass core.

A correlation of compressive strength of a 1000cm^3 TGC cube with the volume of the embedded TGCU was assessed by summarising the experimental data:

- The TGCU.3 and TGCU.4 were embedded into TGC cubes TGCC.3.6 and TGCC.4.6, respectively. The volume of each TGCU is 230.8 cm^3. It was calculated from Table 4.3 that the average compressive strength for the TGCC.3.6 and TGCC.4.6 is 54.8MPa.

- The TGCU.1 and TGCU.2 were embedded into TGC cubes TGCC.1.6 and TGCC.2.6, respectively. The volume of each TGCU is 250.1 cm^3. It was calculated from Table 4.3 that the average compressive strength for TGCC.1.6 and TGCC.2.6 is 68.3 MPa.

These data indicate that there is a tendency for compressive strength of precast 1000cm^3 TGC cube to decrease (from 68.3MPa to 54.8MPa) when the TGCU volume decreases (from 250.1 cm^3 to 230.8 cm^3).

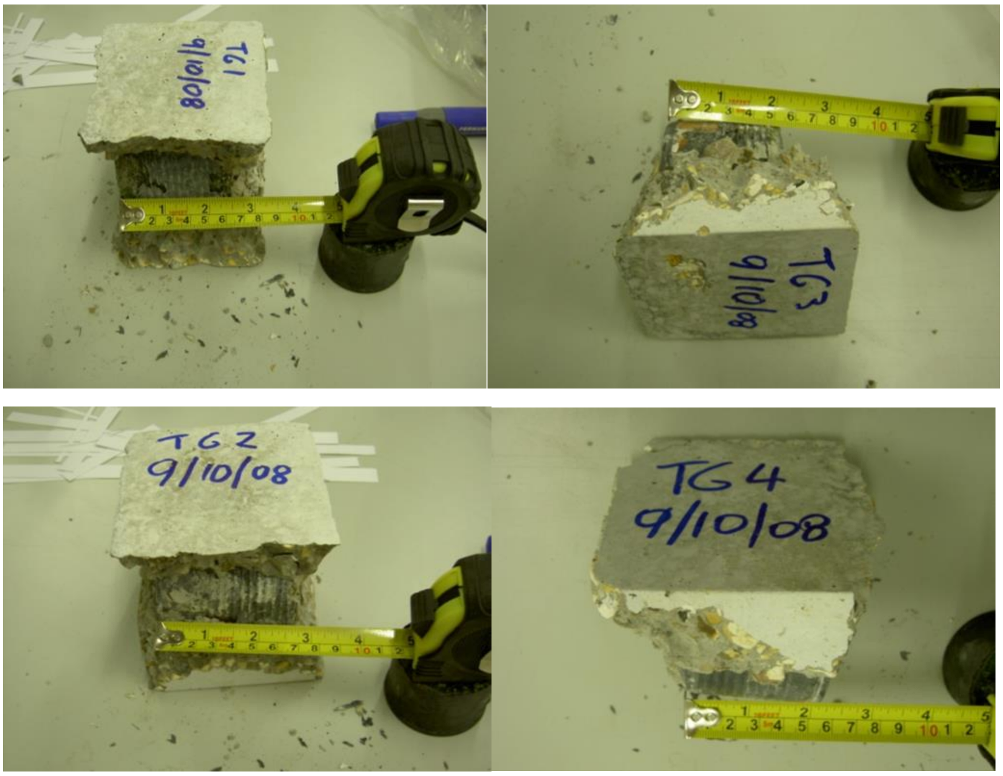


Figure 4.3 The TG1(TGCC.1.6) and TG2(TGCC.2.6) had the height of 6.5 cm, and TG3 (TGCC.3.6) and TG4 (TGCC.4.6) had the height of 6.0 cm as it was measured after destructive compression testing.

Volume expansion: The volume of precast concrete cube of 10cm on the side is 1000 cm^3. A TGCC cube is composed on average of 248 cm^3 of TGCU as is given by Table 2.3. This gives 752 cm^3 for the volume of concrete in a TGCC. The volume expansion measurements before and after the modified ASR test from Table 4.1 show that the volume expansion in the specimen TGCC samples was 0.5% and in the control SC samples without TGCU it was 2%. There is more concrete in the control SC cubes than in TGCC specimen cubes. The difference in expansion could be attributed to the ASR reaction in the concrete whilst TGCU does not contribute into the ASR expansion.

NaOH solution absorption: The amount of NaOH solution absorbed by the SC cubes was also more than for the TGCC samples. A hypothesis is made that volume of absorbed NaOH is proportional to the volume of concrete in a cube under ASR testing. To check this hypothesis, the ratio of the volume of concrete cube (1000 cm^3) to the volume of absorbed NaOH solution (50 ml) in the SC samples is calculated. If the hypothesis is true, then the same ratio can be applied for estimating the volume of NaOH solution absorbed by the concrete in the TGCC samples (whilst taking into account that the volume of concrete in TGCC is 752 cm^3 on average). This gives:

$$\frac{1000\ cm^3}{50\ ml} = \frac{752\ cm^3}{x}$$
$$x = 38\ ml$$

The measured amount of NaOH solution absorbed by the TGCC sample was 40 ml. It well agrees with the calculated value of 38ml within experimental uncertainty. This shows that that hypothesis is correct: the absorption of NaOH solution may be associated with the amount of concrete present in the cube and there is no absorption into the TGCU.

The results suggest that the presence of the TGCU in TGCC samples did not contribute to ASR volume expansion. Indeed, the NaOH absorption appears to be proportional to the amount of concrete present in the cube.

Visual inspection for ASR: The UK Waste and Resources Action Programme (WRAP) sponsored project ConGlassCrete II (2004) that carried out a study of pozzolanic reaction of ground glass has kept several mortar samples for further ASR testing in the future. It recognizes that ASR can be a slow reaction and that its effect may not be evident even if the mortar test standard uses an accelerated approach.

Some discolouration has been reported (BRE 330 Digest1) as shown in Fig.4.4(a) and sometimes it is accompanied by cracking as shown in Fig.4.4(b). The cracks can be fine surface cracks as shown in Fig 4.5 (BRE Digest 330, Part 1 and Part 4)

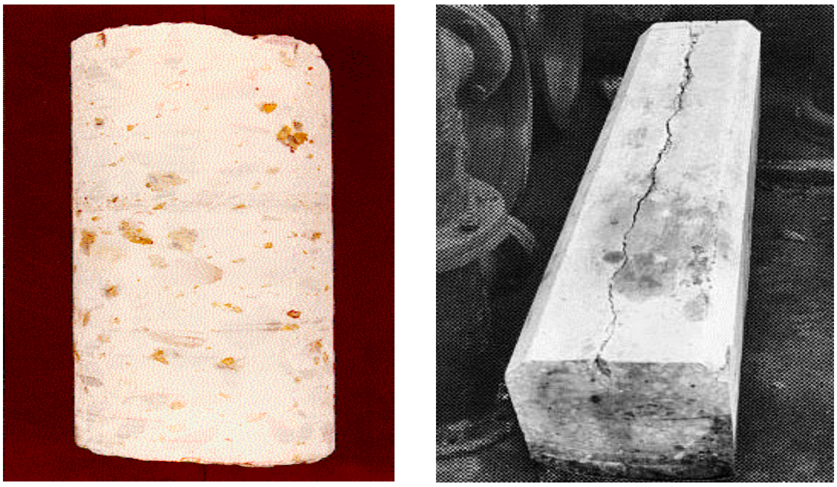


Figure 4.4 (a) Brown spots of a concrete core after ASR; (b) Concrete beam cracked after ASR (BRE 330 Digest1)

Figure 4.5. ASR-related cracking (Reproduced from BRE Digest 330 Part 1 and Part 4)

There was no evidence of cracking in current work as it can be seen in Fig.4.1. Evidence of surface discolouration in the form of brown spots was observed on all tested concrete cubes. The observed presence of the brown spots in Fig.4.1 suggests that there is ASR at an early stage.

The modified accelerated ASR test methodology involved soaking times of 19 days at a temperature of 70°C. It may be that with a longer reaction time or higher temperature, expansion associated with ASR involving TGCU may be observed.

Summary: As an overall conclusion, the data show that TGC can reproduce properties of conventional concrete and hence it can be recommended for further study as a viable way of using coarse mixed glass cullet for partial replacement of concrete in precast elements for construction industry.

CHAPTER 5
COMPRESSIVE STRENGTH TEST

5.0 Introduction

Concrete shall meet a wide range of requirements with regard to mechanical and durability properties. The compressive strength of concrete is predominantly used by engineers in the design of a variety of structures and is measured in compression tests. A compression test is a direct (normal) load applied to a concrete specimen imposed by a hydraulic ram until the specimen reaches failure. The failure load is recorded and is divided by the cross-sectional area of the specimen resisting the load to calculate the compressive strength. It is essential that the load shall be uniformly distributed over the contact area to avoid stress concentrations (Gere and Goodno, 2011). The compressive strength is used as an indication of general quality and is an important assessment index according to BS EN 12390-3-2009.

The preparation of the SCs and the TGCCs meets the requirements of BS EN 12350-1-2009 and BS EN 12350-2-2009 regarding testing of fresh concrete and sampling; they also meet the requirements of BS EN 12390-1:2009 and the BS EN 12390-2:2009 regarding the preparation of specimens and their curing.

The aim of the compression tests carried out in this research is to compare the compressive strength of hardened concrete for SCs and TGCCs samples. In this chapter, the results are presented for:

- the comparison of strength between SC and TGCC cubes cured for 28 days
- the comparison of strength between SC and TGCC cubes cured for 97 days.

The preparation of the precast concrete cubes for compression test has been described in detail in Chapter 3. The cubes are 10cm on the side. The concrete quality and mixture was identical for standard control cubes (SC) compared with TGCU-embedded cubes (TGCC) because they were prepared within the same concrete mix (batch).

5.1 Results

The test has been performed on the Avery 7227 compression rig by recording the maximal load endured by the sample to fracture. Compressive strength has been calculated by the rig based on the cube size that was entered as the input parameter. The measurements of displacement (and hence compression strain) were not available for this compression rig.

Visual inspection: At the end of each test and following the guidelines of the BS EN 12390-3:2009, the precast concrete cubes after failure were compared to those shown in Figs. 2.7 – 2.8 to determine whether the test was satisfactory. The character of failure for all the cubes in the test were compliant with the satisfactory failures in Fig. 2.7.

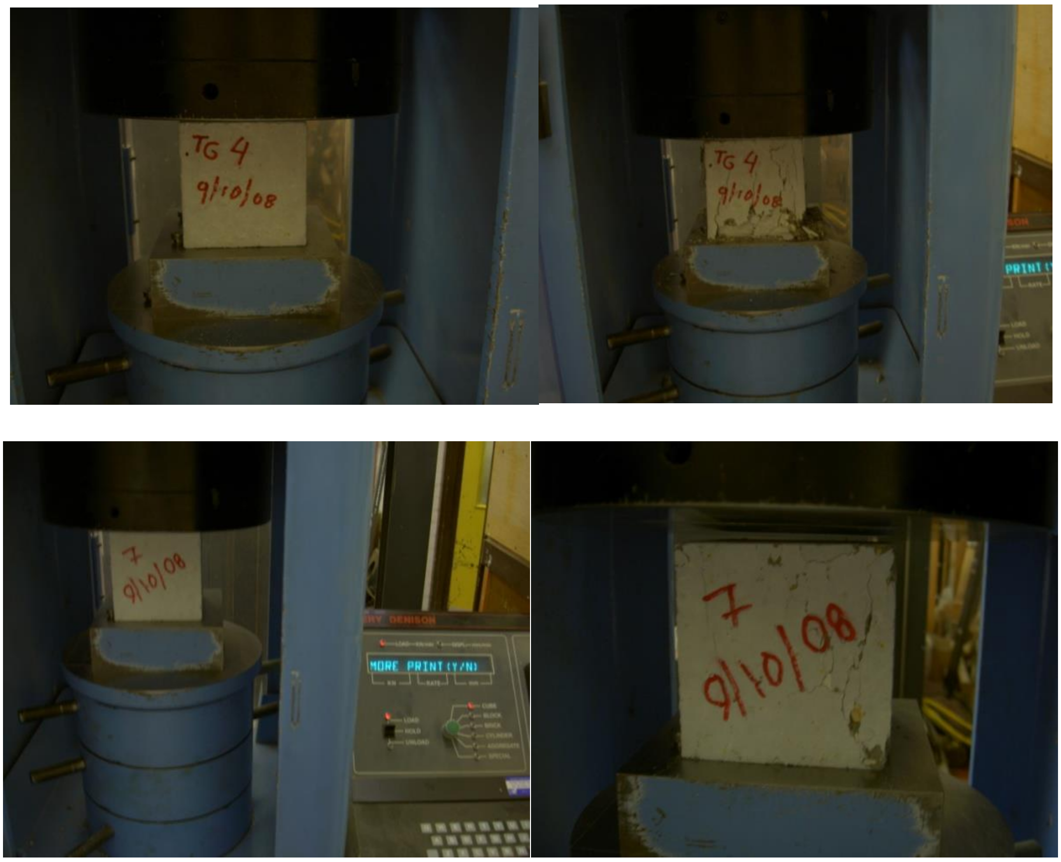


Figure 5.1 Top row from left to right: TGCC before and after the compression tests. Bottom row from left to right: SC before and after the compression tests. The cracks in TGCC were deeper than in the SC (control cube).

The visual inspection revealed that the SC and TGCC cubes behaved similarly under compression, that is, the failure cracks were in the same direction and location; however, the depth of the cracks observed in the TGCC cubes were deeper than those in the SC cubes as shown in Fig.5.1.

Compression test 1: The first column in Table 5.1 lists the concrete cube reference numbers following the notations of Table 3.3.

All the cubes in Table 5.1 were prepared using the same concrete mix (Batch 3), and the same curing and drying conditions. They were cured in water at temperature from 15°C to 25°C for 28 days, and then dried for 14 days.

The results of the compressive strength test are listed in Table 5.1. It shows the measured maximal compression stress before failure for each TGCC and SC samples.

Cube reference	**Compressive strength (MPa)**	**Weight of cube (kg)**
TGCC.1.3	83.5	2.3
TGCC.2.3	71.4	2.4
SC.1.3	65.5	2.3
SC.2.3	63.4	2.3

Table 5.1 Results of the compression test for SCs and TGCCs prepared from the same concrete mix (Batch 3) and under the same curing conditions.

As Table 5.1 shows, the compressive strength tends to be higher for the TGCC samples than for the standard cubes, SC samples.

Compression test 2 has compared properties in compression between SC and TGCC cubes subjected to prolonged curing time. Both TGCC and SC in Table 5.2 were prepared from the same concrete mix (Batch 7) and they were cured in water for 97 days under identical conditions. The results of compression testing are presented in Table 5.2.

Cube reference	Max stress (MPa)	Weight of a cube (kg)
TGCC.1.7	54.3	2.3
SC.1.7	41.3	2.4

Table 5.2 Results of the compression test for Batch 7 after curing for 97 days

Table 5.2 shows that the compressive strength of the TGCC is higher than the compressive strength of the SC.

5.2 Analysis of compression test results

The results show that the TGC cubes tend to have a higher compressive strength than the control cubes (SCs) and this is consistent for all the compression tests including the samples subjected to alkali exposure in Chapter 4. It shall be noted however that the aim is seen in reproducing the properties of conventional precast concrete rather than increasing its strength, as it is stated in Section 1.4. The main advantage of the proposed material, TinGlassConcrete (TGC), lies not in a superior mechanical strength but in partial replacement of concrete by waste materials. For this, the TGC must reproduce precast concrete properties rather than enhance them. The analysis below summarises all observations and facts in a broader discussion than the original aim; this is done with a view of recommendations for further research.

The difference in the compressive strength between control and TGCC appear to become more pronounced for prolonged curing time. For a curing period of 28 days, the compressive strength measured in TGCC on average is 20% stronger whilst for a curing period of 97 days, the strength of TGCC relative to SC increased to 30% as can be seen from table 5.3. There was only a single pair of TGCC and SC studied for the prolonged curing and further study is required. However, this may be an indication that prolonged curing can be an advantage for TGC.

These results are significant since the compressive strength of TGCC is better than the recorded reduction of 5 - 27% when crushed coarse glass is used as an aggregate (Lam et al , 2007). Whilst ASR can be supressed by addition of chemical substances like pulverized fuel ash and metakaolin as shown by Lam et al. (2007), the TGC requires no chemical additives.

Since glass cullet in TGC is not mixed into the concrete, as in the case for conventional use of waste glass as aggregate, it is difficult to make a direct comparison with existing literature. However, within the research group at the University of Brighton, Ojomo (2010) carried out research investigation as an extension of this work (Appendix 5.1). Using the same equipment and procedures as described in this work, Ojomo (2010) has studied the compressive strength of TGCC samples in concrete cubes of different dimensions: larger 15x15x15 cm^3 TGCC cubes *versus* 10x10x10 cm^3 control SC cubes. Eight TGCC samples and three SCs (control samples) were all prepared from the same batch of concrete by Ojomo (2010). The compressive strength of the SC cubes has been measured as 37 ± 1 MPa whilst that of TGCC cubes was 36 ± 2 MPa. The values of compressive strength of TGCCs and SCs coincide within standard deviation. This shows, that for these dimensions of TGCCs (15x15x15 cm^3) , the compressive strength is similar and there is good reproducibility of mechanical properties. Table 5.3 shows the comparison between the work by Ojomo (2010) and this work.

Reference	**Type and number of samples**	**Cubic Dimensions**	**Average compressive strength (MPa)**
Batch 3 of this work, 28 days curing	Two TGCCs	10x10x10 cm^3	77 ± 8
	Two SCs	10x10x10 cm^3	64+ 2
Batch 7 of this work, 97 days curing	One TGCC	10x10x10 cm^3	54.3
	One SC	10x10x10 cm^3	41.3
Test by Ojomo(2010) 28 days curing	Eight TGCCs	15x15x15 cm^3	36 ± 2
	Three SC	10x10x10 cm^3	37 ± 1

Table 5.3 Comparison of compressive strength of TGCCs and SCs as a function of TGCC size

The volume of TGCU is around 248 cm^3 as shown in Table 2.3 (Ojomo, 2010).

- In this work the TGC cubes of 10cm on the side were tested and the ratio of TGCU to TGCC volume is around 25%.
- For larger TGCCs (15 cm on the side) used by Ojomo (2010) the ratio of TGCU to TGCC volume is 7.3%.

The increase in compressive strength appears to be related to the proportion of TGCU in the TGCC.

Ojomo (2010) has investigated the effect of the orientation of the TGCU in relation to the direction of the applied load. This work has explored the orientation of embedded TGCU as shown in Figure 3.17 (horizontal position of TGCU). Two cases were explored by Ojomo(2010): vertical position for the orientation of the TGCU along the applied load direction, and the horizontal position for the TGCU (as shown in Figure 3.17). The results are summarised in Appendix 5.1. There is no evidence within the observed experimental data that changing the orientation of the TGCU relative to the load affects the compressive strength. This might be because the height and diameter of the TGCU are about the same.

The analysis of compression testing data supports the potential for development of an eco-innovative TGC materials as precast concrete with embedded TGCUs without compromising their mechanical properties. This is in accordance with the research aim as stated in Section 1.4. The results for TGCC from this work and by Ojomo (2010) show that the compressive strength is not reduced as a result of embedding TGCU in precast cubes

CHAPTER 6

TESTING OF TINGLASS CONCRETE BEAMS IN BENDING

6.0 Introduction

This chapter is about the experimental investigation of the flexural behaviour of precast concrete beams with embeddded TGCUs. The test setup was a three-point beam: a beam with central load applied to a simply supported beam (Gere and Goodno, 2011). The dimensions of the beams were fixed as 150x150x710 mm (Chapter 3).

The preparation of beams for flexural testing with various number and orientations of TGCUs was described in Fig 3.13. Flexural strength is given by Eqn. 2.2 for the maximal value of load before fracture of a beam.

The performance of TinGlass Concrete Beams (TGCBs) with embedded TGCUs were compared with that of standard beams (SBs). Both TGCBs and SBs were compared under flexural test according to the standards stipulated in the BS EN 12390-5-2009. The data consist of deflections at midspan and applied load. All specimens were tested to failure.

The question that arises is how the beams with TGCUs behave under bending loads. It is obvious that much depends on the character of bonding between TGCU and surrounding concrete, and areas of stress concentrations around embedded TGCU.

The bond of TGCU with concrete has been explored by Ojomo (2010) by using PANalytical X-pert PRO X-ray diffractometer at University of Brighton. A concrete cube with embedded TGCU has been sawn in two halves. Visual inspection has revealed a robust bonding between TGCU and concrete. Powder samples of concrete were drilled at the distances of 1cm, 2 cm and 4cm from the interface of TGCU – concrete for investigation by X-ray diffraction methods. A good encapsulation of TGCU material has been observed (Appendix 2.5). The bond between glass core and oxidised metal shell in TGCU has been explored by Dr M Trenikhin (2012) under FP7 IRES grant with University of Brighton (Appendix 2.6).

Stress concentrations and crack initiation: Cracks will initiate in stress concentration areas and a brittle specimen will fail by crack propagation (Callister& Rethwisch, 2011). This is highly relevant for concrete as a brittle material. Hence the stress concentrations areas must be assessed for concrete beam under bending. Stress concentrations may emerge at the point of load application. If the load act over a small area (concentrated load) it may produce high local stresses in the region around its point of application (Gere and Goodno, 2011). Hence it was ensured in the test setup the load was applied by a roller over an area large enough to avoid stress concentrations as it was described in Section 3.7.

A superposition of flexural stresses and local stresses in the areas of stress concentrations around TGCUs may cause a complex stress distribution. It is difficult to assess it by numerical methods, and hence an experimental investigation is the key to assessment of a composite beam performance.

Characterisation of the flexural behaviour of the new TGCB prototype is a fundamental part of the research in this thesis. The experimental programme has been conducted in a broad range of parameters, such as:

- Type of cement: low performance cement (LPC) *versus* high performance cement (HPC)
- Concrete beam curing times: 14 days *versus* 28 days
- Orientation of TGCUs in two positions with notations A or B (Fig.3.13)
- Number of TGCUs embedded in a beam of the fixed size, 150x150x710 mm.

The preparation of the beams experimental programme for this chapter is described in Section 3.4. The experimental setup is described in Section 6.1; obtained data are shown in Section 6.2; and the analysis of results is performed in Section 6.3. A summary is presented in Section 6.4.

6.1 Experimental setup

It is essential to mention that both TGCBs and the control beams (SBs) used in the tests, are all reinforced in the same manner and by using the same type of steel rods as described in Chapter 3, as it is considered to be of vital importance to compare *like with like*.

The flexural properties of the new beams, TGCBs, are expected to depend on the number of embedded TGCUs and their orientation. Hence the research proceeded in following steps:

Assessment of the influence of orientation of TGCUs on flexural properties: Two orientations of TGCUs, with respect to the beam axis, were explored under current test, as it was shown in Fig. 3.13 and schematically shown in Fig 6.1 below:

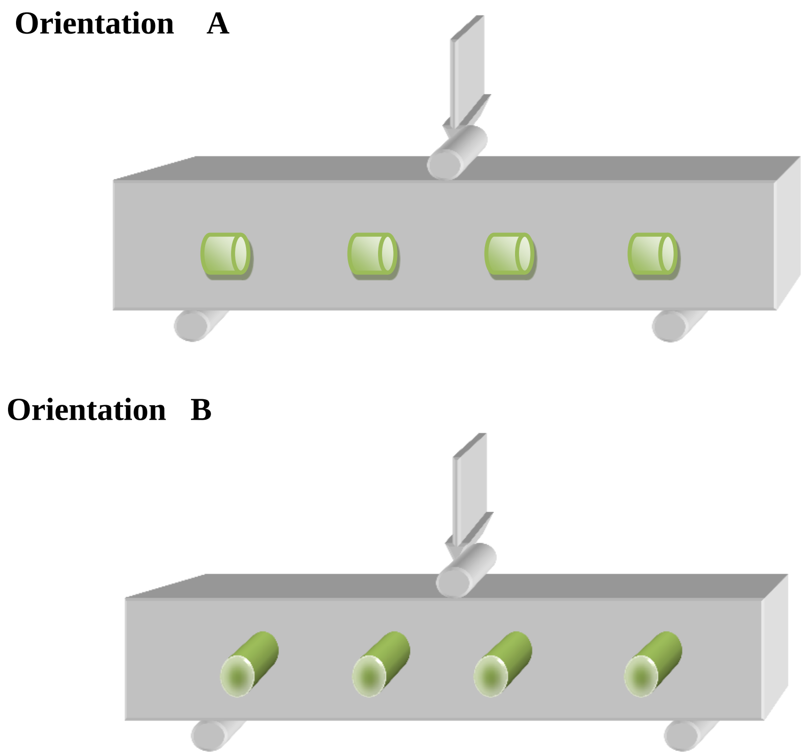


Figure 6.1. Schematic of the orientations of the embedded TGCUs

Assessment of the influence of the number of the TGCUs on flexural properties: The number of embedded TGCUs in the current tests, was varied between four and six. This allows investigation of the influence of

- the number of the embedded TGCUs
- whether the number of the embedded TGCUs was odd (five) or even (four or six), as schematically illustrated by Figs 6.2 and 6.3 Indeed, for an odd number of embedded TGCUs, the concentrated load was applied directly over middle

TGCU. This could worsen stress concentrations in the middle part of the beam, and this is critical area where bending moment reaches maximal value (Gere and Goodno, 2011).

In Fig 6.2, six TGCUs are embedded in the beam; the load is applied between the two central TGCUs.

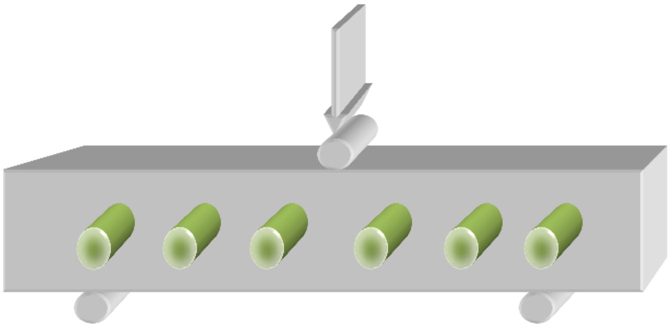


Figure 6.2 A beam with six TGCUs in orientation B

For the case of five embedded TGCUs in Fig 6.4, the load is applied above the central TGCU.

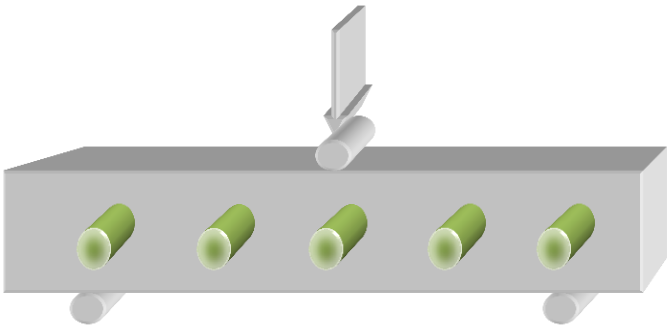


Figure 6.3 A beam with five TGCUs in orientation B

Thus it can be expected that whether it is an odd or even number of embedded TGCUs, it could make a difference under central load. The pattern of stress distribution, especially in the central part of the beam and directly under the area of load application, may be different for these TGCBs, and this may influence the structural properties.

Three-point beam flexural test: The configuration for the test is schematically shown in the Fig 2.9 – 2.10. The preparation of the beams is discussed in Section 3.4, with particular explanation of the proposed design for embedding TGCUs into a concrete beam at casting stage. The TGCBs are prepared with steel rod reinforcements as described in Section 3.4. The SBs (control beams) were prepared in the same manner and with the same steel rod reinforcement but without the TGCUs. The position of the supports is as shown in Fig 3.18; both rods and beam overhang the supports, by 10 cm and 12 cm respectively.

Flexural properties such as flexural strength and stiffness of the TGC beam are the main focus of study in this chapter. They will be assessed by measuring midspan deflection of the beam under the applied load. The plot of load *versus* deflection will allow assessment and comparison of flexural properties of TGCBs and SBs.

6.2 Results

Four batches of beams were prepared and tested in bending. Each batch contained a control SB and one or two of TGCBs, all prepared from the same mixture, and under the same casting and curing procedure. The differences between the batches can be summarised as follows:

- Two types of cement have been explored. Batches 5 and 7 were prepared using high-performance cement (HPC). Batches 3 and 4 were prepared using low-performance cement (LPC) for concrete production.
- Two curing periods have been applied to the specimens. Batch 4 was cured in water at room temperature for 14 days and Batches 3, 5, 7 for 28 days.

Thus the batches are as follows:

- Batch 3 (for 1 SB and 2 TGCBs) was prepared from low performance cement cured for 28 days,
- Batch 4 (for 1 SB and 2 TGCBs) was prepared from low performance cement cured for 14 days,
- Batch 5 (for 1 SB and 1 TGCB) was prepared from high performance cement cured for 28 days,
- Batch 7 (for 1 SB and 2 TGCBs) was prepared from high performance cement cured for 28 days.

The Manual method for data acquisition was used for Batches 3, 4, 5 and the automated Data-logger for Batch 7; the methods are described in Section 3.7.1. The list of tested beams and the results will be summarised in Table 6.1. The load - deflection curves were plotted and shown in Figs 6.4 – 6.7 for each batch. In all these figures, load (kN) is shown on *y*-axis, whilst *x*-axis shows deflection (mm). The curves are shown until fracture to visualise the extent of plastic deformation and energy that goes into fracturing the beam. The slope of curves in their initial part (elastic regime) determines stiffness of a beam in working regime. Magnified view of the curves until deflection of 2mm is shown for better visualisation and comparison of TGCB and SB curves for various batches.

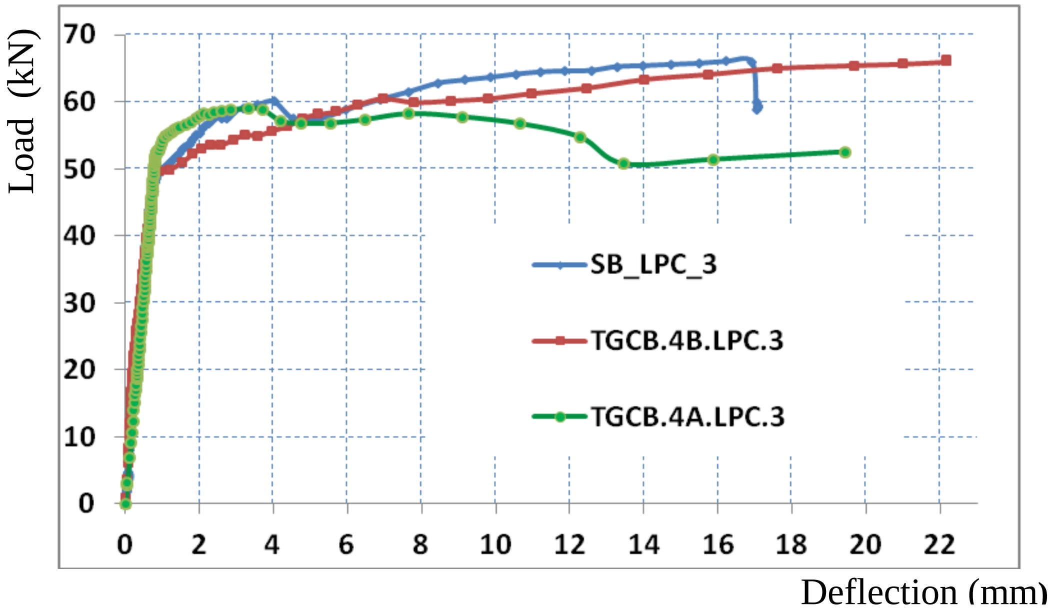


Figure 6.4a. Load – deflection curves for Batch 3 (LPC and cured for 28 days). The TGCBs have four TGCUs each. The red curve corresponds to orientation B, and the green curve to orientation A. The blue curve is the SB without TGCUs.

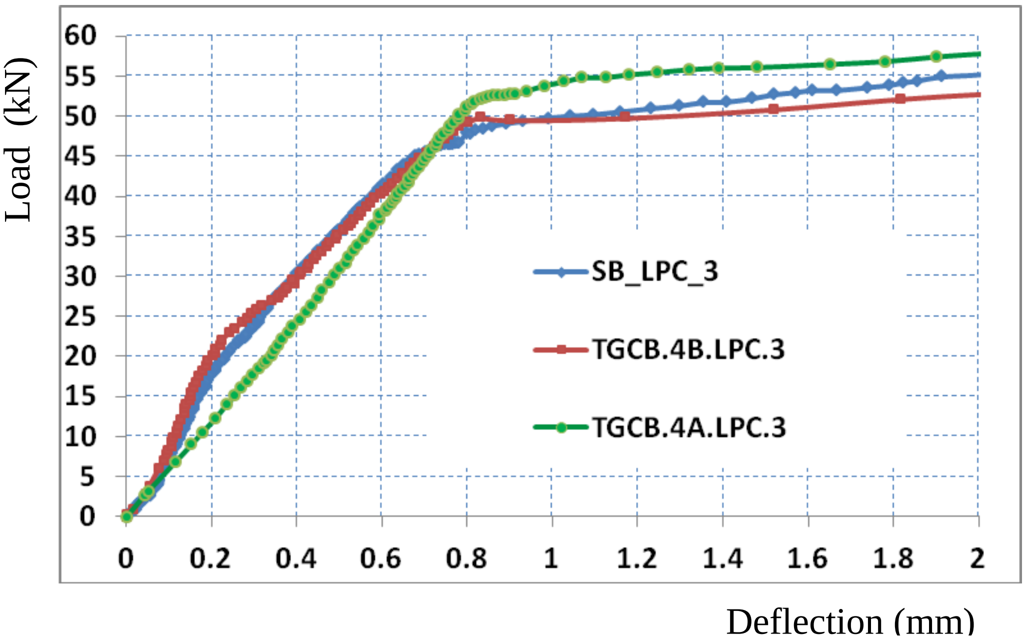


Figure 6.4b Elastic part of the load-deflection curves from Fig.6.4a for Batch 3: LPC and cured for 28 days.

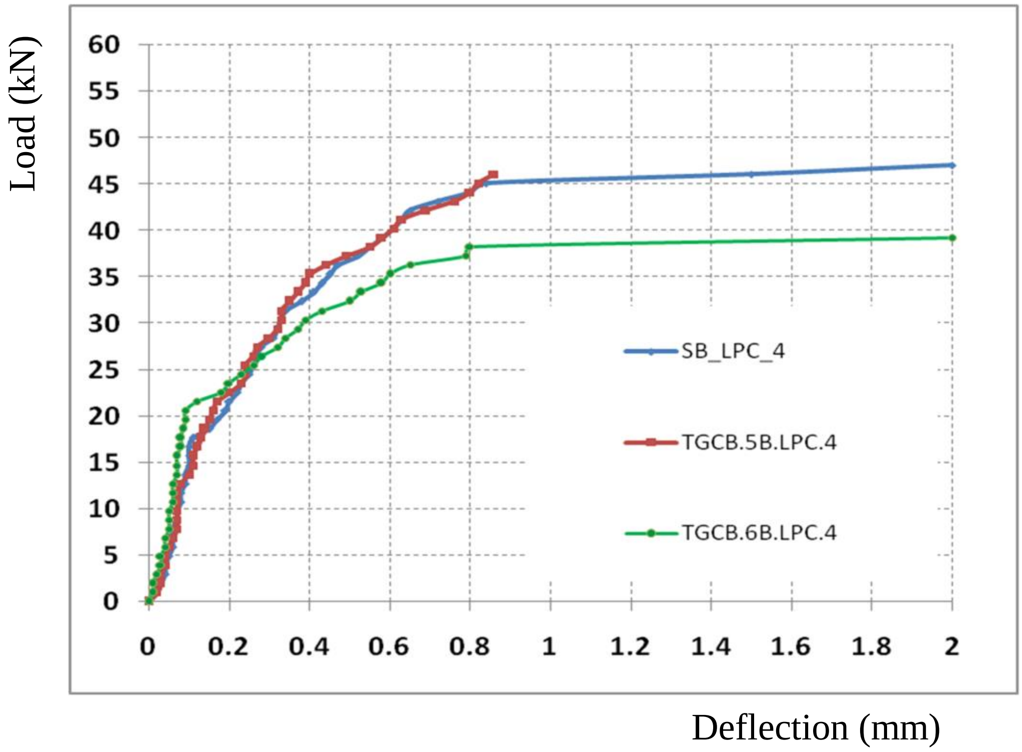


Figure 6.5. Load – Deflection curves for Batch 4 (LPC and cured for14 days). The red curve corresponds to the TGCB with five TGCUs in orientation B, the green curve is for the TGCB with six TGCUs in orientation B, and the blue curve is for control beam, the SB.

The following notations have been introduced for the beams:

- SB_LPC_4 stands for a standard (control) beam of Batch 4 made of low-performance cement (LPC)

- SB_HPC_7 stands for a standard (control) beam of Batch 7 made of high-performance cement (HPC)

- TGCB.5B.LPC.4 stands for a TGC beam of Batch 4 made of low-performance cement (LPC) with five TGCUs embedded in orientation B

- TGCB.6B.LPC.4 stands for a TGC beam of Batch 4 made of low-performance cement (LPC) with six TGCUs embedded in orientation B

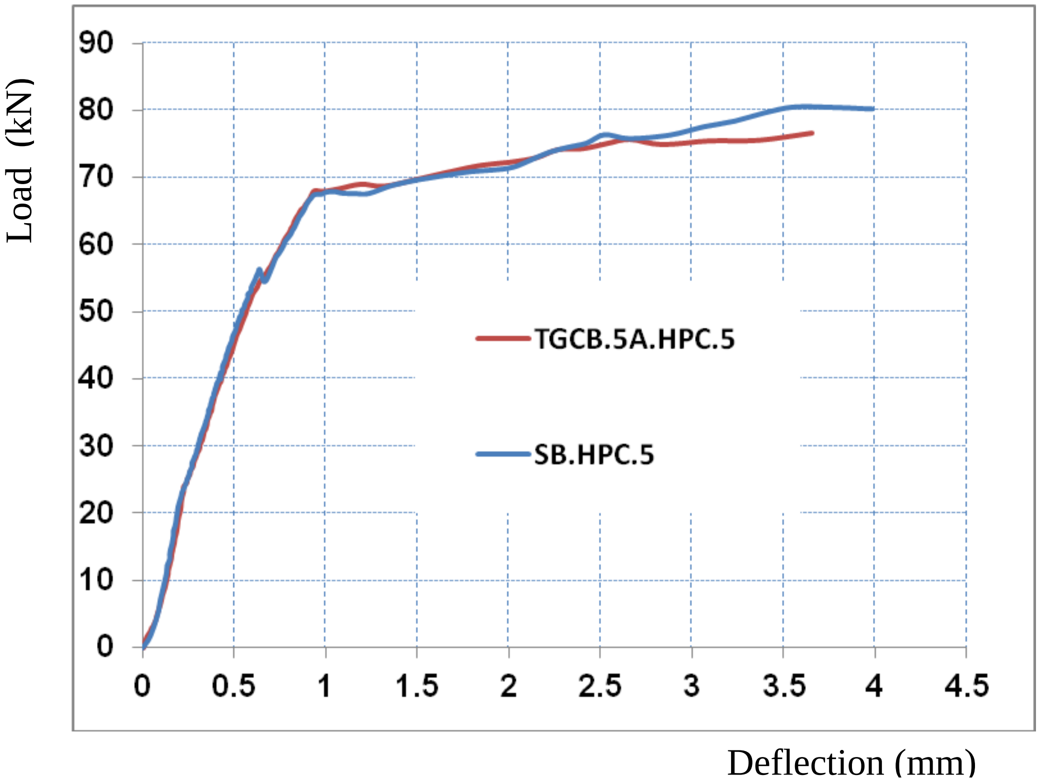


Figure 6.6a. Load – Deflection curves for Batch 5 (HPC and cured for 28 days). The red curve corresponds to the TGCB with five TGCUs in orientation A, and the blue curve to the SB.

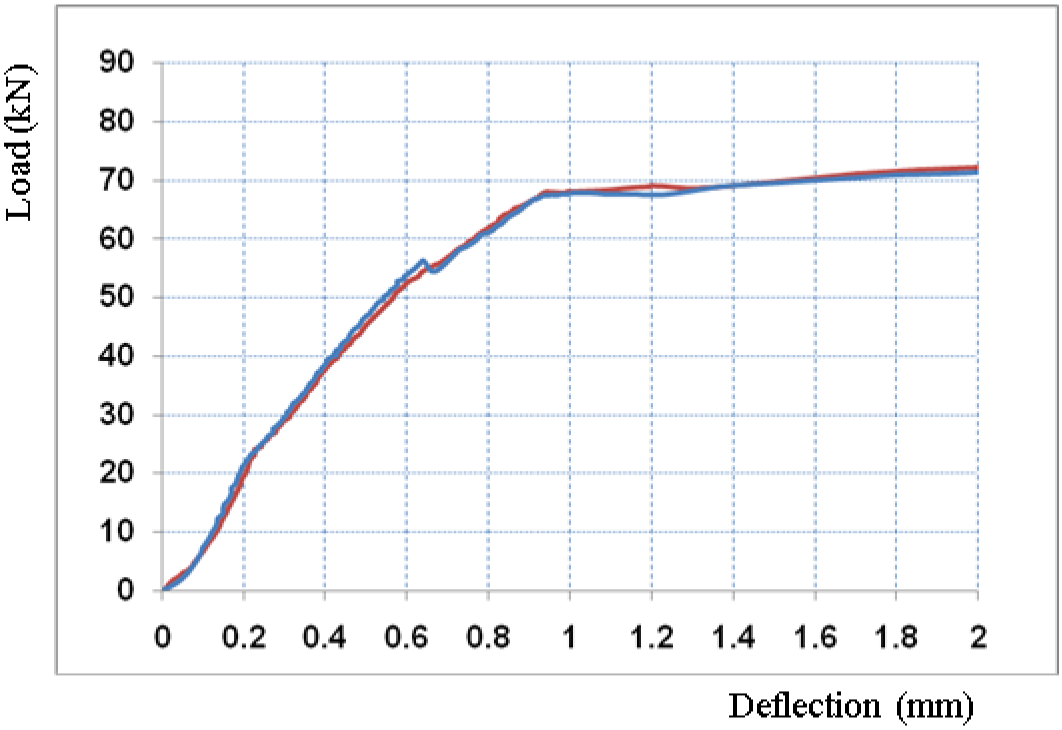


Figure 6.6b. Elastic part of the load-deflection curves from Fig.6.6a (Batch 5 : HPC and cured for 28 days). The red curve corresponds to the TGCB with five TGCUs in orientation A, and the blue curve is the SB for this batch.

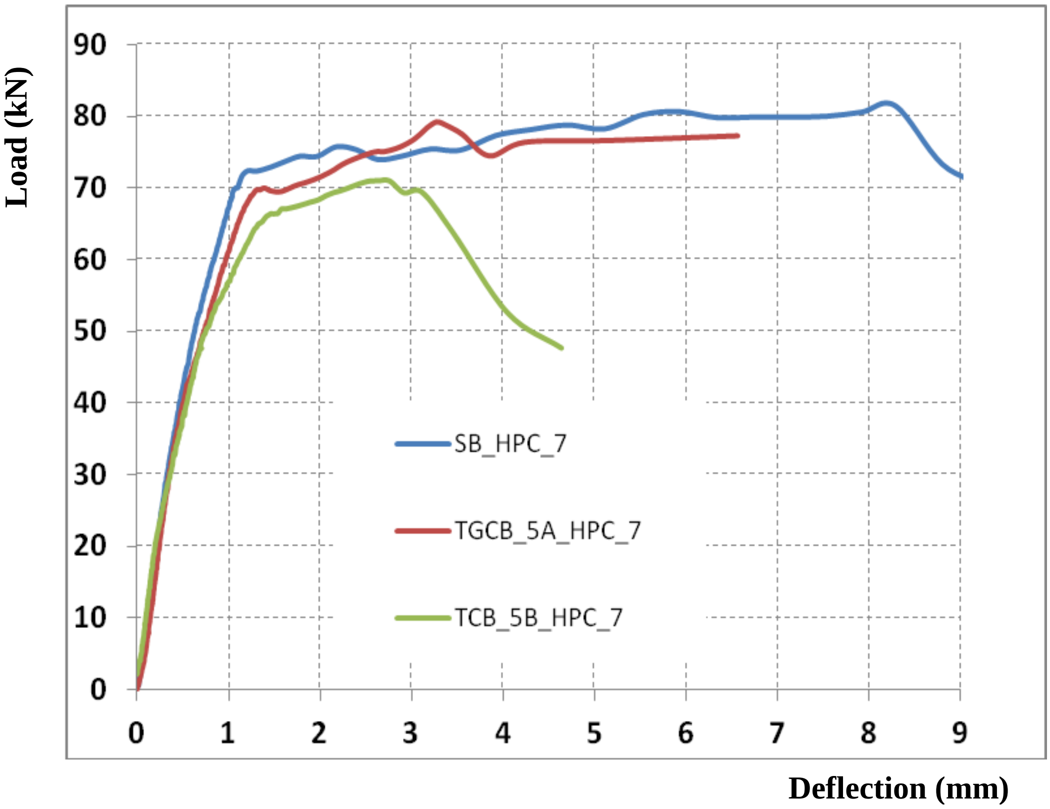


Figure 6.7a. Load – Deflection curves for Batch 7 (HPC and cured for 28 days). The red curve corresponds to the TGCB with five TGCUs in orientation A, the green curve is for to the TGCB with five TGCUs in orientation B and the blue curve is the SB (control beam).

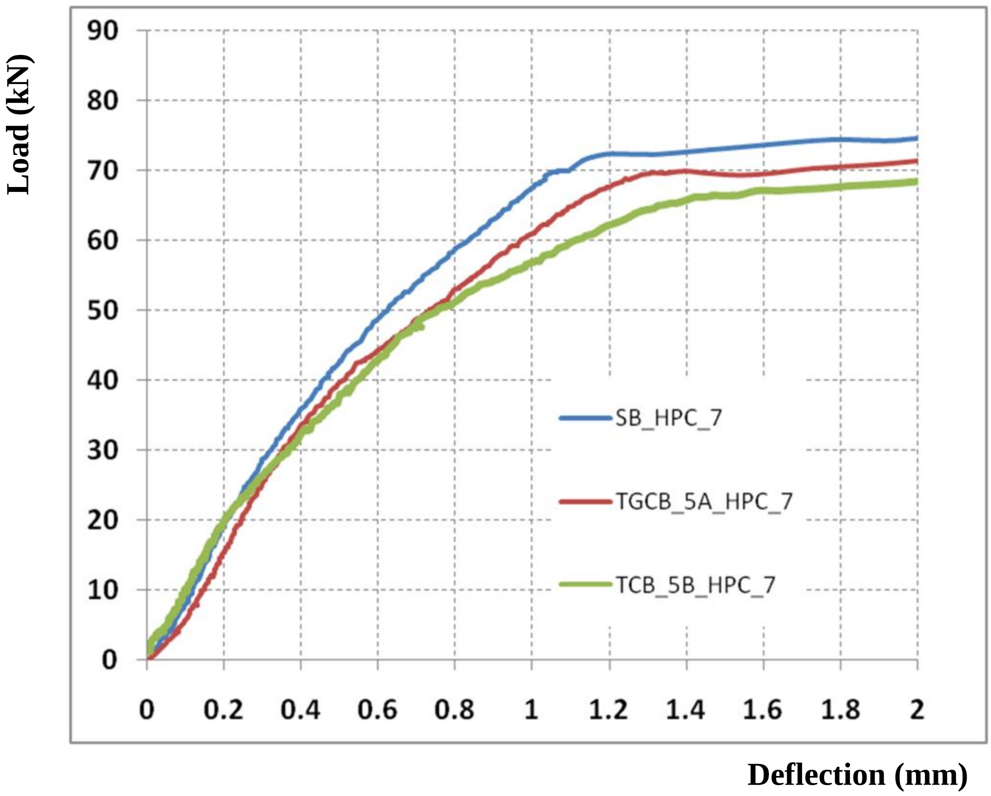


Figure 6.7b. Elastic part of the load-deflection curves from Fig.6.7a (Batch 7: HPC and cured for 28 days)

6.3 Analysis of flexural test results

The results of flexural test for each beam in the four batches 3, 4, 5 and 7 are summarised in Table 6.1. The Table 6.1 shows the variety of conditions across the batches for exploration of flexural properties of TGCBs *vs* SBs from the same batch. The following notation for beam ID has been used: TGCB.4B.LPC.3 stands for a TinGlass Concrete Beam (TGCB) that has four TGCUs embedded in orientation B (hence TGCB.**4B**.LPC.3) and it is made of low-performance cement from Batch 3 (hence TGCB.4B.**LPC.3**).

The Table 6.1 lists the beam ID, the curing time applied, the load corresponding to a midspan deflection of 0.2mm and the maximum load to failure.

Beam ID	**Curing time (days)**	**Load at 0.2mm (kN)**	**Max load (kN)**
SB.LPC.3	28	17.9	66.0
TGCB.4A.LPC.3	28	12.4	59.0
TGCB.4B.LPC.3	28	20.1	66.0
SB.LPC.4	14	21.6	54.0
TGCB.5B.LPC.4	14	20.6	46.0
TGCB.6B.LPC.4	14	23.5	39.0
SB.HPC.5	28	21.0	80.5
TGCB.5A.HPC.5	28	19.7	76.5
SB.HPC.7	28	19.1	80.6
TGCB.5A.HPC.7	28	15.4	79.0
TGCB.5B.HPC.7	28	20.2	71.0

Table 6.1 The characteristics of the beams in flexural bending test

The load-deflection curves have been analysed using the approach of Bhatt et al. (2006). The initial part of the load-deflection curves is of much interest, and it is characterised by the load at deflection of 0.2mm. The higher the load at this deflection, the stiffer is the beam. Flexural strength for all beams is assessed from the characteristic of the plastic regime. The maximum load to failure is a measure of the flexural strength.

The area under the load-deflection curve gives an indication of ductility and toughness. This can be quantified using the concept of Re3, the ratio of equivalent flexural strength to the flexural strength (maximal flexural stress) as it was described in Section 2.6.2 (Jiabiao et al., 2004; Alani and Beckett, 2013). Some researchers monitor the value of CMOD in flexural test (Alani and Beckett, 2013; Zhang and Ansari, 2005) as important characteristic of cracking process. Whilst this was beyond the scope of current work, this investigation can be recommended for future research.

Discussion of the agreement between two methods of data acquisition: For the recommendation of TGCBs as an eco-alternative to conventional precast beams, it is important to show reliability and reproducibility of flexural test measurements. This can be assessed for the beams made of similar concrete mix, by comparing the data taken by two methods, manual method and using data logger, as it is described in Section 3.7.1.

Batch 5 measurements were taken manually whilst Batch 7 beams were tested using load cells and transducer. The load-deflection curves for both batches shall be similar as the batches were produced for the same high-performance concrete (HPC) and for the same curing time duration, 28 days as listed in Table 6.1.

The load-deflection curves for SBs for Batch 5 and Batch 7 are shown in Fig. 6.8. In Fig 6.9, each of TGCBs had five TGCUs in orientation A and the concrete mix was similar for Batch 5 and Batch 7.

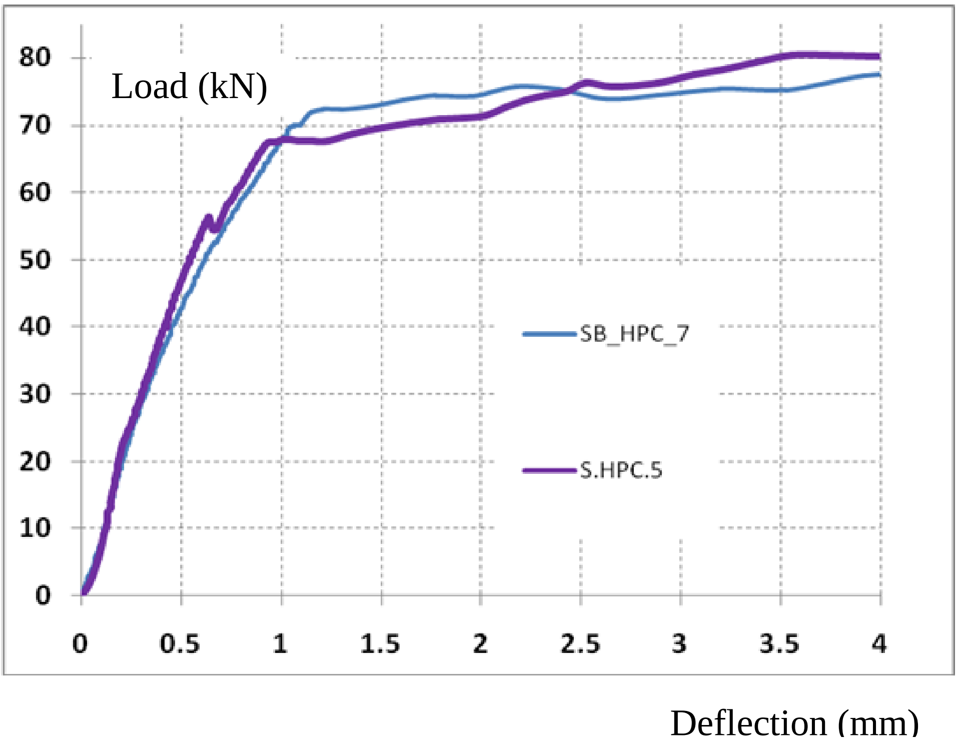


Figure 6.8 Comparison of standard (control) beams, SBs, for Batches 5 and 7

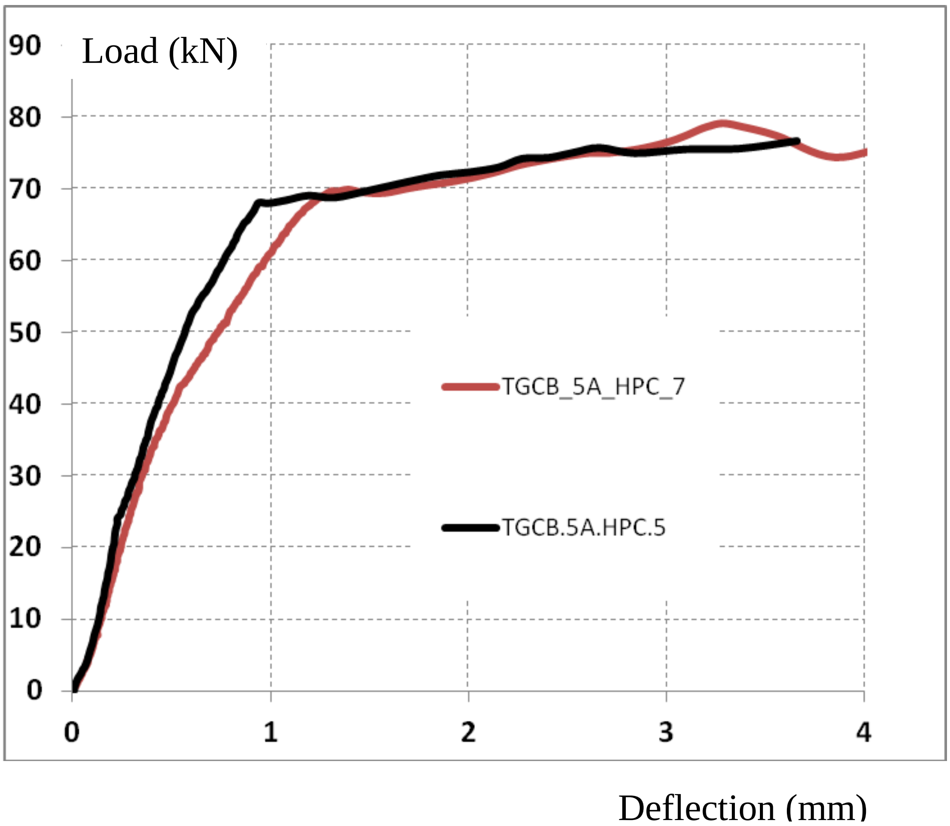


Figure 6.9. Comparison of TGCBs for Batches 5 and 7

There is reasonable agreement between load-deflection curves for SBs in Fig 6.8, and for TGCBs in Fig 6.9. This shows reproducibility of results across the batches, and under various methods of data acquisition.

Assessment of influence of curing times and cement type: It is expected that beam properties will improve with longer curing times and also from using low performance cement to high performance cement. Fig. 6.10 and Fig 6.11 show a comparison of the maximal load (flexural strength) and load at deflection of 0.2mm (stiffness) for SB samples, respectively. As it can be seen from Fig 6.10, the beam strength of the SB specimens is consistent with the expected results, namely

- Longer curing time increases strength
- The LPC (low-performance cement) beams show lower strength than the HPC beams

Moreover, Fig 6.10 shows that there is good reproducibility of strength for Batches 5 and 7 that are both HPC and cured for 28 days. This gives confidence in the stability of the experimental results.

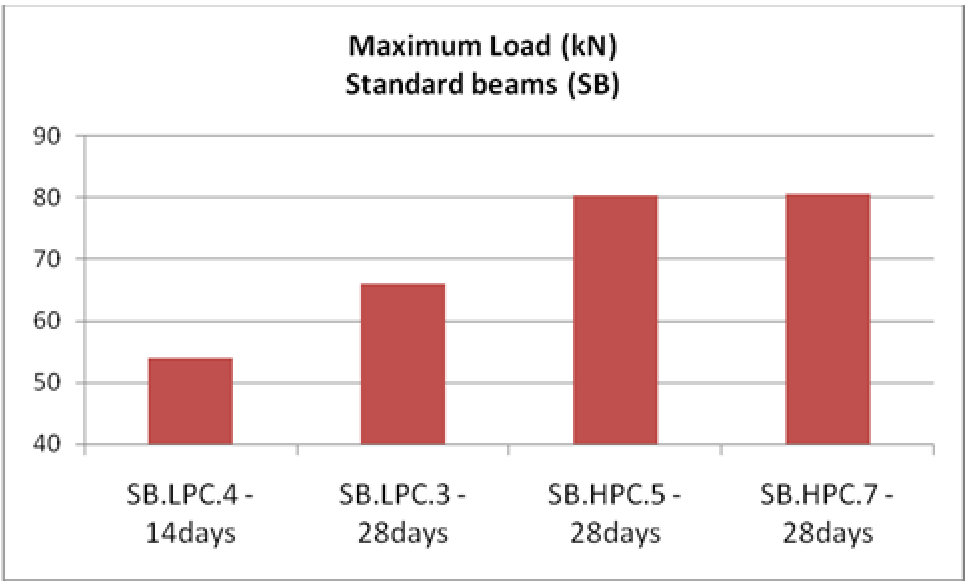


Figure 6.10. Dependence of the strength on cement type and curing time for SBs

There is no observable trends with regard to stiffness in Fig 6.11.

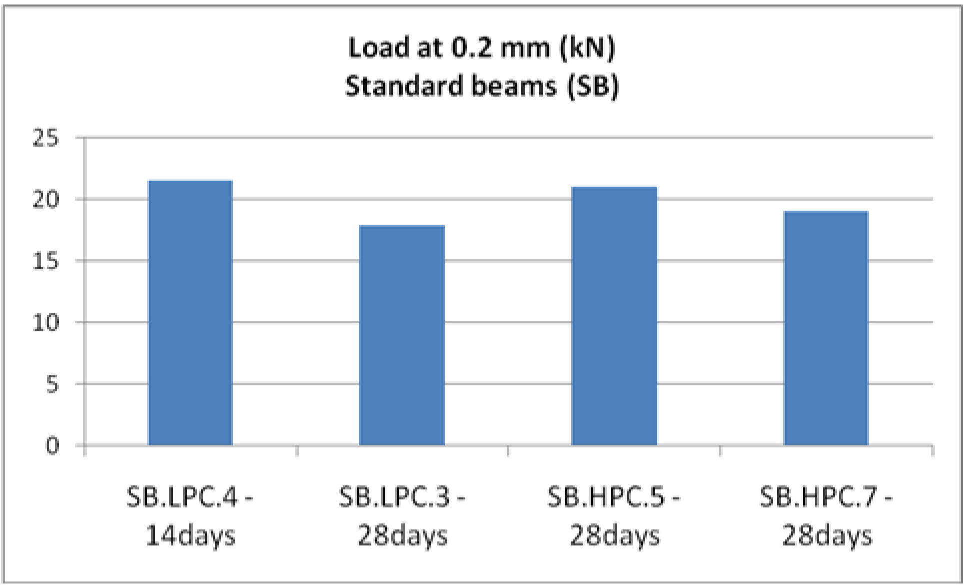


Figure 6.11. Dependence of the stiffness on cement type and on curing time for SBs

Assessment of influence of orientation of TGCUs on flexural properties of a TGCB.

The orientation of TGCUs in a beam is shown in Fig 3.13. The axis of cylindrical TGCU goes along the beam for orientation A, and it is perpendicular to the beam axis for orientation B. The results of flexural testing summarised in Table 6.1 will be revisited for the assessment of the orientation on TGCB flexural properties**.**

Orientation A: Batches 5 and 7 show good reproducibility as shown in Figures 6.8 and 6.9. This encourages the comparison of TGCBs and SBs across these batches.

The comparison of the strength (maximal loads) and stiffness (loads at 0.2 mm deflection) for Batches 5 and 7 is shown in Fig. 6.12 and Fig.6.13, respectively. The TGCB with orientation A have lower strength and are less stiff when compared to their SB counterparts, though the difference is small (about few percent for the maximal load values).

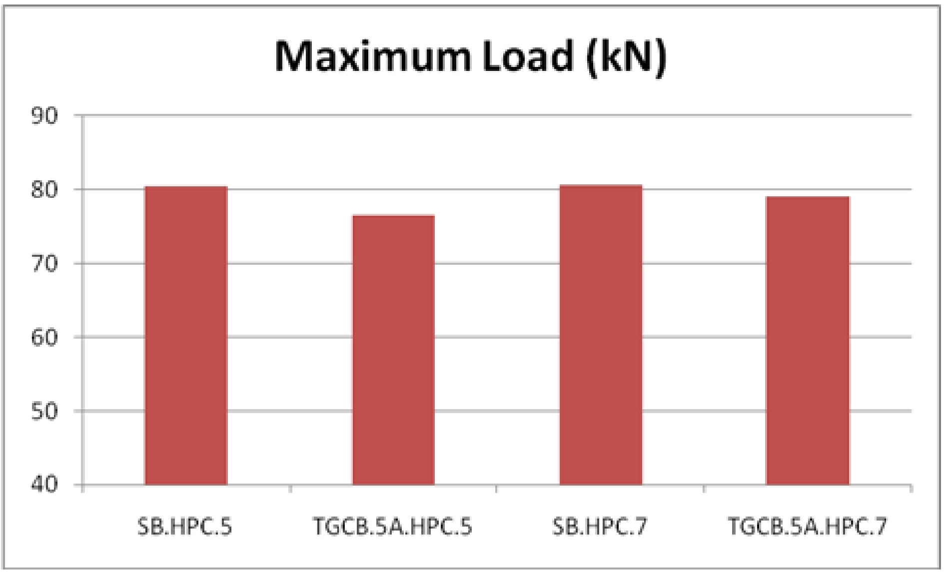


Figure 6.12 Strength of TGCBs vs SBs for orientation A

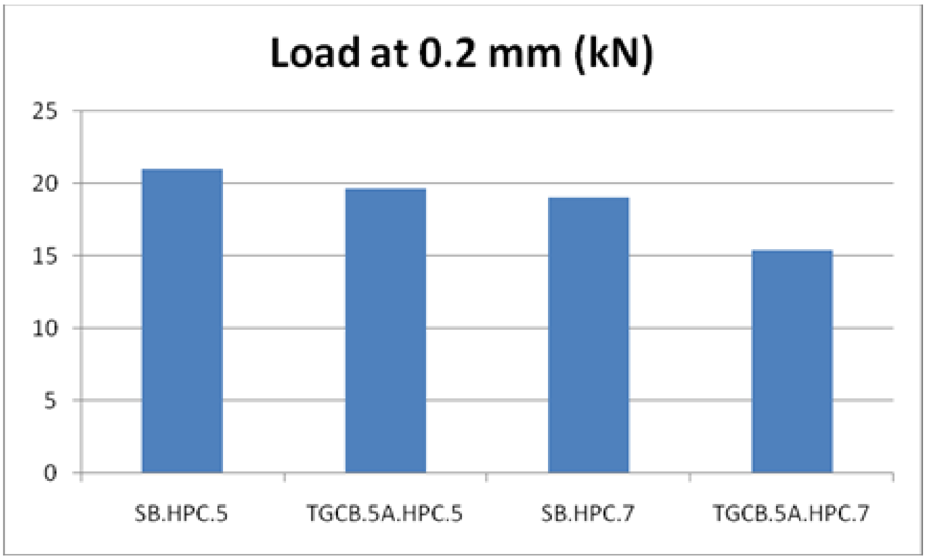


Figure 6.13. Stiffness of TGCBs vs SBs for orientation A

Orientation B: Batch 4 is made with LPC and it is cured for 14 days; Batch 7 is made with HPC and it is cured for 28 days. The TGCBs in Batch 4 and 7 were made with 5 TGCUs in orientation B position. The comparison of the strength (proportional to maximal load) and stiffness (load at 0.2mm deflection) is shown in Fig. 6.16 and 6.17 respectively. The strength decreases in the TGCB relative to its SB by around 15% in the Batch 4, and by 12% in the Batch 7. This a greater decrease than that observed for the orientation A in Fig 6.12 – 6.13. The stiffness does not show any particular trend as it can be observed from Fig 6.15.

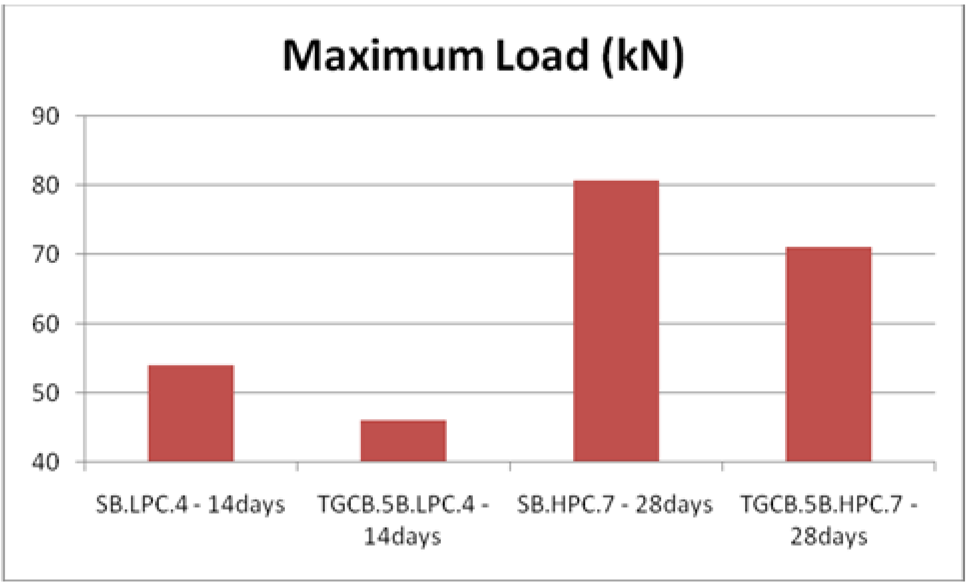


Figure 6.14. Strength of TGCBs vs SBs for orientation B

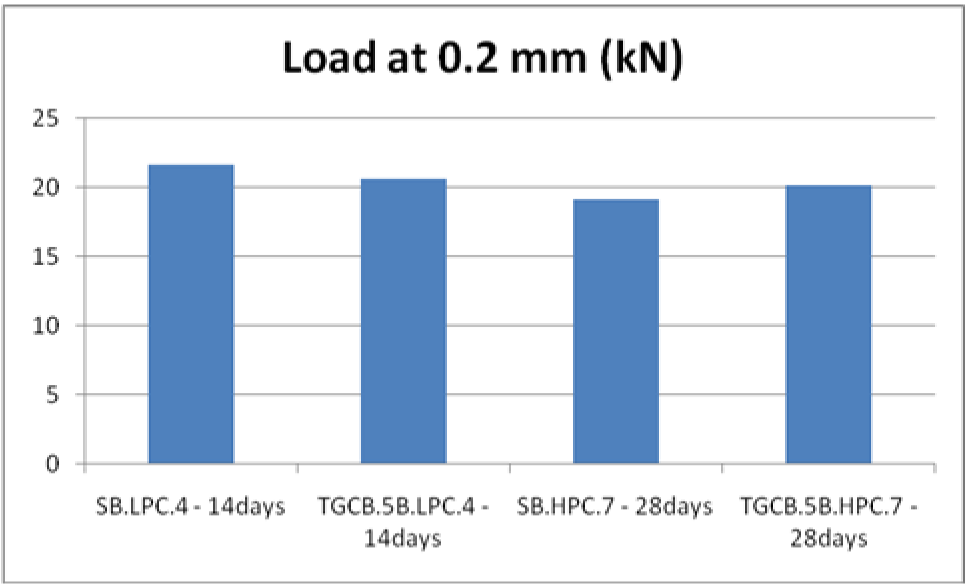


Figure 6.15 Stiffness of TGCBs vs SBs for orientation B

An analysis of batches 3 and 7 should allow to compare TGCU orientations (as shown in Fig 3.13). Direct conclusions can be made by using Table 6.2 which is a relevant extract from Table 6.1.

Beam ID	Curing time (days)	Load at 0.2mm (kN)	Max load (kN)
SB.LPC.3	28	17.9	66.0
TGCB.4A.LPC.3	28	12.4	59.0
TGCB.4B.LPC.3	28	20.1	66.0
SB.HPC.7	28	19.1	80.6
TGCB.5A.HPC.7	28	15.4	79.0
TGCB.5B.HPC.7	28	20.2	71.0

Table 6.2 The characteristics of Batches 3 and 7 in flexural testing (an extract from Table 6.1)

The bottom rows in Table 6.2 show results for Batch 7 with five TGCUs in HPC. The same tendency is observed as in the analysis above of other batches with five TGCUs: the maximal load (flexural strength) for the orientation A (for TGCB.5A.HPC.7) is higher than for orientation B (for TGCB.5B.HPC.7). The stiffness of the beam TGCB.5B.HPC.7 with orientation B is comparable to the SB counterpart, SB.HPC.7, and for orientation A, the TGCB.5A.HPC.7 is less stiff.

The top rows in Table 6.2 show the results for Batch 3 made with LPC. Four TGCUs were embedded in TGCB.4A.LPC.3 in orientation A, and four TGCUs were embedded in TGCB.4B.LPC.3 in orientation B. The results on maximal load show that flexural strength of the beam of orientation B is comparable than SB, whilst the beam with orientation A is less strong (by 10%). The TGCB.4A.LPC.3 (orientation A) is less stiff than the beam with orientation B, TGCB.4B.LPC.3, and the SB (SB.LPC.3).

The next question will be whether the number of embedded TGCUs has an effect, and this will be discussed below.

Assessment of influence of the number of TGCUs on flexural properties. As follows from Table 6.1, the Batch 4 shows the data for beams with 5 and 6 embedded TGCUs. For the case of five (odd-numbered) embedded TGCUs, the load was applied above the central TGCUs. For even-numbered TGCUs (4 or 6 TGCUs), the area of load application was above the space between two TGCUs (see Fig 6.2 – 6.3). This might influence flexural properties. The data in Table 6.3 are extracted from Table 6.1 to assess this.

There is a decrease of strength with increasing number of TGCUs from 5 to 6:

SB.LPC.4	14	21.6	54.0
TGCB.5B.LPC.4	14	20.6	46.0
TGCB.6B.LPC.4	14	23.5	39.0

Table 6.3 Batch 4 in flexural testing (an extract from Table 6.1)

These data suggest that the placement of TGCU directly under the area of load application for odd number of TGCUs (as in TGCB.5B.LPC.4) is favourable. This configuration increases the strength of the beam when compared with the beam for even-numbered TGCUs (TGCB.6B.LPC.4). The stiffness shows opposite tendency.

As a conclusion the data indicate a need for further investigation, including assessment of stress distribution in TGCBs by FEA methods; this is as recommendation for further research.

6.4 Summary

This chapter described the flexural testing of TGCBs and SBs. The TGCBs and their SB counterparts were made from the same concrete mixture and with the same reinforcement by steel rods. All beams were prepared with the dimension of 71 X 15 x15 cm^3 and tested using a simply supported beam with central load (three-point beam) to establish load-deflection curves for analysis of flexural properties.

The experimental programme consisted of tests with the following variables:

- Type of cement: low performance cement (LPC) vs high performance cement (HPC)
- Concrete beam curing times: 14 days vs 28 days
- Orientation of TGCUs in two positions with notations A or B positions (Fig. 3.13)
- Number of TGCUs embedded in a beam

Flexural strength: The flexural strength characterised by the maximum load to failure showed good agreeement fot TGCBs (in Orientation A) and SBs for the HPC samples with five embedded TGCUs as it is shown in Fig 6.12.

For the LPC samples, (Fig 6.14) at 14 days of curing, SB has higher flexural strength than the TGCBs in Orientation B. There is a decrease of strength with increasing number of TGCUs from 5 to 6 as is shown in Table 6.3.

Both TGCBs and standard beams (SBs) show similar performance for all batches. The flexural strength for TGCBs and SBs is similar as it can be seen in Table 6.1.

Stiffness: The stiffness is assessed as the load at 0.2mm of beam deflection. This is seen as an important characteristic of the elastic regime. There appears to be no definitive trend for the stiffness. The estimated stiffness variation between TGCBs and SBs is within experimental uncertainties. As a tendency, the analysis of data may suggest that the orientation B produces a stiffer beam than the orientation A. This conclusion is achieved for TGCBs with four TGCUs (Batch 3) and with five TGCUs (Batch 7) as is summarised by Table 6.2.

Stress concentrations: It should be noted that the plastic spacers placed at casting stage, may act as stresss raisers in a beam (Chapter 3). Hence the enhanced number of spacers in TGCBs puts them in unfavourable position when compared with the control beams, SBs. This shows that the comparison of flexural properties of TGCBs and control beams, SBs are on the conservative side. It can be concluded that a good flexural perfomance of TGCBs is observed even under weakening of the TGCB by additional spacers.

Toughness: The deflection at fracture for TGCBs and SBs is high enough to give the evidence of an ample plastic regime preceding the collapse of the beam. This agrees with the requirements for the desirable mode of failure (Bhatt et al., 2006).

Stability of data: There is good consistency and reproducibility of data across the batches and for different methods of data acquisition as it was shown by Figs 6.8 – 6.9 for Batch 5 and Batch 7. Reliability and stability of properties is an important factor for construction industry. The results are consistent for the variety of curing durations and cement types and shows the versatility and stability of TGCBs performance vs SBs, and this strengthens the possibility of industrial implementation of TGC as the eco-alternative to precast concrete.

CHAPTER 7
ENVIRONMENTAL EVALUATION

7.0 Introduction

The European Union's policy on taxing the excessive emissions of producers, and thus promoting the minimization of CO_2 emissions by producer, is described in the Directive 2003-87-EC (EU Directive, 2003). This EU directive places a requirement on producers to consider not only the cost of their production but also the cost of decarbonisation and the UK supports this policy.

The nation with the highest policy standards within the EU in relation to these environmental concerns is the United Kingdom. The UK government has set a target for the reduction of environmental emissions which is almost three times higher than those set by the other EU-15 nations: for 2012, the UK government has set a 20% reduction in emissions from their 1990 levels, whereas the target of the other EU-15 nations is only an 8% reduction over the same time frame EC (EU Directive, 2003).

Buildings are responsible for almost half of the UK's carbon emissions, about one third of landfill waste and a quarter of all raw materials used in the economy (SSC, 2008). As discussed in Chapter 2, Section 2.1, the UK construction industry is committed to the use of more recycled content in construction materials and reduction of greenhouse gas (GHG) emissions associated with the manufacture of construction materials and their transport.

7.1 Review of the underlying principles for environmental assessment

Earthship Brighton (2006) was the Low Carbon Trust's first project. It was driven by the objective of delivering a sustainable community and changing values in the construction industry. The Earthship features a wall from cut-up glass bottles that are taped together to form glass bricks. The glass bricks are then laid in rows and bonded by cement to form a wall. However, this method is not structurally sound as it can only be applied to structures under light loads (fences, partitions) but not to load-bearing walls.

For structural applications requiring heavy or substantial load bearing capabilities, an obvious innovation is to granulate waste glass into glass cullet to replace aggregate in concrete mixtures. The occurrence of the ASR prevents widespread use or adoption of waste glass cullet to replace aggregate in concrete mixtures, and the research community and the industry are actively seeking a solution as reviewed in Chapter 2.

This research topic is a response to the need to use more recycled product in construction. Hence the author has investigated the new material, TinGlassConcrete (TGC) as an eco-alternative to precast concrete. The TGC construction elements Tin Glass Concrete Cubes (TGCC) and beams (TGCB) differ from standard precast concrete cubes and beams by the incorporation of the TinGlass Construction Unit (TGCU) embedded in the concrete. TGCU is embedded at the casting stage and the details are given in Chapter 3.

As shown in Chapters 4 – 6, the TGC products have comparable ASR stability to standard precast concrete. Both TGCC and TGCB products have good characteristics in relation to the compression and bending tests used to measure the strength and toughness of structural materials. The bond between TGCU and concrete has been explored by X-ray diffraction as shown in Appendix 2.5 (Dr M Smith, private communication, 2010; Ojomo, 2010). The results have shown a good intimate bonding between TGCU and concrete, in a precast concrete cube with embedded TGCU.

A proper analysis of the value of the TGCU approach requires an additional component: the environmental assessment of material selection for building construction. The development of a systematic performance methodology in material selection is possible through the internationally accepted framework ISO 15686-6 (2004), which provides a number of clear guidelines for the environmental assessment of the building materials. However, it is the viewpoint of the author that this standard is not comprehensive enough. Other expert commentators share this viewpoint. “The standard itself would not be a sustainable tool but would dictate what is required for such a tool”. “There are no standards available in the UK or other countries that dictate what should be involved in a sustainable tool” (BRE, 2006).

Generally, buildings are designed to meet the requirements of building regulations. However, green building design requires designers to go beyond the regulations in a quest to improve overall building performance while at the same time minimizing the environmental impact of the construction and maintaining control of costs. Most of the building evaluation tools have been developed to transform the design goal into specific performance objectives such as environmental, economic and social benefits. These are used by professionals for making design decisions for materials selections and for determining the performance of particular aspects of them (TEEART, 2005).

Different tools are available for the varying requirements of a user, depending on the nature of the technology or the design strategy being evaluated. The methodologies of these building assessment tools vary and may include, as shown in Table 7.1:

- Assessment tools: LISA, ENVEST, ATHENA EIE, Ecoquantum, Ecoprofile, BEES and EQUER – which provide quantitative performance indicators to help make decisions on design alternatives (TEEART, 2005).
- Ratings tools: Ecospecifier, Evergen, GBTool, BREEAM – which determine the performance requirements and level of green building rating based on the rating methodology used; often it is rather subjective (TEEART, 2005).

Lack of reliable information concerning embodied energy (EE) consumed for the production of materials, the related emissions and their combined interrelationship with the economics of building design has long been a barrier to effective selection – as highlighted in the report for the SUE-MOT consortium in 2004 (BRE, 2006)

	Assessment Tools		Rating Tools	
TOOL	BEES	ECOQUANTUM	EVERGEN	ECOSPECIFIER
PURPOSE	Material selection	Material selection	Material selection	Material selection
PHASE	Design End of Life	Design End of Life	Design Operation Maintenance	Design Operation Maintenance
ATTRIBUTE	material resource, transport, energy, water, environmental loading biodiversity	material resource, transport, energy, water, environmental loading biodiversity	material resource, transport, energy, environmental loading biodiversity	material resource, transport, energy, water, environmental loading biodiversity
PROVIDER	NIST, USA	IVAM,NETHER LANT	CSIRO	RMIT & Eco Recycle Victoria

Table. 7.1 The comparison of tools regarding material selection (TEEART, 2005)

For this study, the following applies:

PURPOSE: the selected materials are waste glass and waste steel cans. Both are considered theoretically "infinitely recyclable" (BritGlass, 2011; SCRIB, 2011). Waste glass is selected as a material to replace concrete; and waste steel cans are selected to protect the waste glass from the cement in order to limit the occurrence of ASR.

PHASE: a new material, TGC, is created when embedding TGCU made from these two waste materials, into precast concrete. The selected material is designated as a new product, which would be used from the start of the life of the building till the end of its construction life. The UK average total glass recycling rate is 61% (Miltek, 2012). The recycling of waste by creating a product will offset the environmental impact of the 25% of recycled waste glass used for road aggregates and the estimated 37% of recycled waste glass destined for landfill sites. The new product can be created which has a potential life cycle of at least 50 years.

ENVIRONMENTAL ATTRIBUTE: the selected material will attribute in material resourcing, transport, energy, environmental loading. The environmental indicators are: embodied energy, the environmental emissions for the production, the quantity of prime material saved, the transportation of material, and the recyclability of the material.

7.2 Evaluation of eco-properties of TGCU

7.2.1 Savings of prime materials

The use of TGCUs reduces the volume of concrete required in a construction project and this creates savings in the use of prime materials. The amount of saved prime materials – such as cement, sand and aggregate – can easily be evaluated for a construction element (cube or beam). The evaluation is based on the known volume of the TGCU in a cube or beam and the proportion of cement, sand and aggregate in the concrete mixture of known density.

The calculations shown are per TGCU made of standard tin-plated steel can of diameter 0.07m and height 0.06m. This makes the equivalent volume of TinGlass as 230.79cm^3.

The standard dimension of a concrete cube used in this study is 1000 cm^3. Hence a TGCC cube with TGCU is composed of 230.79cm^3 of TGCU and 769.21cm^3 of concrete.

The density of the concrete used for this study was also determined using the calibrated balance in the concrete laboratory for weight determination and the water displacement method described in Chapter 3 for volume measurement (Ojomo, 2010). Using 10 prepared control cubes (without TGCU) with dimension 10x10x10cm, the average density obtained was 2370 kg/m^3. From the materials database (CES, 2011), the density of concrete varies between 2300 – 2600 kg/m^3.

The virgin materials of a standard concrete block are partially replaced by TGCU in a TGC precast element. From the preceding paragraphs, the 230.79 cm^3 of TGCU is equivalent to a partial replacement of 0.55 kg of virgin concrete in a TGCC.

This constitutes an incremental saving per cube. For example, a wall of $1m^2$ of thickness 10cm, will require a hundred cubes – producing a saving of 55kg of virgin concrete.
The proportion of materials to make the concrete in this study is Water: Portland Cement: Sand: Aggregate equal to 0.6: 1 : 2: 4 (CES, 2011).

Hence the individual materials savings for a wall of $1m^2$ of thickness 10cm (100 TGCCs) will comprise approximately of:

Aggregate of 10mm in size	Sand	Portland cement	Water
28.9 kg	14.5 kg	7.2 kg	4.3 kg

7.2.2 Production energy

The production of a precast element requires both materials and energy input. The allocation for the energy involved in the production step of precasting has been ignored, as the laboratory procedure of producing the precast element was carried out manually.

The consideration covered under this section is the embodied energy (EE) associated with the production of TGCUs. It will be compared with the embodied energy associated with the production of the concrete that is replaced by TGCU in a precast concrete construction element.

The EE associated with the production of TGCUs can be conservatively estimated from the experimental procedure under laboratory conditions. The energy required to produce a TGCU was measured using a Powerperfector Plug-in Power and Energy Monitor (www.powerperfector.com) used by University of Brighton, Waste and Energy Research Group (WERG) in their field work for surveying (Firoozmand, 2010). It takes 2 hours of heating in an electric furnace for a batch of 8 TGCU. The temperature is ramped up and maintained at 950°C for an hour.
The energy consumption of the furnace was 3.93 kWh. Hence the maximum energy consumed for the production of one TGCU is about 4 kWh / 8 = 0. 5 kWh. Using the relationship of 1kWh = 3.6MJ, then the EE associated with the production of a single TGCU is 1.8 MJ.

The average embodied energy (EE) of concrete is 1.9MJ/kg (CES, 2011). The weight of concrete as replaced by the TGCU is around 0.55kg which amounts to an EE of concrete of 1.04 MJ.

It should be noted however that production of TGCU is considered under laboratory conditions, whilst the production energy of concrete (CES, 2011) is estimated under industrial conditions. The estimate for embodied energy under an established and well-researched industrial process with economies of scale in place is bound to be lower than for laboratory-based production. Thus, the comparison of production energy for TGCU *versus* the equivalent weight of concrete is biased against the TGCU. Such a comparison will seriously overestimate the cost of TGCU production at comparable conditions to concrete.

It is beyond the scope of this Thesis to give an estimate of TGCU production costs under industrial conditions, because of the novelty of the current proposal of the TGC concept, it is currently developed and manufactured under laboratory conditions only.

Nevertherless, the estimates below will be based on the comparison for TGCU at laboratory conditions *versus* the equivalent concrete weight produced under industrial conditions. This unequal footing shall be kept in mind when assessing viability of future industrial implementation of TGC.

It will take 1.8MJ of energy to make a single TGCU but it will take 1.04MJ of energy to make the concrete it will be replacing. This means that under these conservative estimates, a precast element with TGCU will have a higher production EE than its comparable normal precast element (without TGCU).

The embodied energy of the product must also take into consideration the embodied energy of the materials used to make it. Under the heading of PHASE and PURPOSE as given above, the selected materials are waste glass and waste steel cans for the purpose of making a new product, TGCU.

There is no EE associated with the production of the glass and cans as these materials are derived from the post-consumer waste stream. However there is energy associated with the alternative end-of-life uses for these materials.

The end-of-life scenario for post-consumer recycled waste glass is indicated below:

Glass bottles → 61% Recycling rate →
- 38% Remelt
- 25% Aggregate
- 37% Landfill → **TGCU**

There is no associated EE for an alternative end-of-life use as the glass material is derived from recycled waste glass that is likely to end up in landfill sites.

The end-of-life scenario for post-consumer recycled packaging tin-plated steel can is indicated below (SCRIB, 2011):

Waste steel can → 65% Recycling rate →
- Recycled steel (A packaging can is made up of 50% recycled steel).
- **TGCU**

The use of steel for TGCU can be at the expense of closed-loop recycling to make new cans. The average embodied energy of virgin steel and recycled steel is 33.7 MJ/kg and 9.8 MJ/kg respectively (Lee, 2010). Recycled steel can is a valued commodity. The weight of an average baked bean steel can with lid is 51g with a corresponding estimated embodied energy of 0.50MJ (9.8MJ/kg x .051kg). The steel can is made from around 50% recycled content (Tata, 2011), so the allocation for the can is approximately half, 0.25MJ. However, the average UK steel packaging rate is taken as 65% for packaging recycling efficiency as reported for 2010 (Tata, 2010) and a target of 71% for 2012 (DEFRA, 2010), so the corresponding allocation is reduced accordingly to 0.16MJ.

If it is assumed that the can used for making TGCU is to be taken from the same stock that will go towards closed-loop recycling of the can, then the diversion from closed-loop recycling will go towards the allocation for the TGCU product. The EE of the TGCU product is estimated to be equal to the production energy needed to make a single TGCU plus closed-loop steel recycling diversion, 1.8MJ + 0.16MJ = 1.96MJ.

The EE of the product is dominated by the production energy. The production of TGCU in future applications may require reconsideration. It is noted that the estimates are conservative because the production is carried out in the laboratory, a small scale production scheme and notably using an electric furnace. It is anticipated that a commercial production may introduce economy in scale and reduce the estimates below 1.8 MJ per TGCU.

7.2.3 Relative CO_2 emissions

The CO_2 emissions will depend on the source of fuel used for energy production. In the case of TGCU, the 1.8MJ = 0.5kWh of energy needed may be derived from either electricity or natural gas. The equivalent CO_2 emissions using electricity is 0.27 $kgCO_2$/TGCU and for gas is 0.09 $kgCO_2$/TGCU. The following conversion factors taken from the Carbon Trust, "Energy and Carbon Conversions 2010 Update" have been used: grid electricity is 0.545 $kgCO_2$ per kWh and gas is 0.185 $kgCO_2$ per kWh (Carbon Trust, 2010). Thus the CO_2 emissions are lower if natural gas is used in future production. In future analysis, for carbon counting, it will be necessary to identify the source of fuel for the production process for TGCU.

TGCU will replace some of the concrete in the precast element. Ideally, the CO_2 emission associated with the production of TGCU will be less than that of the concrete. BRE Environmental Profiles database, Building Research Establishment (BRE) has compiled a comparison of the embodied carbon dioxide (ECO_2) in different construction materials and has provided information for the ECO_2 for concrete. The data below are taken from the reference (BRE, 2008)

The value of 300 kg/m^3 is a representative value for the Total Cementitious Content of concrete as it is close to the average cementitious content of ready mixed concrete. In practice the actual cementitious content may depend on the quality and performance of the materials available but the value of 300 kg/m^3 is a representative one.

The ECO_2 value of cementitious material is taken as the UK Weighted Average Cementitious of 720 kgCO_2/tonne as set out in the Information Sheet P12, entitled Embodied CO_2 of UK cement, additions and cementitious material. This includes the CO_2 released during cement production.

The water content is a representative value that aligns with the cementitious content and strength of the concrete. The ECO_2 value for water is 0.3 kgCO_2/tonne.

The aggregate content assumes an overall concrete density of 2380 kg/m^3. The designated ECO_2 value for aggregate is 4 kgCO_2/tonne. (This figure is assumed even if the density of concrete for this study is 2370 kg/m^3).

In Box 7.1, the calculation for ECO_2 of concrete is illustrated by a typical example (BRE, 2008), and an ECO_2 of 0.094 kgCO_2/kg is obtained for of 'UK concrete'.

Box 7.1: ECO2 of UK Concrete

An example of the calculation for ECO_2 of concrete is illustrated as follows (BRE, 2008). The ECO_2 for concrete is calculated by multiplying the mass of each ingredient by its ECO_2 value and adding them together. For example, a cubic meter, 1m^3, of 'UK Concrete' is comprised of 300 kg cementitious, 165 kg water and 1,915 kg of aggregate . Using the ECO2 values given above, the ECO_2 of 1m^3 concrete is:

$$0.300 \text{ tn} \times 720 \text{ kgCO}_2/\text{tn} + 0.165 \text{ tn} \times 0.3 \text{ kgCO}_2/\text{tn} + 1.915 \text{ tn} \times 4 \text{ kgCO}_2/\text{tn} = 224 \text{ kgCO}_2 \text{ per m}^3$$

Dividing by the density of concrete, 2380 kg/m^3, gives an

ECO_2 of 0.094 kgCO_2/kg of 'UK concrete' .

The proportion of materials to make the concrete in this study is:

Water : Portland Cement : Sand : Aggregate = 0.6 : 1 : 2 : 4 .

Using the same calculation method as above and applying it for the amount of concrete replaced by 100 TGCUs (see Section 7.2.1) gives the cementitious content of 7.2 kg, water of 4.3 kg and aggregate (sand + coarse) of 43.4 kg.

Then the ECO_2 of the concrete replaced by 100 TGCUs is estimated as:

$$0.0072 \text{ tn x } 720 \text{ kgCO}_2\text{/tn} + 0.0043 \text{ tn x } 0.3 \text{ kgCO}_2\text{/tn} + 0.0434 \text{ tn x } 4 \text{ kgCO}_2\text{/tn} = 5.36 \text{ kgCO}_2$$

The ECO_2 of the 0.55 kg concrete replaced by a single TGCU is 0.054 $kgCO_2$.

The carbon balance will also include the contribution from the material selection. Around 570g of waste glass is used to make a single TGCU. The estimated CO_2 benefits of diverting waste glass from landfill and recycling it, as cited by DEFRA in a waste strategy report (DEFRA, 2012b) is 0.500 $kgCO_2$ per kg of glass for closed-loop recycling. The glass for use in TGCU is recyclate that has no designated open-loop use and likely to end up in the landfill.

By comparison, steel is diverted from a closed-loop recycling option where recycled cans contribute to reduce the CO_2 emission of the steel industry. On average 2.38 $kgCO_2$ are emitted for every kg of virgin steel produced (Worldsteel, 2011). If it is assumed that the recycled content of steel is 50% steel scrap, then a kg of recycled steel can save 1.19 $kgCO_2$ for using only half of virgin materials. However, there is also an estimated decrease in the energy required to process recycled steel compared to virgin steel from 33.7 MJ/kg to 9.8 MJ/kg; a reduction of around a 70%. Overall, it is estimated that recycling one tonne of steel scrap saves 80% of CO_2 emissions produced when making steel from iron ore (Tata, 2011).

The weight of an average baked beans can with lid is 0.051kg. A can of baked beans is responsible for 0.121 $kgCO_2$ (2.38$kgCO_2$/kg x .051kg) if sourced from virgin steel and 0.024 kgCO2 if sourced from recycled steel. Recycling saves 0.097 $kgCO_2$ per can in a closed loop recycling scheme. The UK recycling rate for packaging steel is 65%, so the saving to the steel industry is 0.06 $kgCO_2$. Ideally, an alternative recycling scheme for the steel can should save more CO_2 emission than the closed loop recycling.

The CO_2 counting for TGCU including end-of-life alternatives for its materials are:

A	CO2 due to production of TGCU using electricity	0.27 kgCO2
B	CO2 due to production of TGCU assuming gas	0.09 kgCO2
C	Embodied CO2 of concrete replacement	0.05 kgCO2
D	CO2 for diversion from landfill of waste glass per TGCU	0.0 kgCO2
E	CO2 to offset for diversion of steel can from closed loop recycling	0.06 kgCO2

TGCU replaces concrete in TGC. Ideally, the CO_2 associated with the production of TGCU (A or B) is less than the ECO_2 associated with concrete it is replacing (C): (A-C) or (B-C) is negative. Under laboratory conditions (A - C) is + 0.22 $kgCO_2$ but if gas is used instead of electricity then (B - C) is +0.04 $kgCO_2$, this is a better situation.

The production of TGCU was based on the energy used to prepare 8 TGCUs, the capacity limited by the size of the furnace used. It is estimated that about the same amount of energy will be needed to prepare twice as many TGCUs and with this adjustment, the carbon balance between production of a TGCU and concrete will be comparable. With the best case scenario using a gas furnace and the economy associated with scaling up production, the production and use of TGCU in precast concrete elements can contribute towards an overall reduction in carbon emissions.

The waste glass used is diverted from landfill and represents no equivalent CO_2 (D), but the steel can is diverted from closed loop recycling of steel cans, which represents a CO_2 offset for the steel industry (E) and must be made up by any alternative recycling scheme. The CO_2 allocation due to the material selection is (-D + E) is 0.06 $kgCO_2$.

In the future, with better recycling rates, the offset for closed-loop recycling of steel may not have to be considered as an alternative recycling option may be desirable such as the use of the steel can in TGCU. This will require a thorough life cycle analysis after industrial implementation of TGC which is outside the scope of this thesis.

7.2.4 End-of-life of TGCU

There is no data for end-of-life use of the TGCU because of its novelty as a product. Some indications of its potential can be made based on the work of this Thesis. Following the compression test (Chapter 5), it was observed that the TGCU remained practically intact after TGC cube failure. It is therefore possible to reuse the TGCU, as it keeps its structural integrity. Given that the life cycle of concrete is 50 years, the TGCU can be potentially continually re-used, or recycled by remelting. TGCU is regarded as a material that is theoretically "infinitely recyclable".

7.2.5 Rapid cooling and possibility of energy recovery

A novel experiment has been carried out as part of the work on this Thesis, to identify an energy-efficient process for making TGCU. It came out the observation that a considerable amount of energy was dissipated into the environment at cooling stage (annealing) after fusing the glass cullet in the tin-plated steel cans.

An innovative idea was identified: to cut annealing times and to retrieve part of thermal energy needed for TGCU production.

In the original procedure describe in the patent (Bataneih, 2006), the annealing of TGCU occurred overnight in the switched-off electrical furnace with temperature naturally ramping down, thus allowing the TGCU to eventually return to room temperature.

In the new procedure, after fusing the glass cullet at 900°C for 1 hour, the temperature is ramped down and when it reaches 600°C, the TGCU is taken out of the furnace and placed in a container of water. The resultant increase of the water temperature in the container under this new methodology demonstrates that it is possible to have energy recovery from the process of making the TGCUs.

The TGCU kept its structural integrity after rapid cooling. This is in stark contrast with a fused glass brick (without protective metal shell provided by fused-on waste steel can as in TGCU). A glass brick at 600°C will defragment catastrophically if placed in water.

The TGCU at 600°C did not show surface cracks and kept its integrity after being placed into water.

The visual inspection of the TGCU produced by this new methodology was not markedly different from a TGCU which came out of the furnace following the original slow annealing procedure. No cracking appeared on the surface of the TinGlass. This observation demonstrates that annealing time can be greatly reduced for TGCU production when compared with a waste glass brick of comparable size.

7.3 Discussion on environmental evaluation

It has been shown that TGCU is an eco-innovative product for partial concrete replacement in precast elements. To realise its full potential, from energy and carbon reduction point perspective, it is important to identify a suitable energy source to supply the energy for TGCU production. Natural gas is better alternative to electricity; a low carbon renewable resource (*e. g.* wind or solar energy) will be even more attractive. It is anticipated that in the future, progress in cement and concrete manufacturing will lower the embodied energy of concrete and as TGCU replaces concrete then a lower energy and CO_2 emission from the production of TGCU will be desirable.

Local transportation has not been accounted for in the carbon balance in Section 7.2 as there is transportation involved in both closed-loop and open-loop recycling schemes. Glass is an inorganic material and there is no landfill greenhouse gas emissions associated with it.

The UK collects more glass through its recycling program than can be returned to closed-loop recycling. Hence while the UK average total glass recycling rate is 61%, only 38% of this is being sent for remelting, 25% is used for aggregates and the remaining bulk is destined for landfills (Miltek, 2012). Landfilling of the excess of coloured mixed glass is costly; the UK Landfill Tax for inactive Qualifying Material including glass is £2.50 per tonne and it is rising (Letsrecycle, 2014)

Moreover, if waste glass is mixed with other waste, it may be not classified as Qualifying Material for lower landfill tax. Then the landfilled amount of waste glass will be charged the standard rate of £72 per tonne (HMRC, 2012) and it is rising with inflation (Letsrecycle, 2014). The high rate for landfill tax is reflective of the national situation of shortage in landfill sites.

A rise in mixed glass collections from 1.18 million tonnes a year in 2008 to 1.97 million tonnes a year by 2015 is predicted by WRAP (Letsrecycle, 2007). Mixed glass has low price when compared with colour-sorted glass. Mixed glass cannot be used in the closed-loop (bottle-to-bottle remelting) industry where colour purity is vital, and must instead go to alternative uses (Letsrecycle, n.d.). This Thesis proposes an alternative use for mixed waste glass: production of TGCUs for partial concrete replacement in TGC.

If the glass recyclate is shipped overseas using a freighter then the CO_2 conversion is around 15 grams of CO_2 per kilometre for each tonne of goods carried (Greenwise, 2011). If the recyclate is sent to South America, Chile for example, a distance of around 11,500 km then the emission will amount to 0.17kgCO_2 per kg glass. The estimated CO_2 benefits of using waste glass in closed-loop recycling to make new glass, as cited by DEFRA in a waste strategy report (DEFRA, 2012c) is 0.500 kgCO_2 per kg of glass. Sometimes, it may make ecological sense to ship excess glass in the UK to countries overseas that have a demand for the glass (green for wine bottles) to offset the emissions from melting glass from virgin materials. As the emission is associated with the energy needed to process glass, then use of recycled glass also decreases the demand on energy and there are also economic and sustainable arguments for this. The savings in energy and greenhouse gas emissions can sometimes offset the cost and emissions due to transportation (shipping and land transportation) and can be more economical than the cost of landfilling. There will be even more savings for shorter distances, even to Europe. The debate continues.

While it has not been included in the carbon balance discussed in Section 7.2.3 because the allocation considered is landfill emission as this is the deemed destination of the recyclate, in line with UK recycling objectives, any alternative open-looped scheme must be compared to closed-loop glass remelt scheme with all allocations considered. This can be a future line of study and for TGCU will include options for mass production and offsets attributable to both construction and glass industries including transportation.

It has been the vision of the glass recycling workshop at the University of Brighton (UoB) to turn waste glass into a viable and valuable resource, and in TGCU it has such a product. The EU SDS (2009) recognises that investments in human, social and environmental capital, as well as technological innovation, are the prerequisites for long-term research and economic prosperity. The UoB development is not only fully consonant with this policy imperative but indicates how it can be applied in real world situations.

The traditional practice of transporting glass sometimes over vast distances, simply to then crush this glass in large granulators, is challenged by the current research study. Its proposition that a network of small-scale granulator workshops be established by a glass collector located on site has a large number of ecological, commercial, social and educational benefits over the existing practice of large recycling centres. These benefits are in addition to the savings made in transportation costs.

Theoretical estimations based on CES 2011 of such elements as embodied energy in TGCU indicate that TGCU requires more production energy than the EE for the same volume of concrete standard beams. As noted earlier, the most obvious savings gained when using TGCUs are those derived from the reduced volume of concrete that is required – which leads to savings in the use of prime materials such as cement and sand. The research has also identified and considered the savings made from the reduced costs relating to landfill sites and to transporting waste glass and cans over long distances. The two products proposed for use in the TGCUs, waste glass and tin-plated steel cans, satisfy the directives on environmental profiles allocation procedures for post-consumer recycling and reuse. Mention has also been made of the fact that these latter elements are in accord with European legislation on landfilling and on the diversion of waste from landfill sites.

The following points need to be taken into consideration when it comes to the material selection of TGCU.

- Measures for offsetting the TGCU production energy by attributing negative embodied energy to waste glass. This should reflect the benefits of using waste glass rather than landfilling it.
- Measures for reducing TGCU production energy by using cheaper ways of fusing glass than by electricity. In an industrial production, a cheaper fossil fuel such as natural gas would be a better option.

  Even better would be options for on-site renewable energy supplies such as those provided by wind farms.

CHAPTER 8

DISCUSSION AND CONCLUSIONS

8.0 Introduction

This research starts with a review of the existing knowledge on using mixed coarse waste glass in concrete, with a view to developing it further by applying TinGlass Construction Unit (TGCU) as a component in precast concrete elements. This is performed by embedding TGCU into precast concrete elements at casting stage. The new material is referred to as TGC, TinGlass Concrete. The research aims to establish whether TGC is able to reproduce mechanical properties of traditional concrete. Any enhancement of properties (*e.g.* strength in compression) is seen as a bonus rather than the aim. The TGC has the benefit of partial replacement of traditional non-renewable materials in concrete by the same volume of waste materials comprising a TGCU. A good resilience of TGC to alkali silica reaction (ASR) is observed under testing to ASTM standards with relevant modifications.

The aim of the research was formulated in Section 1.4 as developing a novel and sustainable technique of producing precast concrete elements by partially replacing concrete with waste materials (including mixed coarse waste glass) without compromising the mechanical properties of the final product.

In other words, the novel precast concrete material, TinGlass Concrete (TGC), shall reproduce all the specifications of traditional precast concrete as expected by a consumer whilst decreasing the environmental impact.

It shall be emphasised that the focus of this research was on reproducing rather than enhancing the mechanical and physical properties of conventional precast concrete with the additional environmental benefits resulting from the use of waste materials.

The Thesis does not aim to propose a stronger, denser or tougher material by introducing the TGC. The aim is to provide a more eco-friendly material than traditional concrete whilst keeping its properties and specifications.

The objectives (shown in italic below) were met throughout the Thesis in the following Chapters:

- *To determine a viable and easily repeatable configuration for the embedment of the TGCU units into precast concrete elements that meets industry standards*. Chapter 3 describes a novel methodology of producing TGC precast concrete elements such as cubes and beams in accordance with current codes of practice (British Standards) for concrete preparation and testing.

- *To determine the compressive strength of concrete with embedded TGCU units and compare it to conventional concrete. Sample preparation and testing to be carried out in accordance with current codes of practice (British Standards).* Chapter 3 describes the setup of compressive testing. Chapter 5 shows the results under testing to British Standards. Compressive strength of TGC is close to (or even exceeds) that of traditional concrete under testing to British Standards.

- *To determine the flexural strength of reinforced concrete beams with embedded TGCU units and compare it to conventional reinforced concrete beams. Sample preparation and testing to be carried out in accordance with current codes of practice (British Standards).* Chapter 3 describes the setup of flexural testing. Chapter 6 gives flexural testing results under testing to British Standards. Flexural strength and stiffness of TGC are similar to that of traditional concrete within reasonable experimental accuracy. No systematic dependence on the number and orientation of TGCUs embedded in a beam is observed.

- *To assess the effect of the Alkali Silica Reaction (ASR) on the concrete elements with embedded TGCU units in accordance with current codes of practice (ASTM).*

Chapter 3 describes the setup of modified ASR testing. Chapter 4: TGC has shown good resilience to ASR under modified ASR test for concrete cubes. The performance of TGCCs was better than SCs, as confirmed by volume expansion method, and by subsequent compression testing of TGCCs *versus* SCs of the same concrete mix.

- *To assess the environmental benefits of partially replacing concrete with waste materials by embedding TGCU units into precast concrete elements.*

Chapter 2 and 7: Savings of non-renewable materials for production of concrete comprise about 23% - 25% for a TGCC. This estimate is based on volume of TGCU of 230 – 250cm^3 embedded in a concrete cube of 10cm on the side. For a TGCB of 15 x 15 x 71 cm^3 containing six TGCUs of 248cm^3, the volume ratio is 9%. Density of TGCU (Table 2.3) is close to density of concrete, and this is important for ergonomic considerations. The weight of TGC precast concrete element is reproducing the weight of traditional recast concrete element closely enough for the ease of industrial implementation.

Reassessing research motivation in Section 1.4, it is concluded that the TGC concept is a good vehicle *to decrease the depletion of non-renewable materials going into concrete production.* The italic shows the original wording of research motivation in Section 1.4.

Moreover the production of TGC is very forgiving regarding the quality of glass cullet when compared with other methods of adding glass cullet into concrete since the preparation of the TGCU embraces all post-consumer glass waste streams. No sorting of bottles by colour, or cleaning from drinks' residues and labels is required. The cullet can be mixed (by colour and granules' size), it may contain organic impurities (paper and glue of bottles' labels, drink and food residues). All this is acceptable for TGCU preparation.

The fusing process is forgiving due to the metal shell (provided by waste steel can) that forms a permanent mould for fused glass cullet with good bonding properties. The annealing process is shorter than traditional cooling of fused glass bricks (Section 7.2.5).

Thus the research motivation *to recycle coarse mixed glass in concrete products in response to government and industry directives supporting the use of recycled materials in construction as a means of landfill avoidance* (Section 1.4) is met by accepting mixed green and brown glass for TGC production. These types of glass are difficult to recycle as UK glass industry favours clear glass (Letsrecycle, 2011) and hence they are frequently landfilled due to low economic value of mixed glass cullet (Letsrecycle, n. d.)

Eco-accounting of TGC *versus* traditional concrete is based on concepts of embodied energy (EE), embodied carbon dioxide (ECO_2). The precise estimates are hindered by lack of industrial implementation of TGC and the evaluation is made on conservative basis. Life cycle analysis shows a good recyclability for end-of-life TGCUs as reusing or remelting them into new TGCUs in a closed loop.

In general, it is shown that TGC has much potential in meeting the target of alleviating the environmental impact of concrete production.

The layout of this Chapter is as follows:

Section 8.0 is *Introduction* outlining the results in relation to the thesis aim and objectives as specified in Chapter 1

Section 8.1, *Results and Discussion*, is this thesis' general discussion section. This section will discuss the results of mechanical tests, of the ASR testing and assessment of the environmental impact.

Section 8.2 *Conclusions* will start with a summary of background knowledge and motivation for research, followed by the summary of what has been achieved in relation to the thesis aim specified in Chapter 1.

Section 8.3 is *Recommendations for Future Research*. There is novelty in this project as there has been no previous literature on the use TGCU in TGC, and so this work has indicated several areas for further investigation which will enhance the understanding of this new construction material and its environmental impact in view of its potential applications.

8.1 Results and Discussion

The gap in knowledge is seen in investigating whether TGCU can be used as an insert in precast concrete elements without compromising the mechanical properties whilst meeting the environmental aims of reduction of waste glass landfilling, and saving of non-renewable materials, energy and emissions associated with concrete production. If it is the case, then TGCU will be a candidate for secondary use of waste glass and contribute a recycled product to the construction industry, a sector keen to reduce its dependence on virgin materials. The scope of the research is to obtain data that will be needed to define appropriate applications for these new materials in the construction industry.

TGCU is a macro-component and not mixed in with the concrete in the manner that sand or aggregates are. Before undertaking this research, the author could not predict how TGCC or TGCB would behave under compression and flexural bending tests.

The objectives of the Thesis have been to determine a viable and easily repeatable configuration for the embedment of the TGCU units into precast concrete elements that meets industry standards, to assess their ASR resilience, to measure the compressive and flexural strength of these novel precast concrete elements, and to compare these with conventional precast elements, and assess the environmental impact of precast concrete with embedded TGCUs against conventional precast concrete..

8.1.1 TGCU configuration in precast concrete elements

The manufacture of TGCUs does not require any virgin materials. They are prepared purely from waste materials, by fusing granulated mixed waste glass in a tin-plated steel can that serves as a permanent fused-on mould. Their production is seen as labour-efficient because sorting of waste glass by colour and chemical composition is not needed.

The design and preparation of precast concrete elements with embedded TGCUs constitutes the original research by the author. In particular, the following contributions are seen as important ones:

- the preparation of TGCU such that contact between glass and concrete is minimal to reduce alkali silica reaction (ASR)
- assessment of manufacturing process for TGCU and demonstrating that it requires shorter annealing times (when compared with fused glass bricks)
- the preparation of TGCBs in terms of how to support the TGCUs within the beam relative to reinforcing rods and inserting additional spacers.

As discussed in Section 3.1, in order to achieve adequate bond between the lid and the fused glass core of a TGCU, specially designated steel weights were placed on top of the assembly before the fusing process commenced. The load over the melting glass helped to compact the TGCU. However there will be challenges in terms of rolling out this procedure in a production line. It is unlikely that the can and its lid in the waste stream will be easy to collect together. The production lends itself to potential mass production capability.

A possible production line scenario is not to use recycled tin-plated steel cans but purposely and expressly design a container steel can for use in TGCU production that will accept a glass gob dropping from a forehearth as in glass production (Quinn Glass, n.d.). The gob is a specific amount of molten glass that will fill the bespoke can and while still hot, the TGCU can be capped and sealed as with any packaging. This option is a recommendation for a future study.

8.1.2 Design of the experiment for assessment of alkali-silica reaction in TGC

Lee (2011) studied the effect on the flexural strength of concrete samples with glass as replacement aggregate after they had been exposed to NaOH environment; his results showed approximately 50% reduction in the flexural strength of the samples using glass as a replacement aggregate, while the reduction in the flexural strength of the control samples was only 10%.

The modified accelerated ASR test described in Section 3.5 of this thesis using TGCC samples showed that the TGCU did not contribute to after-ASR expansion. The expansion could in part be attributed to the ASR reaction in the concrete as observed by Lee (2011). There is more concrete in the SC cubes than in TGCC cubes, and this explains larger volume expansion of SCs (2%) when compared with TGCCs (0.5%).

The compressive strength test (Seaction 8.1.3) results also support the hypothesis that the metal shell of the TGCU inhibits ASR serving as barrier between silica in glass and alkali in concrete. This agrees with the studies of the TGCU-concrete chemical interaction by Ojomo (2010) as shown in Appendix 2.5, and with SEM exploration of the TGCU glass-metal interface by Trenikhin, 2012 (Appendix 2.6).

Corrosion of the TGCU embedded into concrete was not studied as part of this thesis. For steel-reinforced concrete, the problem is well known. Corrosion damage in steel-reinforced concrete structures can occur after long service (Jin and Zhao, 2001). The study of the bond between steel rod and concrete has shown that initial stage of corrosion increases the strength of the bond. The authors (Jin and Zhao, 2001) argue that the microstructure of corroded steel surface provides a better bond with concrete.
This might be relevant to explain the good bond between oxidised surface of TGCU and concrete. The outer surface of tin-plated steel can gets oxidised during glass fusing process. The oxide film protects good bonding, and it may protect it from further corrosion inside TGC.

The accelerated corrosion tests for TGC were beyond the scope of this Thesis. However, a study of corrosion properties for uncovered TGCU immersed into sea water has been made by Filippatos (2011) as summarised in Appendix 8.2.

8.1.3 Compressive strength of TGCC In Chapter 4, a set of TGCC and SC samples subjected to the modified accelerated ASR test (exposure to NaOH) were also tested under compression. Four TGCC samples were tested and were found to have 11% higher compressive strength on average compared to the control (SC) samples.

As presented in Chapter 5, TGCC samples which were prepared without NaOH soaking were found to exhibit 20% higher compressive strength than the control samples (SC).

Supporting work by Ojomo (2010) indicates that the strength is related to the ratio of the volume of TGCU to the volume of the cube. Overall, the findings from the research presented here agree with Ojomo's (2010) results that the presence of TGCU in TGCC up to a volume ratio of 25% does not compromise the cube's compressive strength.

The results of the compressive strength tests indicated that embedding TGCU in a cube does not cause deterioration in compressive strength for ratios of volume of TGCU to surrounding volume of concrete up to 25%. This is seen as a good result compared with the results on coarse glass cullet presented in the literature and discussedin Section 2.5.2. Higher ratios of TGCU volumes to surrounding volume of concrete have not been studied and this may be recommended for future research.

8.1.4 Characterisation of TGCB performance in flexural tests

The results of the flexural test indicated that it is possible to embed several TGCUs in a beam without compromising strength when 4 to 6 TGCUs are embedded into 15 x 15 x 71 cm^3 beam as shown in the technical drawings of TGCBs (Appendix 6.2). The concrete mix, number of TGCUs and TGCU orientation in the beam were explored as parameters that could influence the flexural strength results as presented in Chapter 6.

TGCU is a macro-component and not mixed in with the concrete in the manner that aggregates are. Therefore,the behaviour of TGCC or TGCB under compressive and flexural strength tests could not be predicted in advance.

The load-deflection curves presented in Chapter 6 were analysed using the approach of Bhatt et al. (2006). Figure 8.1 shows the relevant regimes as defined by Bhatt et al. (2006) and an example as applied to a specimen beam, TGCB.5B.HPC.7.

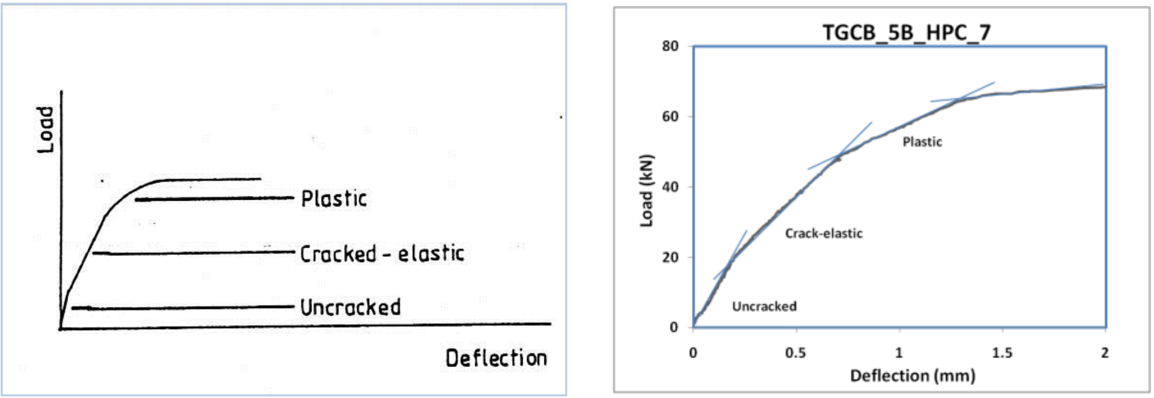


Figure 8.1. Regimes in load-deflection curves as defined by Bhatt (2006) and as applied to the TGCB.5B.HPC.7.

For reinforced beams, the implication according to Bhatt et al. (2006) is that at very small loads, the stresses are elastic and the section under tension is uncracked. At moderate loads, the tensile stresses of the concrete will be exceeded, the concrete will crack (hairline crack), and the steel rods will resist tensile stresses, thus the stresses will be elastic and the section cracked (cracked-elastic). With further load increases, the plastic regime starts in compression part of the beam, the concrete has cracked and the process is irreversible (plastic deformation) and the steel rod will yield and not return to its original length.

The stiffness in Chapter 6 is assessed as the load at 0.2mm of beam deflection. This is seen as an important characteristic of the elastic regime. There appears to be no definitive trend for the stiffness. The estimated stiffness between TGCBs and SBs are within experimental uncertainties.

The cracked-elastic and plastic regions have variability in both SB and TGCB samples. This is not discussed further in this Thesis. There is scope for further investigations and more research is needed.

As stated in Section 6.4, the deflection at fracture for TGCBs and SBs is high enough to give the evidence of an ample plastic regime preceding the collapse of the beam. This agrees with the requirements for the desirable mode of failure (Bhatt et al., 2006).

A starting point for more detailed studies is the result that load-deflection curve for the HPC TGCB with five TGCUs in orientation A, is very close to that of its SB counterpart. Thus, this TGCB may be recommended as a first choice for the replacement of the precast beam of given size.

8.1.5 Environmental evaluation of the TGC precast structures

The environmental assessment in terms of energy and CO_2 emission associated with the production of TGCU has also been undertaken. It has been shown that TGCU is an eco-innovative product. To realise its potential, from an energy and carbon reduction point perspective, it is important to identify an energy source, other than electricity, to supply the energy to produce TGCU.

This research also recognizes that there is much work needed in terms of life cycle analysis to appreciate the eventual impact of this new product. This kind of new research will impact into new government policies and legislation.

Since the UK average total glass recycling rate is 61% (Miltek, 2012) then 39% of post-consumer glass is not collected as recyclate; this is an estimated 1Mt of waste glass. If this glass is not classified as Qualifying Material for lower landfill tax (because it is mixed with other waste and does not meet the requirement for exemption) then this amount of waste glass can be charged the standard rate of £72 per tonne (HMRC, 2012). The high rate for landfill tax is reflective of the national situation of shortage in landfill sites. Assuming 10% of the non-recyclate glass is mixed in with other waste and sent to landfill then this will amount to £7.2 million in landfill tax annually. Thus, there is an urgency to increase the recycling rate and an urgency to find a secondary use for the glass collected.

8.1.6 Contribution to knowledge

The research study presented here is aimed at developing a novel and sustainable technique of producing precast concrete elements by partially replacing concrete with waste materials (including mixed waste glass) without compromising the mechanical properties of the final product. This technique makes use of the TGCU unit which comprises of waste glass cullet encapsulated in a metal (waste steel) shell and has been developed in previous studies carried out at the University of Brighton. Due to the dimensions of the TGCU unit its application is considered more suited to precast concrete elements.

TGCU is a macro-component much larger in size than aggregates (sand and gravel) used in concrete and thus its impact on the behaviour of concrete elements could not be predicted using conventional analytical or empirical methods To gain knowledge, tests and measurements were carried out to compare the behavior of TGCCs and TGCBs to their control counterparts. The results are encouraging in terms of reproducing the properties of conventional concrete with reasonabe accuracy, and showing good resilience to ASR.

A brief summary of contribution to knowledge is given below:

- The research study introduces the concept of adding a macro-component constituent to concrete which is not used as a replacement for aggregates, but is instead used to replace an equivalent volume of the concrete mixture.

- Consequent to the above, a new strand of inquiry has been initiated which assesses the mechanical properties of precast concrete elements with embedded TGCUs.
    a. The compressive strength of the concrete element is not compromised by embedding TGCU up to a volume ratio of TGCU to concrete of 25%.

    b. It is demonstrated that several TGCUs can be embedded to produce a TGC precast beam. For the beam of given size 15cm x 15 cm x 71cm, the number of embedded TGCUs varied from four to six. For six TGCUs, the volume ratio of TGCUs to the beam is 9% . The best agreement between TGCBs and SBs results of flexural testing has been observed for five TGCUs embedded into 15 x 15 x 71 cm^3 beam. This design of TGCB gives practically identical properties to the SB (control beam without TGCU) of the same size and with the same degree of steel-rod reinforcement.

c. As an illustration of the modification of existing standards as relevant to TGCU embedded in cubes, this thesis has developed a modified ASR test, which specifically addresses the fact that the replacement material should not be an aggregate as stipulated in the standard ASR test but a macro-component. The results of the ASR test supported the hypothesis that the oxidised steel shell of the TGCU acts as a barrier between glass and cement, thus helping to inhibit the ASR. Good glass-encapsulation properties of TGCU have been further confirmed by scanning electron microscope (SEM) studies (Trenikhin, 2012) and X-ray diffraction test (Ojomo, 2010)

This study is seen as a starting point for further research on the environmental impact of the TGC and life cycle analysis for waste glass. Presently the UK has a limited scope for recycling green glass which comes in bountiful amounts from consumption of wine from foreign imports. This work creates a new large-scale application for the excess of mixed coloured glass in the UK, and opens the possibility for it to be recycled instead of either being transported overseas to wine producers for bottle remelting or for landfill.

8.2 Conclusions

The aim of the research is the development of a novel and sustainable technique of producing precast concrete elements by partially replacing concrete with waste materials (including mixed waste glass) without compromising the mechanical properties of the final product.

A recent patent for TGCU (TinGlass Construction Unit) has been used as a vehicle to achieve this purpose. The TGCU concept is based on fusing waste glass cullet in a steel can (such as a tin-plated steel food cans for baked beans or tuna). The glass cullet of inferior quality (mixed coloured glass with organic impurities) is suitable for TGCU production, as opposed to glass bricks and tiles that require careful control over glass cullet composition, in order to prevent cracking on cooling (annealing) stage. The ease of TGCU processing is due to the encapsulation of glass core within the metal shell; this prevents glass cracking and shortens the required annealing times.

Additional benefits of the TGCU concept come from its ability to alleviate thalkali silica reaction (ASR) in concrete with glass additives. ASR is a well-known obstacle for using coarse mixed glass cullet as admixture to concrete. When a TGCU is embedded into concrete, a protective barrier between glass and cement is formed by fused-on steel shell (waste steel can).

A major strand of enquiry of the Thesis was focused on determining the properties of TGC regarding its resilience (or vulnerability) to ASR. This has been achieved by modifying existing standards, ASTM C 1260 test for ASR, in view of specific character of TGC. The ASR testing of TGC *versus* conventional concrete has shown a good resilience of TGC to ASR in terms of after-ASR expansion and compression strength. After the modified ASR test, the volume expansion in the TGCCs was 0.5% on average, and in the SCs, the control cubes without TGCU, it was 2%. The compressive strength of TGCCs after the modified ASR test was slightly higher than that for the SCs after the identical ASR test.

The urgency of this research stems from excess of pubglass (mixed green and brown container glass, mainly wine and beer bottles) that finishes in landfills. The United Kingdom collects more container glass through its recycling program than can be returned to closed-loop recycling. This imbalance is particularly acute for pubglass. Also, commingled glass (mixed clear, green and brown container glass) needs sorting by colour, and this limits its applicability for closed-loop recycling. To prevent excessive landfilling, a large-scale uses and applications for pubglass and/or commingled glass are needed.

Thus the novel material, TinGlass Concrete (TGC), responds to this need by proposing a viable large-scale secondary use for pubglass. Partial replacement of concrete by waste glass cullet of any colour, impurity and granules' size in precast concrete elements was achieved in the Thesis by using the concept of TGCU, an innovative product patented at the University of Brighton comprising mixed glass cullet fused in a tin-plated steel can. The steel can forms a permanent fused-on mould; it can be sourced from waste stream.

The environmental impact of the proposed precast products was assessed regarding avoidance of landfilling and replacement of non-renewable materials in concrete production by waste materials. Estimates for embodied energy and embodied carbon dioxide (eCO_2) for TGC are made on conservative basis.

It is proposed to use TGCUs in precast concrete by embedding them into concrete elements, cubes and beams, during casting. To establish how well TGC could reproduce properties of conventional concrete, a series of tests in compression and flexure have been performed. The TGC products, TinGlass Concrete Cubes (TGCCs) and TinGlass Concrete Beams (TGCBs), were prepared in the same way as their counterparts (control elements), by using the same concrete mix and curing procedure (and steel reinforcement for the beams). For TGCC preparation, a TGCU has been embedded in concrete cube of 10 cm on the side at casting stage. This corresponds to the replacement of 25% concrete by waste materials comprising a TGCU. The compressive strength of TGCCs well reproduces (or even exceeds) that for the control cubes.

The flexural test used simply supported beams with single-point central load for the 15x15x71 cm^3 beams reinforced by three steel rods of 6 mm in diameter and length of 0.67 m in the tension part. The TGC beams were prepared as identical to the control beams but with a number of TGCUs embedded at casting stage (from 4 to 6 TGCUs in a beam). The six TGCUs in the beam of given size correspond to 9% of concrete replacement by volume. Comparison of flexural properties of TGC beams with the control beams has shown reasonable agreement.

8.3 Recommendations for further research

Future work should repeat the experiments carried out here to obtain a better statistical analysis. The present work was carried out in laboratories that lacked the facilities for larger-scale production of concrete mixes. This work was limited by the capacity to prepare huge concrete batches at a time. This is needed in order to produce more beams and cubes in one batch. This explains the need for a more extensive statistical analysis in future. Particular areas of interest are the subject of compressive and flexural strength that will benefit from a further study involving more samples, both of TGCCs and TGCBs.

This thesis used the cubic samples for compression, and the single-point central loading for flexural tests as shown in Fig.2.10. This setup followed available testing facilities of the concrete laboratory at University of Brighton. In the UK, compressive testing of concrete is specified for cubic samples and this has been used in this study. The Eurocode 2 standards are based on cylinder samples when testing for compressive strength. In the future, cylindrical samples should be prepared and tested to meet Eurocode 2 (EC2) requirements.The two-point loading flexural bending test should be added for future research.

In comparing the data for TGCC and SC, the relative error defined as the ratio of the standard deviation to the average value, is an important factor. Research into standardising the TGCU production procedure will contribute vastly towards its adoption by the construction industry. An experimental limitation of current work was due to the fact that there were no facilities for production and mechanical testing of large-scale concrete elements (larger than those used for this study). The macro-size of TGCU lends it to exploration for embedding into much larger elements than the TGCCs and TGCBs of current study. Large-scale TGC elements can be used for foundations, dam-building and sea defences, to name just a few areas of possible applications.

Research towards anchoring the TGCB will be of interest.There should also be more studies directed into ways of supporting the TGCUs in the beam, perhaps without the reinforcing steel rods to evaluate the contribution of TGCU alone. It should be noted that the plastic spacers placed at casting stage, may act as stresss raisers in a TGCB beam. Hence the enhanced number of spacers in TGCBs puts them in unfavourable position when compared with the control beams, SBs. This shows that the comparison of flexural properties of TGCBs and SBs, the control beams, is on conservative side.

It is recommended to extend the mechanical testing and incorporate the test forflexural toughness in further research. Currently the load – CMOD curves (Figs 2.14 – 2.15 of Section 2.6) are mainly applied for testing of fibre-reinforced concrete. Extension of these methods to TGC is seen as a promising and interesting line of research.

The accelerated ASR testing for TGC is another recommended extension ofcurrent research. In relation to ASR the following further studies are suggested: (i) It is possible that a longer reaction time with NaOH is needed for the effect of TGCU to be observed; (ii) The research on the ASR test could be further extended by looking at samples from the concrete area close to the border of the lid, where a small area of glass core is in direct contact with the concrete. This is to identify any gel formation, and investigate it by using electron microscopy; (iii) a chemical analysis of the amount of silica probably dissolved in the NaOH solution during the incubation period could also be measured and normalized to the original volume to correlate ASR and volume expansion.

The corrosion testing for TGCU was discussed in Section 8.1.3 and Appendix 8.2. Recommendations for future research include the design of accelerated corrosion test for TGC based on existing knowledge for steel-reinforced beams (Jin and Zhao, 2001).

Further, issues of freeze and thaw have not been studied and should be given consideration in future work. This study could lead to further understanding of the nature of bonding between concrete and TGCU.

It has been mentioned that the nature of TGCU lends itself to potential mass production capability; a steel can filled with glass equipped with a lid is similar to packaging a baked bean can. This production technique will solve the issue of capping and exposing some glass to ASR expansion. Industry implementation of TGC production can be based on applying robotic methods that are increasingly applied in construction.

REFERENCES

Afentouli L. (2007) Innovative Technical Solutions for Waste Glass Processing. *MSc Thesis*, School of Engineering, University of Brighton, Brighton, UK.

Agenda 21 (2002) Available from: http://sustainabledevelopment.un.org/index.php?page=view&nr=23&type=400&menu=35 [Accessed 02/07/20014]

Alani, A. M. and Beckett, D. (2013). Mechanical properties of a large scale synthetic fibre reinforced concrete ground slab. *Journal of Construction and Building Materials*, Vol. 41. pp. 335-344

ASTM C1609 (n.d.) *Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete*, Available from: http://www.astm.org/Standards/C1018.htm [Accessed 05/07/20014]

ASTM C 1260 (n.d.) *The Accelerated Mortar Bar Test.* Available from: http://www.astm.org/Standards/C1260.htm [Accessed 02/07/2014]

ASTM C496 / C496M – 11 9 (n.d.) *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.* Available from: http://www.astm.org/Standards/C496.htm [Accessed 02/07/20014]

Bataineh, M. A. (2006) Innovative recycling and cooling solutions, *MSc Thesis*, School of Engineering, University of Brighton, Brighton, UK

BEES (n.d). *Building for Environmental and Economic Sustainability*, Available from: http://ws680.nist.gov/BEES/ [Accessed 01 -12-2011]

Bhatt, P., MacGinley, T.J. and Choo B. S. (2006) *Reinforced concrete: design theory and examples,* 3rd Ed, Taylor and Francis

BRE Digest 330 Part 1. Available from: http://cement.mineralproducts.org/documents/Concrete-Jul-09-BRE-Digest-330-Alkali-silica-reaction-in-concrete-the-case-for-revision-Part-I [Accessed 02/07/20014]

BRE (2004) *Cement and concrete sustainability.* Available from: http://cement.mineralproducts.org/downloads/cement_and_concrete_sustainability.php

BRE (2006) *Assessment of Sustainability Tools. Report number 15961*. Available from: http://download.sue-mot.org/envtooleval.pdf [Accessed 2/07/2008].

BRE (2008) *BRE Environmental Profiles Database, Sheet C1 - Embodied CO2 of Concrete and Reinforced Concrete.* Available from: http:// www.sustainableconcrete.org.uk/ CO2_emissions.aspx [Accessed 01 -12-2011].

BREEAM (n.d*.) Sustainable Building.* Available from: http://www.thelkgroup.com/sustainable_building/breeam.php?gclid=CPG0mfbo3LECFUYNfAodPUkAlg [Accessed 01 -12-2011]

BritGlass (2011*). British glass recycling.* Available from: http:// www.britglass.org.uk/recycling [Accessed 23 -07-2012]

Bryson, L.S., Maynard, C., Castro-Lacouture, D., Williams, R.L. (2005) Fully autonomous robot for paving operations. *Construction Research Congress* , pp. 1-10. Available from: http://ascelibrary.org/doi/abs/10.1061/40754%28183%2937 [Accessed 23 -05-2013]

BS EN 13225:2013. *Precast concrete products. Linear structural elements. British Standards Institution.* Available from: http://shop.bsigroup.com/ProductDetail/?pid=000000000030231845 [Accessed 23 -02-2014]

BS 1881-125:2013. *Testing concrete. Methods for mixing and sampling fresh concrete in the laboratory*. Available from: http://shop.bsigroup.com/SearchResults/?q=BS+1881-125:2013 [Accessed 23 -02-2014]

BS EN 12350-1-2009. *Testing fresh concrete. Part 1: Sampling. British Standards Institution.* Available from: http://shop.bsigroup.com/ProductDetail/?pid=000000000030164879 [Accessed 2 -08-2014]

BS EN 12350-2-2009. *Testing fresh concrete Part 2: Slump-test. British Standards Institution.* Available from: http://shop.bsigroup.com/ProductDetail/?pid=000000000030164882 [Accessed 2 -08-2014]

BS EN 12390-1:2009. *Testing hardened concrete. Shape, dimensions and other requirements for specimens and moulds. British Standards Institution*. Available from: http://shop.bsigroup.com/ [Accessed 2 -08-2014]

BS EN 12390-2-2009. *Testing hardened concrete, Part 2: Making and curing specimens. British Standards Institution.* Available from: http://shop.bsigroup.com/ [Accessed 2 -08-2014]

BS EN 12390-3-2009.*Testing hardened concrete, Part 3: Compressive strength of test specimens. British Standards Institution.* Available from: http://shop.bsigroup.com/ [Accessed 2 -08-2014]

BS EN 12390-4-2009. *Testing hardened concrete Part 4: Compressive strength. Specification for testing machines. British Standards Institution*. Available from: http://shop.bsigroup.com/ [Accessed 2 -08-2014]

BS EN 12390-5:2009. *Testing hardened concrete. Flexural strength of test specimens. British Standards Institution.* Available from: http://shop.bsigroup.com/ [Accessed 2 -08-2014]

BS EN 450-1:2012. *Fly ash for concrete. Definition, specifications and conformity criteria.* Available from: http://shop.bsigroup.com/ProductDetail/?pid=000000000030216589 [Accessed 2-08-2014]

BS ISO 15686-6:2004. *Buildings and constructed assets. Service life planning. Procedures for considering environmental impacts. British Standards Institution.* Available from: http://shop.bsigroup.com/ProductDetail/?pid=000000000030114083 [Accessed 2 -08-2014]

Butler, J. and Hooper, P. (2005) Dilemmas in optimising the environmental benefit from recycling: A case study of glass container waste management in the UK. *Resources, Conservation and Recycling* 45 (2005) 331–355

Callister, W.D. (2007) *Materials Science and Engineering: an introduction*, 7th ed., Wiley.

Callister W.D. Rethwisch D. G. (2011) *Materials Science and Engineering*, 8th ed., Wiley.

CASBEE, *Comprehensive Assessment System for Built Environment Efficiency*. Available from: http://www.ibec.or.jp/CASBEE/English/overviewE.htm [Accessed 21-07-2012].

CD&E Waste (2010). *Halving Construction, Demolition and Excavation Waste to Landfill by 2012 compared to 2008.* Available from: http://www.stratrgicforum.0rg.uk/pdf/Waste_reprot_4_draft_22-3-10V4.pdf [Accessed 21-07-2012].

CES (2011), *CES Edupack 2011*, Cambridge, UK, http://www.grantadesign.com/

Construction 2025 (2013) *Industrial Strategy: government and industry in partnership* Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/210099/bis-13-955-construction-2025-industrial-strategy.pdf [Accessed 02/07/2013]

Controls Group (n.d.), *Displacement transducer for measurement of crack opening,* Available from: http://www.controls-group.com/eng/concrete-testing-equipment/displacement-transducer-for-measurement-of-crack-opening.php [Accessed 02/09/2014]

CPR (2011). *REGULATION (EU) No 305/2011.* Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:088:0005:0043:EN:PD[Accessed 21-07-2014].

Carbon Trust (2010) *Energy and Carbon Conversions 2010 Update.* Available from: http://www.carbontrust.co.uk [Accessed 01 -12-2011].

DEFRA (2010) *UK packaging recycling targets for 2011 and 2012.* Available from: http://www.defra/gov.uk/news/2010/10/26/ [Accessed 23 -07-2012].

DEFRA (2011) *Government Review of Waste Policy in England 2011*. Available from: http://www.defra.gov.uk/publications/files/pb13540-waste-policy-review110614.pdf [Accessed 27-07-2012].

DEFRA (2012a) *Ministry of Justice annual report and accounts 2011-2012*. Available from: http://sd.defra.gov.uk/2012/03/sustainable-construction-and-innovation-through-procurement-supplier-consultation/ [Accessed 23-07-2012]

DEFRA (2012b) *Waste legislation and regulations* Available from: http://www.defra.gov.uk/statistics/environment/waste/ recycling and recovery from packaging 14 Mar 2012 [Accessed 21-07-2012].

DEFRA (2012c) *Composition of local authority collected waste.* Available from: https://www.gov.uk/government/statistics/composition-of-local-authority-waste [Accessed 23 -07-2012].

DEFRA (2012d) *Construction and demolition waste, England*. Available from: https://www.gov.uk/government/statistics/construction-and-demolition-waste [Accessed 23 -07-2013].

DTI (2012) Available from: www.bis.gov.uk/files/file37180.pdf [Accessed 13 -07-2012]

Dyer, T. D. and Dhir, R.K. (2004) Hydration reactions of cement combinations containing vitrified incinerator fly ash, *Cement and Concrete Research*, vol 34, issue 5, pp. 849-856

Earthship Brighton (2006). Available from: http:// www.lowcarbon.co.uk/earthship-brighton [Accessed 23 -07-2012]

ECTP (2009) *Innovation in Construction: Taking the lead in greening the future*. Available from: http://www.ectp.org/conference2009.asp [Accessed 21-07-2012]

ENVEST (n.d.) *Environmental impact and whole life costs analysis for buildings.* Available from: http://envest2.bre.co.uk/ [Accessed 13 -01-2009].

Enviros (2003) *British glass recycling*. Available from: http://www.britglass.org.uk/recycling [Accessed 13 -07-2012].

EPA (2012) Available from: http://www.epa.gov/osw/conserve/rrr/greenscapes/pubs/glass.pdf [Accessed 3 -03-2012].

Eurocode 2 (n. d.) Available from: http://www.concretecentre.com/codes__standards/eurocodes/eurocode_2.aspx[Accessed 3 -03-2012].

EU SDS (2009). *Review of the EU Sustainable Development Strategy*. Available from: http://ec.europa.eu/environment/eussd/ [Accessed 21-07-2012]

EU Directive (2003) Available from: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32003L0087 [Accessed 02 -03-2012].

EU 2004/12/EC (2004) *EU Waste Framework Directive 2004/12/EC.* Available from: http://www.publications.parliament.uk/pa/ld200708/ldselect/ldsctech/163/16305.htm [Accessed 02 -03-2012].

Ferraris, C.F. (1995) *Alkali-Silica Reaction and High Performance Concrete.* Available from: http://fire.nist.gov/bfrlpubs/build95/art004.html [Accessed 08-12-2011].

Filippatos, C. (2011) Mechanical Properties of thermally processed waste glass in marine environment. *XE336 Final Year project*, School of Computing, Engineering and Mathematics, University of Brighton, Brighton, UK.

Firoozmand, F. (2010) Private communication, University of Brighton, Waste and Energy Research Group (WERG)

Gere, J.M. and Goodno, B.J. (2011) *Mechanics of Materials,* 8th ed, Nelson Engineering

Glass Recycling (n.d.) *Glass recycling*. Available from: http://www.uk-energy-saving.com/glass_recycling.html [Accessed 21-07-2014].

Greenblast (n.d). Available from: http://www.greenblast.eu/[Accessed 23 -06-2014]

GreenWave Eco Festival (2008) Available from: http://www.transitionbrightonandhove.org.uk/2008/05/green-wave-festival-sat-5-sun-6-july.html [Accessed 25 -02-2009].

Greenwise (2011) *Sea change: cutting shipping's carbon emissions.* Available from: http://greenwisebusiness.co.uk/news/ [Accessed 23 -07-2012].

HRMC (HM Revenue and Customs) (2012) Available from: http://www.hmrc.gov.uk/budget2012/ootlar-main.pdf [Accessed 09-03-2014]

Idir, R., Cyr, M. and Tagnit, A. (2010) Use of fine glass as ASR inhibitor in glass aggregate mortars. *Construction and Building Materials*, 24, pp. 1309–1312

Ismail, Z.Z. and AL-Hashmi E.A. (2009) Recycling of waste glass as a partial replacement for fine aggregate in concrete. *Waste Management* 29, pp. 655–659

Jani, Y. and Hogland, W. (2014).Waste glass in the production of cement and concrete. *Journal of Environmental Chemical Engineering,* pp. 1767–1775

Jiabiao J., Loh, S., Gasho, T. (2004) Synthetic structure fibers for toughness and crack control of concrete, *29th Conference on our world in concrete & structures*, Singapore, Available from: http://cipremier.com/100029039 [Accessed 09-08-2014]

Jones-Mantle, R. (2008). Mr R. Jones Mantle, Magpie Coop, www.magpie.coop. Personal communication.

Karamberi, A. and Moutsatsou, A. (2005) Participation of coloured glass cullet in cementitious materials. *Cement and Concrete Composites*. Vol. 27, Issue 2, pp. 319-327.

Khayat, K., Bickley, J., Hootoon, R. (1995*). High-Strength Concrete Properties Derived from Compressive Strength Values, ASTM Digital Library.* Available from: http://www.astm.org/DIGITAL_LIBRARY/JOURNALS/CEMENT/PAGES/CCA10138J.htm [Accessed 2/08/2014].

Koutras, K. (2006) Novel Solutions for Waste Glass Processing. MSc Thesis, School of Engineering, University of Brighton, Brighton, UK.

Kovler, K. and Roussel, N. (2011) Properties of fresh and hardened concrete. *Cement and Concrete Research* Volume 41, Issue 7, pp. 775–792

Kozlova, S., Millrath, K., Meyer, C., Shimanovich, S. (2004) A suggested screening test for ASR in cement-bound composites containing glass aggregate based on autoclaving. *Cement & Concrete Composites* 26, 827–835

Krysteline Ltd (n. d.) *Advanced material processing technology*. Available from: www.krysteline.net, [Accessed 02 -02-2012].

Lam, C., Poon, C., Chan, D. (2007) Enhancing the performance of pre-cast concrete blocks by incorporating waste glass – ASR consideration. *Cement and Concrete Composites* Volume 29, Issue 8, pp. 616-625.

Lee, B., Trcka, M., Hensen, J. (2010) Embodied energy of building materials and green building rating systems – a case study for industrial halls. *SET2010 - 9th International Conference on Sustainable Energy Technologies.* Shanghai, China.

Lee, G., Ling, T.C., Wong, Y., Poon, C.S. (2011) Effects of crushed glass cullet sizes, casting methods and pozzolanic materials on ASR of concrete blocks. *Construction and Building Materials* Volume 25, Issue 5, pp. 2611-2618.

Letsrecycle (n.d). *Glass price indicators.* Available from: http://www.letsrecycle.com/prices/glass [Accessed 02 -02-2012].

Letsrecycle, (2007). *Mixed blessings for future of glass.* Available from: http://www.letsrecycle.com/news/latest-news/mixed-blessings-for-the-future-of-glass-recycling/[Accessed 02 -02-2012].

LetsRecycle (2011) *Glass sector faces mix of cullet challenges*.
Available from: http://www.letsrecycle.com/news/latest-news/glass/glass-sector-faces-mix-of-cullet-challenges [Accessed 02 -02-2012].

LetsRecycle (2012) UK glass recycling rate remains below EU average, 27 March 2012. Available from: http://www.letsrecycle.com/news/latest-news/glass/ [Accessed 23-07-2012].

LetsRecycle (2014) *Landfill tax to rise in line with inflation.* Available from: http://www.letsrecycle.com/news/latest-news/landfill-tax-to-rise-in-line-with-inflation/ [Accessed 23-07-2012]

Ling, T.C., Poon, C.S., and Kou, S.C. (2011) Feasibility of using recycled glass in architectural cement mortars. *Cement & Concrete Composites*, 33, pp. 848–854.

Maier, P. L. and Durham, S. A. (2012) Beneficial use of recycled materials in concrete mixtures. *Construction and Building Materials*, 29, pp. 428–437.

Magpie Coop (n. d.) *Magpie Recycling*. Available from: www.magpie.coop [Accessed 02 -02-2014].

Maynard C. (2005) *A novel approach for road construction using an automated paving robot.* Masters Thesis, Russ College of Engineering and Technology. Available from: etd.ohiolink.edu/send_pdf.cgi/Maynard%20Christopher%20M.pdf [Accessed 24 July 2012].

Meyer C. (2009) The greening of the concrete industry. *Cement & Concrete Composites* Vol. 31, pp. 601–605

Miltek (2012) *Increasing lagging behind europe for glass recycling.* Available from: http://www.miltek-uk.co.uk/news/uk-increasing-lagging-behind-europe-for-glass-recycling. [Accessed 21-07-2012].

Mladenovič, A., Šuput, J.S., Ducman, V., Škapin, A.S. (2004) Alkali–silica reactivity of some frequently used lightweight aggregates. *Cement and Concrete Research*. Vol 34, Issue 10, pp. 1809-1816.

Nassar, R. and Soroushian, P. (2012) Strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement. *Construction and Building Materials* Vol 29, pp. 368-377.

National Technology Platform (NTP) (n.d.) *National Technological Platforms in Construction and Build Environment,* Available from: http//www.ectp.org/ntps.asp . [Accessed 24-07-2014].

Neville, A. M. (1995) *Properties of Concrete*. Publisher: Longman Group Ltd, UK

Ojomo, L. (2010) XE336 Final Year Project, School of Computing, Engineering, Mathematics, University of Brighton, Brighton, UK.

Osmond, Z. (2007) Business Services of the University of Brighton, private communication.

Ozkan, O. and Yüksel, I. (2008) Studies on mortars containing waste bottle glass and industrial by-products. *Construction and Building Materials* Vol 22, Issue 6, pp. 1288-1298.

Quinn Glass (n. d.) Quinn Glass Bottle Production Facility, UK. Available from: http://www.packaging-gateway.com/projects/Quinn [Accessed 02 -03-2014].

Precast Concrete (2008). *Be Aware Supply Chain Resource Efficiency Sector Report: Precast Concrete.* Available from: http://www.bre.co.uk/file library/pdf/rpts/BeAware_Precast_Concrete_Sector_Report [Accessed 02 -03-2009].

Pritschow, G., Kurz, J., Fessele, T., Scheurer, F. (n.d.) *Robotic on-site construction of masonry.* Available from: http://www.iaarc.org/publications/fulltext/ Robotic_on_site construction_ of_ masonry.pdf. [Accessed 24 July 2012].

Rani, D.A., Gomez, E., Boccaccini, A., Hao, L., Cheeseman, C.R. (2008) Plasma treatment of air pollution control residues, *Waste Management* Vol. 28, Issue 7, 2008, pp. 1254–1262

Remade (2009), Diana Lock, www.remade-southeast.co.uk. Personal communication.

Resilica (2007) Available from: www.resilica.com [Accessed 2/05/2014].

Richardson, A., Coventry K., Graham, S. (2009) Concrete manufacture with un-graded recycled aggregates. *Structural Survey* 27 (1), pp. 62-70

Robot bricklayer (2009a) *Robot Bricklayers Builds Swiss Winery*. Available from: www.treehugger.com/green-architecture [Accessed 24 July 2012].

Robot bricklayer (2009b) *Robot Bricklayer Comes to New York.* Available from: www.treehugger.com/sustainable-product-design [Accessed 24 July 2012].

Saccani, A. and Bignozzi, M. C. (2010) ASR expansion behaviour of recycled glass fine aggregates in concrete. *Cement and Concrete Research* Vol 40, pp. 531–536

Sangha, C. M., Alani A., Walden P. (2004) Relative Strength of green glass cullet concrete. *Magazine of Concrete Research.* Vol. 56 pp. 293-297

SCRIB (2011). Available from: http:// www.scrib.org.uk/recyling_steel.asp [Accessed 23 -07-2012].

Shayan, A. and Xu, A. (2004) Value-added utilisation of waste glass in concrete. *Cement and Concrete Research.* Vol 34, pp. 81–89

Shi, C., Wu, Y., Riefler, C., Wang, H. (2005) Characteristics and pozzolanic reactivity of glass powders. *Cement and Concrete Research*, 35, pp 987-993

Shi, C. and Zheng, K. (2007) A review on the use of waste glasses in the production of cement and concrete. *Resources, Conservation and Recycling* Vol 52, pp. 234–247.

Sleeuw, M. (2011) *A comparison of BREEAM and LEED Environmental Assessment Methods.* Available from: http://www.uea.ac.uk/estates/enviornmentalpolicy/BREEM+vs+LEED.pdf [Accessed 21-07-2012].

Soronis, G. (1996) Standards for design life of buildings: utilization in the design process. *Construction and Building Materials* Vol. 10, Issue 7, pp. 487-490

SSC (2008) *The Strategy for Sustainable Construction. Department for Business, Innovation & Skills.* Available from: http://webarchive.nationalarchives.gov.uk/+/http://www.bis.gov.uk/policies/business-sectors/construction/sustainable-construction/strategy-for-sustainable-construction [Accessed 3 -05-2012].

Swamy, R. N. (Ed.) (1998) *The Alkali-Silica Reaction in Concrete.* Publisher: CRC Press

Taha, B. and Nounu G. (2008) Using lithium nitrate and pozzolanic glass powder in concrete as ASR suppressors. *Cement and Concrete Composites,* Vol 30, Issue 6, pp. 497-505

Taha, B. and Nounu G. (2008) Properties of concrete containing mixed colour waste recycled glass as sand and cement replacement. *Construction and Building Materials* 22, pp. 713–720.

Tarmac (2008), private communication. Available from: http://www.tarmacbuildingproducts.co.uk/ideas_for.aspx [Accessed 12/06/2012].

Tata (2007) *Sustainable Steel.* Available from: http:// www.tatasteeleurope.com/ file_source/StaticFiles/ [Accessed 23 -07-2012].

Tata (2010) *UK packaging recycling.* Available from: http:// www.tatasteeleurope.com/ file_source/Functions/CSPR/Documents/ PRN_2011_Final.pdf [Accessed 23 -07-2012].

TEEART (2005) *Technical Evaluation of Environmental Assessment Rating Tools.* Final Report Project no: PN05.1019. Prepared for the Forest & Wood Products Research & Development Corporation (FWPRDC, Australian Government)

Times (2007) *Robo-builder threatens the brickie. The Sunday Times, 14 January 2007.* Available from: http://www.thesundaytimes.co.uk/store/; [Accessed 3/07/2012]; also at http://engineering.curiouscatblog.net/2007/01/15/concrete-houses-1919-and-2007/.

Topcu I., Boğa, A., Bilir, T. (2008) Alkali–silica reactions of mortars produced by using waste glass as fine aggregate and admixtures such as fly ash and Li_2CO_3, *Waste Management* Vol. 28, Issue 5, pp. 878-884.

Trenikhin, M.V. (2012). Electron Microscopy investigation of TGCU interface, Private Communication. Institute of Hydrocarbons Processing, Siberian Branch RAS, Omsk, Russia

TR64 (2007) *Guide to the design & construction of reinforced concrete flat slabs.* Available from: http://www.concretebookshop.com/tr64-guide-to-the-design--construction-of-reinforced-concrete-flat-slabs-1851-p.asp, [Accessed 2/7/2014]

TR65 (2007*) Guidance on the use of macro-synthetic fibre reinforced concrete. Concrete Society.*

Available from: http://www.concretebookshop.com/tr65-guidance-on-the-use-of-macro-synthetic-fibre-reinforced-concrete-1853-p.asp, [Accessed 2/7/2014]

UN (2012) *Prototype Global Sustainable Development Report Resources, Conservation and Recycling.* Available from: http://sustainabledevelopment.un.org/content/documents/1454Prototype%20Global%20SD%20Report.pdf [Accessed 2/7/2014]

Waste Data Overview (2011) http://www.defra.gov.uk/statistics/files/20110617-waste-data-overview.pdf [Accessed 11-05-2012].

Winter, N. (2012) Understanding Cement, www.understanding-cement.com/alkali-silica.html [Accessed 11-05-2012].

Worldsteel (2011). Available from: http://www.worldsteel.org/publications/fact-sheets.html [Accessed 23 -07-2012

Zain, M. F. M., Mahmud, H. B., Ilham, A., Faizal, M**.** (2002) Prediction of splitting tensile strength of high-performance concrete. *Cement and Concrete Research* Vol. 32, Issue 8, pp 1251–1258

Zhang, Z. and Ansari, F. (2005). Crack tip opening displacement in micro-cracked concrete by an embedded optical fiber sensor, *Engineering Fracture Mechanics* Vol. 72, pp. 2505–2518

Appendix 1.1

Patent for

TinGlass Construction Unit

University of Brighton

2007

(WO/2008/135739) CONSTRUCTION UNIT

Latest bibliographic data on file with the International Bureau

Pub. No.: WO/2008/135739 **International Application No.:** PCT/GB2008/001536
Publication Date: 13.11.2008 **International Filing Date:** 02.05.2008

IPC: *E04C 5/07* (2006.01)

Applicants: **UNIVERSITY OF BRIGHTON** [GB/GB]; Mithras House, Lewes Road, Brighton, East Sussex BN2 4AT (GB) (
BATAINEH, Morad, Adam [GB/AE]; (AE) *(US Only)*.
SAZHINA, Elena [GB/GB]; (GB) *(US Only)*.
MANZANARES-TAYLOR, Elizabeth, R. [GB/GB]; (GB) *(US Only)*.

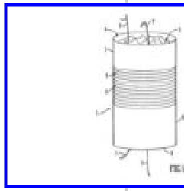
Inventors: **BATAINEH, Morad, Adam**; (AE).
SAZHINA, Elena; (GB).
MANZANARES-TAYLOR, Elizabeth, R.; (GB).

Agent: **FRANK B. DEHN & CO.**; St Bride's House, 10 Salisbury House, London EC4Y 8JD (GB).

Priority Data: 0708603.6 03.05.2007 GB

Title: CONSTRUCTION UNIT

Abstract: A construction unit (1) includes a metal shell in the form of an open-topped waste steel can (3) having a glass core (5). The glass core (5) is a solid glass core provided by a quantity of waste glass cullet which has been heated in the can to fuse the cullet, before allowing to cool in the can. The construction unit (1) may have a plurality of linking members in the form of metal wires (7) extending from one end to the other through the entire length of the glass core (5) and projecting from its ends (4, 8). The wires (7) may facilitate joining of the construction unit (1) to other construction units (1) in use. The construction units (1) may be embedded in concrete to provide a composite concrete cpnstruction unit. The alkali-silica reaction which may occur between cement and glass may be reduced or avoided due to the reduction or elimination of direct contact between the glass and cement. The composite concrete construction unit may also provide environmental advantages through the reuse of glass and metal materials.



Appendix 2.1

Material properties:

soda-lime glass

and

concrete

Reproduced from CES Edupack 2011

www.grantadesign.com, **Cambridge UK**

Concrete (high performance)

Density	2.2e3	-	2.6e3	kg/m^3
Porosity (closed)	0			%
Porosity (open)	0	-	0.03	%
Price	* 0.0515	-	0.103	GBP/kg
Mechanical properties				
Young's modulus	32	-	43	GPa
Flexural modulus	* 32	-	43	GPa
Shear modulus	* 13.9	-	18.7	GPa
Bulk modulus	* 15.2	-	20.5	GPa
Poisson's ratio	* 0.1	-	0.2	
Shape factor	3			
Yield strength (elastic limit)	* 5.3	-	9.3	MPa
Tensile strength	* 5.3	-	9.3	MPa
Compressive strength	*** 53.3**	**-**	**93.3**	**MPa**
Flexural strength (modulus of rupture)	* 6.4	-	11.2	MPa
Elongation	* 0.01	-	0.03	% strain
Hardness - Vickers	* 20.1	-	22.2	HV
Fatigue strength at 10^7 cycles	* 3.15	-	4.94	MPa
Fracture toughness	0.35	-	0.45	
	MPa.m^0.5			
Primary material production: energy, CO2 and water				
Embodied energy, primary production	1	-	1.3	MJ/kg
CO2 footprint, primary production	0.0903	-	0.0998	kg/kg
Water usage	1.7	-	5.1	l/kg
Material processing: energy				
Grinding energy (per unit wt removed)	* 6.08	-	6.72	MJ/kg
Material processing: CO2 footprint				
Grinding CO2 (per unit wt removed)	* 0.456	-	0.504	kg/kg
Material recycling: energy, CO2 and recycle fraction				
Recycle	True			
Embodied energy, recycling	* 0.758	-	0.838	MJ/kg
CO2 footprint, recycling	* 0.0631	-	0.0698	kg/kg
Recycle fraction in current supply	13	-	14.4	%
Downcycle	True			
Combust for energy recovery	False			
Landfill	True			
Biodegrade	False			
A renewable resource?	False			

Typical uses

Large buildings; Floor slabs for livestock - low permeability prevents bacteria growth; Civil engineering construction where high resistance to Cl- is required.

Other notes

Air cured. Wider ranges on values are generally 7 day-28 day values.

Soda-Lime glass

Soda lime glass is the glass of windows, bottles and light bulbs, used in vast quantities, the commonest of them all. The name suggests its composition: 13-17% NaO (the "soda"), 5-10% CaO (the "lime") and 70-75% SiO2 (the "glass"). It has a low melting point, is easy to blow and mold, and it is cheap. It is optically clear unless impure, when it is typically green or brown.

Composition (summary)
73% SiO_2/1% Al_2O_3/17% Na_2O/4% MgO/5% CaO

General properties					
Density		2.5e3	-	2.54e3	kg/m^3
Price	*	0.876	-	1.03	GBP/kg
Mechanical properties					
Young's modulus		68	-	72	GPa
Bending modulus	*	68	-	72	GPa
Poisson's ratio		0.22	-	0.24	
Yield strength (elastic limit)	*	30	-	35	MPa
Tensile strength		31	-	35	MPa
Compressive strength	*	360	-	420	MPa
Bending strength		31	-	35	MPa
Elongation		0			% strain
Thermal and combustion properties					
Thermal conductor or insulator?		Poor insulator			
Thermal resistivity		0.909	-	1.11	m.°C/W
Thermal expansion coefficient		8.5	-	9.5	µstrain/°C
Specific heat capacity	*	850	-	950	J/kg.°C
Glass temperature		442	-	592	°C
Maximum service temperature		200	-	230	°C
Flammability		Non-flammable			
Emissivity		0.86	-	0.95	
Hygro-thermal properties					
Water absorption		0			%
Water vapor permeability		0			kg/s.m.Pa
Frost resistance		Very good			
Electrical properties					
Durability					
Water (fresh)		Excellent			
Water (salt)		Excellent			
Weak acids		Excellent			
Strong acids		Acceptable			

Weak alkalis	Excellent			
Strong alkalis	Unacceptable			
Organic solvents	Excellent			
UV radiation (sunlight)	Excellent			
Wear resistance	Excellent			
Industrial atmosphere	Excellent			
Rural atmosphere	Excellent			
Marine atmosphere	Excellent			

Primary material production: energy and CO2

Embodied energy, primary production	14	-	17	MJ/kg
CO2 footprint, primary production	0.7	-	1	kg/kg

Material processing: energy

Glass molding energy	* 7.82	-	9.46	MJ/kg
Grinding energy (per unit wt removed)	* 25.6	-	28.3	MJ/kg

Material processing: CO2 footprint

Glass molding CO2	* 0.625	-	0.757	kg/kg
Grinding CO2 (per unit wt removed)	* 1.92	-	2.12	kg/kg

Material recycling: energy, CO2 and recycle fraction

Recycle	True			
Embodied energy, recycling	6.16	-	7.48	MJ/kg
CO2 footprint, recycling	0.308	-	0.44	kg/kg
Recycle fraction in current supply	22	-	26	%
Downcycle	True			
Combust for energy recovery	False			
Landfill	True			
Biodegrade	False			
A renewable resource?	False			

Supporting information

Design guidelines

Soda lime glass is an exceptionally versatile material. It is easily cast, rolled, blow-molded, pressure molded or drawn to a great variety of shapes. It can be cut, polished, and toughened. It is an exceptionally durable material, surviving weathering and normal handling with no trace of degradation, sometimes for hundreds of years.
Glazing of widows and cladding.

Technical notes

Glass is available in many different forms, clear, tinted, wire-reinforced and toughened. The data given here are for flat glass for normal glazing. Toughened glass has tensile strengths as high as 175 MPa. Low-e-glass has similar properties to soda-lime glass except it has a microscopically thin low emittance coating of metal or metallic oxide to reduce the U-factor by suppressing radiative heat flow.

Typical uses

Windows, bottles, containers, tubing. lamp bulbs, glazes on pottery and tiles.

Appendix 2.2

SET for BRITAIN 2009

eChannel

University of Brighton April 2009:

Researchers inform Parliament

'...Brighton researcher Vassilios Bugas has fought off national competition from over 600 university researchers to present his research at the House of Commons on methods to recycle glass **'**

SET for BRITAIN:
Early-Stage Researchers in Science,

9 March 2009

House of Commons

Westminster

London

SET for BRITAN

Vassilios Bugas

The Parliamentary and Scientific Committee organised a major scientific competition competition. The number of entries were over 600. The panel of judges has selected 180 entries including mine. The participation in **SET for BRITAN** awards are made solely on the basis of the research work by early-stage or early-career researchers. The presentations by Britain's Early-Stage Researchers in Science, Engineering, and Technology was held at the House of Commons held on Monday, 9 March 2009.

Poster presentation by the author at the *SET for Britain* event,
House of Commons, London, March 2009

A wide range of important scientific and engineering institutions are lending their support to this event, including the Association of the British Pharmaceutical Industry, the Institute of Biology, the Institute of Physics, the Institution of Chemical Engineers, the Royal Academy of Engineering, and the Royal Society of Chemistry.

My poster presentation was in engineering session at 6.30pm - 8.30pm. The title of the poster was: **PRODUCING WEALTH FROM WASTE GLASS (E9)**.

Briefly, an acute problem of landfilling pubglass (mixed waste glass from pubs and restaurants) has inspired a patent for TinGlass (TG) used as a construction unit for implementation in building industry. The benefits are: reducing landfilling and saving construction industry prime materials. My research focuses on construction industry and architectural applications for waste glass.

Most of the people at event endorsed the potential of the new product. Questions regarding the new product focused on:

- What is needed to make a TG construction unit
- Level of conventional reinforcement in TGC beams
- Range of applications for TG: sea defences, gabions, pavements and wall finish

The event renewed my motivation for current research. It put it in the context of industrial needs and governmental policies by broadening my knowledge and outlook.

CERTIFICATE

SET for BRITAIN

Sponsoring Member

Dr Douglas Naysmith MP

Chairman of the Parliamentary and Scientific Committee

Vassilios Bugas

was selected to present a Poster at the SET for BRITAIN Exhibition in the Engineering Section held at the House of Commons on Monday 9 March 2009

SET for BRITAIN

Doug Naysmith

Dr Douglas Naysmith MP
Parliamentary and Scientific Committee

Lord Browne of Madingley, President,
The Royal Academy of Engineering

RSC | Advancing the Chemical Sciences

abpi

INSTITUTE OF BIOLOGY

IOP Institute of Physics

The Royal Academy of Engineering

International Agri-Technology Centre Ltd

Pi plantimpact

LGC Setting standards in analytical science

Appendix 2.3

Dissemination of the research at *Greenwave* ecofestival, Brighton, 2008

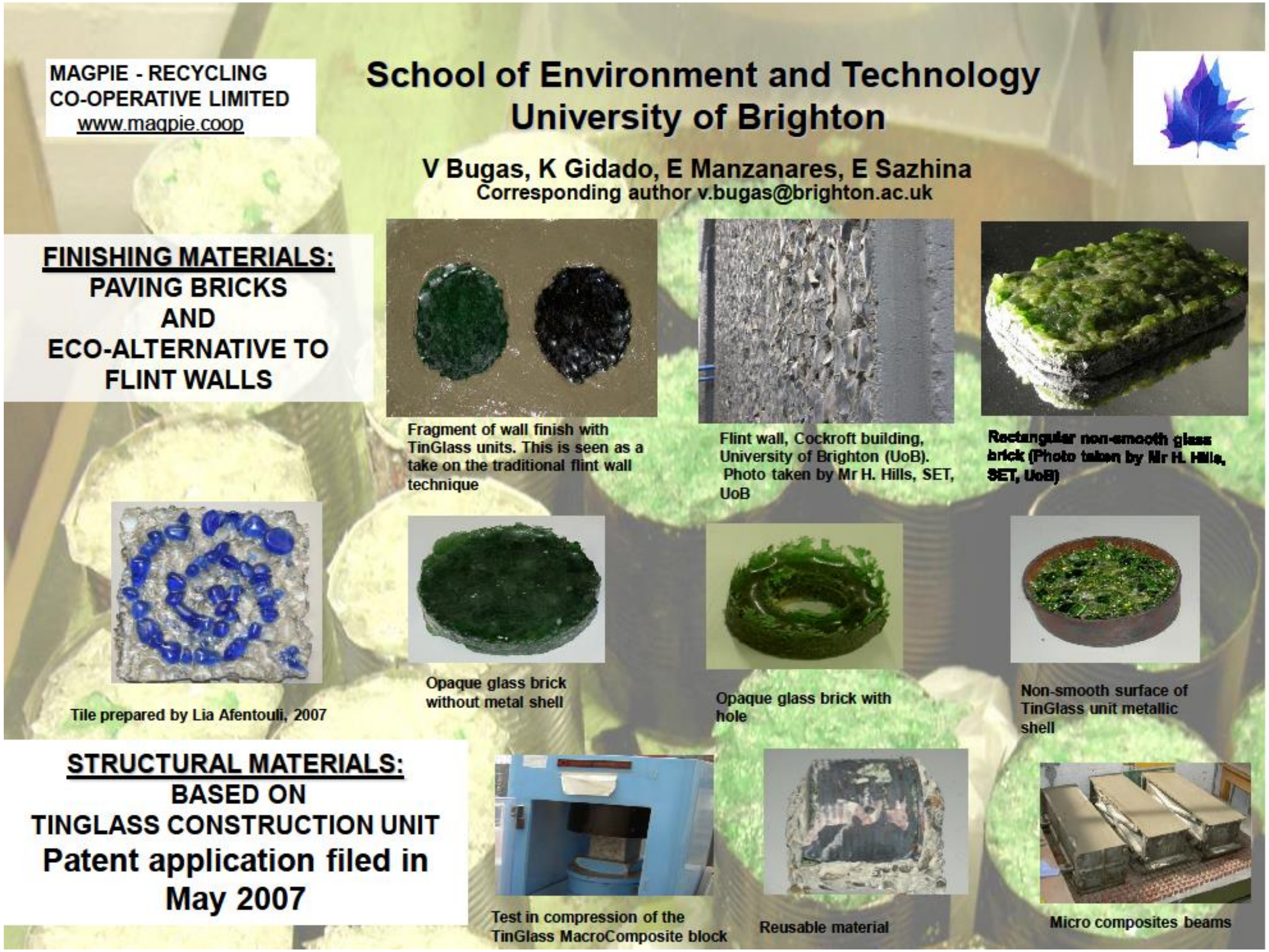
A poster has been presented by the author

to

general public at the *GreenWave* eco-festival

held in Preston Park of Brighton in July 2008

The festival was organised in collaboration with *Magpie Recycling* Cooperative, www.magpie.coop


MAGPIE - RECYCLING
CO-OPERATIVE LIMITED
www.magpie.coop
School of Environment and Technology
University of Brighton
V Bugas, K Gidado, E Manzanares, E Sazhina
Corresponding author v.bugas@brighton.ac.uk
FINISHING MATERIALS:
PAVING BRICKS
AND
ECO-ALTERNATIVE TO
FLINT WALLS
Fragment of wall finish with TinGlass units. This is seen as a take on the traditional flint wall technique
Flint wall, Cockroft building, University of Brighton (UoB). Photo taken by Mr H. Hills, SET, UoB
Rectangular non-smooth glass brick (Photo taken by Mr H. Hills, SET, UoB)
Tile prepared by Lia Afentouli, 2007
Opaque glass brick without metal shell
Opaque glass brick with hole
Non-smooth surface of TinGlass unit metallic shell
STRUCTURAL MATERIALS:
BASED ON
TINGLASS CONSTRUCTION UNIT
Patent application filed in
May 2007
Test in compression of the TinGlass MacroComposite block
Reusable material
Micro composites beams

Appendix 2.4

Publications by the author:

- V Bugas et al. (2008) Producing wealth from waste glass: ecological, commercial and social dimension. SB08MED&EXPO conference, Athens, Greece

- V. Bugas et al. (2012) Novel Designs of Tin-Glass for Structural and Finishing Materials.

Proceedings of the 3rd International Conference on Engineering, Project and Production Management. EPPM2012, ISBN 978 – 1 – 905593 – 86 - 6

V Bugas et al. (2008) **Producing wealth from waste glass: ecological, commercial and social dimension,** SB08MED&EXPO conference, Athens, Greece

Book of Abstracts: **Bougas Vassilis** (UK) : **"Producing wealth from waste glass: Ecological, commercial and social dimension"**

This work aims to outline the potential of waste glass recycling for meeting the targets of High Environmental Quality (HQE) approach. The paper examines state-of-art of waste glass collection in a city of Brighton, England, UK both from academic and practical aspects. The latter is based on the established links with a local glass collector company, Magpie Coop. It is suggested that a locally based on-site waste glass granulation and processing has much potential as a vehicle for economic prosperity and local community creativity. Granulation of beer and wine bottles onsite in restaurants and pubs can produce glass cullet that is a useful and saleable commodity straightaway. A glass granulation workshop in a remote village can avoid transportation costs and landfilling of waste glass; it can also facilitate a local production of useful and decorative items for home and garden. Social and educational potential of creative glass recycling is explored. A range of waste glass products is developed at the pilot workshop for glass recycling of University of Brighton. Estimates are made for the savings of prime materials for TinGlass & concrete macro-composite construction block. Savings in embodied energy for the construction block are evaluated whilst bearing in mind the possibility of cutting the costs when mass producing TinGlass construction blocks

Novel Designs of TinGlass for Structural and Finishing Materials

V. Bugas, M. Diakoumi, E. Manzanares, E. Sazhina, and K. Gidado

Proceedings of the 3rd International Conference on Engineering, Project and Production Management, EPPM2012

ISBN 978 – 1 – 905593 – 86 - 6

September 2012, University of Brighton

Keywords: Tin-Glass, sustainable, Tin-Glass cube, Tin-Glass beam, structural design;

Abstract

The various environmental, commercial and social benefits of products made from waste glass and concrete which conform to the current sustainable composite materials' regulations of the UK have previously been outlined by the authors of this study (Bugas et al. 2009). The completion of this outline was preceded by a review of the state-of-the art research on composite materials made from recycled waste glass (Bugas et al. 2008). The present paper is focussed on two novel designs of composite materials. The first is a design of cube blocks made from recycled Tin Glass (TG); the second is a design of control beams made from recycled TG. With regard to the design of cube blocks, TG is placed inside the core of the material; and in the design of the control beams, TG is placed in three different orientations. Two main categories of products are posited as applications for this set of novel designs: structural materials and finishing materials. In the case of structural materials, a new method is proposed which involves placing a metal cover on top of the TG when it is fully immersed in the concrete. This method of assembly removes the possibility of any of the glass coming into contact with the concrete – thereby ensuring that an Alkali Silica Reaction (ASR) is not precipitated. In the case of finishing materials, another new method is proposed which involves leaving one of the surfaces of the TG uncovered by concrete but externally visible for improved aesthetic effect. A detailed account of the design and assembly of the cube blocks and control beams, along with an analysis of their application in structural and finishing materials, is also provided.

1.0 Introduction

The scope of this paper is the development of innovative solutions for waste glass for use in the construction industry. The environmental benefits of using waste glass products in building materials for the construction industry are also explored, with particular emphasis placed on the TG construction unit, utilising ideas contained in a patent filed in May 2008. The TG construction unit consists of a glass core encapsulated in a metal shell; it is produced by fusing glass cullet placed in a waste steel can. The glass cullet is produced by on-site granulation of various waste glass streams without needing to segregate glass of different colours. Thus two waste streams – the waste glass cullet and the waste steel – are processed together resulting in a construction unit of high mechanical compression strength. The current study looks into the utilization of the TG unit as a product for the construction industry. The main focus of the study will be on structural elements such as pre-cast beams. In addition, a range of finishing materials such as glass bricks are designed and manufactured by the primary author of this paper (primary author). Both areas of interest – structural elements and finishing materials – are seen as eco-alternatives to traditional techniques used with building materials.

1.1 Structural elements

Reinforcing concrete with a TG construction unit is proposed as an extension of the traditional technique of reinforcing concrete by using steel rods. This new technique and its traditional counterpart are subject to corrosion when the building materials are exposed to air. This is not a problem when the reinforcing rod is contained within the concrete (BS 1881-125:1986) and (B.S. 8110: Part 1:1985); and it is inferred by primary author that the same is true with TG reinforcement. Both new and traditional techniques crucially depend on a strong bond being formed between the steel and the concrete in the building material. Whilst it is an established fact of conventional steel rod reinforcement that the steel component forms a secure bond with concrete, the strength of the bond formed with TG reinforcement units remains to be demonstrated empirically. The bonding strength and characteristics of TG reinforcement is a notable gap in empirical knowledge and it provides the focus of the present study. In order to fulfil the requirements of the study, TG Concrete Beams (TGCBs) were designed and manufactured for structural applications: in effect, an extensive experimental programme designing and manufacturing TG for testing in concrete beams and concrete cubes was required. The analytical calculations and assessments used in the study have been based on British Standards Institution (BS) specifications in compression (BS EN 12390-3:2002) and tests of bending (BS EN 12390-1:2001). The ultimate aim is to formulate recommendations for the construction industry in relation to using pre-cast beams with TG reinforcement. The use of pre-cast beams with TG reinforcement is also postulated as a viable way of combating ASR. Other benefits deriving from this design method include the replacement of prime materials by waste materials, in the form of the TG unit, and the enhancement of mechanical and thermal properties

1.2 Finishing materials

Wall finishing using TG bricks with an exposed glass surface is an eco-alternative to a flint wall design. Prototypes of glass bricks and a wall fragment have been designed and manufactured by the primary author. A technique for producing glass bricks without a metal shell has been developed by the primary author as a by-product of the work. Bricks of various colours and shapes (round, hollow, rectangular) have been, and can be, produced in a cheap and efficient manner.

2.0 Background of the research

Recent research at the glass recycling workshop of the School of Environment and Technology, University of Brighton, has resulted in the development of a number of prototypes of cheap and energy efficient products made from waste glass.

In 2006, Mr M Bataineh formulated the concept of TG blocks in his thesis research work supervised by Dr E Sazhina and Dr E Manzanares. A patent was granted for the design and concept in May 2008 TG construction units are produced by fusing waste glass cullets in a waste steel can. Further development of this area of work by the primary author is in continuing progress. This developmental work began with the production of TG blocks for incorporation in beams for use in the construction industry, utilizing the existing methodology of the patent. In the course of this work, however, the primary author developed his own methodology, which has resulted in a number of novel glass brick prototypes being produced. In what follows, the novel methodology for TG bricks and TG beams is demonstrated.

2.1 Modified TinGlass for structural purpose

The scope of the mechanism for producing a modified functional unit from the ideas presented in the thesis of Mr M. Bataineh requires the TG to be embedded in the concrete mixture as a replacement for the concrete mass. It was not possible to use the proposed method of Mr Bataineh's research to imbed that functional unit because the use of a TG lid was missing from his original work. As previously indicated, a TG unit that does not have a lid might have the glass surface in direct contact with the concrete after the TG has been imbedded in it, which would make the material subject to ASR.

A new design was prepared by the primary author based on Mr Bataineh's blueprint but the new design would need to be placed in concrete cubes and concrete beams. One of the design criteria of the primary author's new design is that it has to be suitable for use in the construction industry. Consequently, the new design for the TG unit would need to cause a minimum number of modifications to an existing assembly line for producing concrete beams. As a result, no wires were placed in the TG, as this saves time in the preparation of the TG unit; it would also be problematic to establish a standard configuration or specification for the wires as they could easily be bent in packing or transportation. One of the primary author's initial designs placed hooks on each side of the cylinder, which would help to boost certain structural and mechanical characteristics of the TG unit. However, this design change required greater precision than the blueprint version because it was important to ensure that the lid was securely bound to the hooks. Such work also demands more labour in the laboratory and a lot of changes to an existing assembly line to produce. There is approximately a 30% increase in the time taken to prepare the TG used in the new material when compared to a non-TG application, and this production feature makes the use of hooks an impractical design element. Ultimately, the primary author decided to abandon its use with structural or finishing materials.

The lid was placed on top of the melted glass which bound with it and created a barrier stopping any direct contact between the glass and the concrete. The new product (the TG unit) is easily placed in a cube or beam, as time is not needed to connect the wires in the beam or to change the production process significantly. You simply need to put some TG in the cube and place the TG on the supports of the reinforcing rods of the beam. The process of producing TG concrete cubes is described later (as shown in the next figures)

Fig. 1 TGCU prepared for the patent (Bataineh et al., 2007)

Fig. 2 Alternative design of TGCU with embedded hooks made by the author

Fig.3 New final design of TG to apply in cubes and beams made by the author

2.2 Way of producing the new TG

The first stage of the process is to granulate the available bottles and jags in the granulator. The granulated glass is then place in tin cans, which is put in an oven and preheated for one hour at 300^{o}C. The temperature of the oven is then increased to 950^{o}C and the mixture of glass and metal is left for another two hours. The glass melts in the oven during the two hour curing process at 950^{o}C and it is then left cooling in the oven for another ten hours during which time a smooth exterior surface is formed. TG embedded in concrete, in such a way that the concrete surrounds only the metallic part of the TG, creates an alternative to the flint wall method.

Different periods of time allocated to the curing process and differences in the size of granulates will usually cause the finished TG material to have an uneven horizontal top surface. This is because of the differences in time needed to melt granulates of different sizes – larger pieces of granulate take longer to melt, while smaller ones take proportionately less time. The result is shown in Fig.4. In view of the impact of granulate size on melting time, it was decided to sieve the glass to ensure uniformity in the size of the granulates, which then allows a totally flat horizontal surface to be formed at the top of the TG.

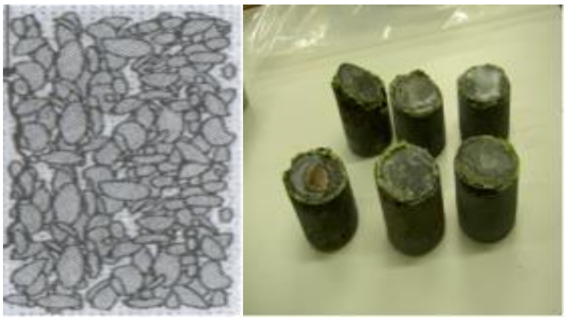


Fig.4. The bigger grains of the glass were melting later than the smaller and the surface of the lid was not horizontal as gaps are created during the melting process.

A new technique was developed in the laboratory of University of Brighton (UoB) to create TG's with horizontal lids (Fig.3) to satisfy the needs of the new composite product. A lid was placed over the glass insert while the glass was still warm. As the glass cooled, the lid adhered to the solidified insert of glass. Alternatively, for safety reasons, the lid can be placed on the insert from the beginning, before the tin can and the glass cutlet are put in the oven. The results with both methods were good. However, there is a health and safety issue with the first method because it is dangerous to place a lid on the glass insert when the material is at a temperature of 950^{o}C. Consequently, a cylindrical dick of 150g of weight and 67mm in diameter was designed, which was placed on the top of the lid (see Fig. 5). The stages of preparation of the TG, before it is placed in the oven, are presented in Fig. 6

Fig. 5.Cylindrical dick of 150gr of weight and diameter 67mm placed on the top of the lid

Fig.6. Stages of RG's 1st sieved granulated glass, 2nd after being placed in the tin can, 3rd after being placed on the lid, 4th after placing the appropriate weight on the top of the lid before being put in the oven.

Thus the problem is solved by putting small layers of granulates of the same size in the tin can and then placing very fine grains of glass under the lid, as shown in Fig 6. In this way, the very fine glass sticks to the bottom of the lid when it melts, after appropriate weights are place on top of the lid. This procedure keeps the lid horizontal. In these embodiments, the shell therefore acts as a permanent mould. The orientation of the lid is horizontal and corresponds to the dimensions of the TG for the composite cubes and beams as in fig 5.

3.0 Embedding TG in concrete for structural purposes

This part of the research is focused on developing an innovative composite material by embedding a TG unit in concrete to form a Tin Glass Concrete Unit (TGCU) for structural purposes. The inclusion of TG units provides a way of reusing glass and other waste materials (e.g. metal) whilst at the same time reducing the need to use non-renewable materials, and also increasing the level of recycling – all of which are increasingly important in the construction industry. Thus, it is almost self-evident that embedding TG units in concrete is advantageous in its own right for environmental reasons. The mechanical properties of glass and concrete should be close to those of conventional materials commonly used in building structures. To investigate any difference in structural behaviour between TG composite materials and conventional concrete units, tests were conducted in the laboratory. The concrete mixture and sampling were prepared according to standard specifications (BS 1881-125:1986) adopted by the construction industry.

The composition of the concrete mixture consisted of water, cement, sand and aggregate. The ratio of water, cement, sand and aggregate used in the mixture was 0.6:1:2:4 conforming to BS specifications (BS 1881-125:1986) and the materials were mixed in the laboratory. The type of cement used was Portland cement; the sand was natural, composed of grain sizes given in Table 1. The coarse aggregates were local crushed aggregates with a maximum diameter of 100mm and a semi-rounded shape and had been sourced from a river bed

Sieve size [mm]	A1 Quantity of aggregate 1049 (g)	A2 Quantity of aggregate 1040 (g)
2.36	174	168
2.00	25	25
1.18	54	54
0.71	44	45
0.60	15	15
0.30	161	173
0.25	140	132
0.15	431	424
	5	6

Table 1: Results obtained from the sieving test of sand.

3.1 Description of the design of the Tin Glass Concrete Cube

The dimensions used for casting of the cubes are specified by BS EN 12390-1:2001[4]. The internal dimensions of each mould in the BS are 10X10X10 cm^3.

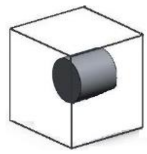


Fig.7. TG construction cube

The volume of the TG placed in the mould is 270 cm^3. The dimensions of the TGCU are: a diameter of 7cm and a height of 7cm. After placing the TGCU in the core of cube, the distance of the TGCU from all surfaces of the cube is 1.5cm (as shown in Fig.7). The rest of the mould is filled with concrete.

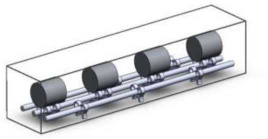
3.2 Description of the design of TGMC beams

The purpose of the new design is to replace prime materials with TGCUs. It is an innovation which can be seen as an extension of the traditional technique. Hence the TGCBs were produced by placing the TG units along the neutral axis of the beam – this means that the centre weight point does not change the uniform mass of the TG. Consequently, there should not be any significant changes in the behaviour of the beam in terms of compression or tension capabilities

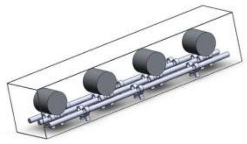
The TG units were placed in the beam in three different orientations. The longitudinal axis of the TG unit corresponded with the longitudinal axis of the beam; the longitudinal axis of the TG unit corresponded with the transverse axis of the beam; and the longitudinal axis of the TG unit corresponded with the vertical axis of the beam. The dimensions of all moulds used were the same and were 0.71m by 0.15m by 0.15m. The shape and dimensions of the moulds agreed with the BS specifications (BS EN 12390-1:2001).

The TGCBs had an approximately similar weight to the control beams. This can be explained by the fact that the density of the concrete is 2.3E3- 2.6E3 kg/m3, close to the density of Soda-lime glass – 2.44E3- 2.49E3 kg/m3 – as reported in the CES EduPack (CES Selector software 2010). The dimensions of the TG as a construction unit are designed to be 7cm in height and 7 cm in diameter. As an example, the weight of a given batch before testing the control beam was 36.8kg, and the other two composite beams were 38.0 kg and 37.5kg respectively.

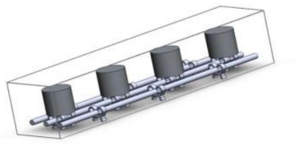
The concept of a neutral axis is defined here as the location of zero bending stresses in a beam. The neutral axis passes through the centroid of a cross-section, and the bending stresses in concrete develop linearly with distance (Gere 2001). This is a realistic assumption for the elastic analysis of the beam before the appearance of any cracks. After that, the reinforcing rods in the tensile part of the beam hold the concrete together.



Orientation A



Orientation B



Orientation C

Fig. 8. Cylindrical TG blocks, embedded in concrete beams

It is advanced that the distances of the TG when the orientation is changed but not the number or height of the TG's; it is important to compare the control with the TGCB's from the same batch. Further to this, the standard reinforcement of each beam is provided by three steel rods in all cases: control and TGCB.

The TGCBs have a quantity of TG embedded into the beam at the casting stage. The TG units are positioned above the steel rods, using additional plastic spacers placed in the marked positions. The neutral axis of the TG is parallel to the x axis, longitudinal to the x axis and vertical to the x axis of the beam. The TG is placed at the centre of the cross section of the beam. What this means is that during the test in bending of the TGCB the areas that have been created to produce a concentration of stress that make the beams weaker should be more uniform around the symmetric distribution of the TG on the neutral axis.

4.0 Different products under the form of finishing materials

A methodology for producing glass bricks from waste glass has been developed by the primary author with a view to making the finished product decorative and practical. A range of attractive glass bricks and wall finishes emulating conventional flint walls has been designed and manufactured by the primary author. However, the main focus of the current research continues to be place on pre-cast beams with embedded TG construction units.

4.1 TinGlass surface finish as an eco-friendly alternative to flint wall

The first prototypes produced by the primary author were based on existing methodology for the TG. Melting and fusing of waste glass cullet in a tin-plated steel waste can is performed at 900°C with a soaking time of 40 minutes. Subsequent annealing is performed by gradually reducing the temperature to 500°C for two hours and then, without opening the kiln, switching off the power and leaving it overnight.

The novelty of the approach of the primary author resides in applying this concept for creating a wall finish that can be seen as an eco-friendly alternative to the conventional method of flint walls. A TG block is produced with the top surface of the glass remaining exposed. It is embedded into mortar mixture, thus emulating the flint wall surface.

The finished wall consists of a composite material made from concrete and recycled glass. TG bricks are placed in the concrete, leaving some glass visible. It can be compared with flint wall but it uses recycled glass instead of natural stone.

A fragment of the wall finish was designed and manufactured in the workshops of the School of Environment and Technology (SET). The boundary between glass and mortar on the wall surface can be left exposed, with rough edges of TG brick protruding – similar to a flint wall surface (see Fig.9a and Fig.9b; photo of Mr H Hills, SET). Conversely, if a flush wall finished is preferred, the rough ends of the TG can be removed by polishing them off with a metal file

TG bricks can be used for a variety of applications: including garden walls, vehicle crush barriers, flood or sea defences. It combines high density and mechanical strength and toughness with an attractive surface finish, allowing creation of artistic patterns and novel architectural features.

Fig9a. Fragment of wall finish with TGCUs embedded in mortar. This is seen as a take on the traditional flint wall technique as shown in Fig 9b.

Fig.9b. Flint wall, Cockroft building, University of Brighton.

4.2 Surface smoothness, opacity and density of the TinGlass Construction Unit

In the course of extensive experimentation with various production regimes for TG bricks, it has been established by the primary author that significant variations in surface roughness and density of the TG unit can be achieved by varying the length of the soaking time in the kiln. Under the standard regime of soaking time, 40 minutes at 900^{o}C, the surface of the fused glass is rough (see Fig.10 and Fig.11). Increasing the soaking time by up to 2 hours at this temperature will create a smooth opaque surface and reduced the volume of the glass core (hence the higher density). This is because glass granules melt under this regime, whereas they fuse under the 40 minutes soaking time regime. Heat transfer inside the glass core is the product of heat conduction, and longer soaking times raise the temperature inside the glass cullet. Sufficient energy is supplied for the glass to change from a solid to a liquid state. TG resembles a natural stone under this production regime. This is a desired result for some of the applications where higher density and enhanced mechanical toughness are needed.

It has been observed by the primary author that the size of glass cullet granules exercises a considerable influence on the appearance of the final product. Large size glass cullet granules give a brighter and more translucent appearance to TG than powdered glass.

Fig.10 Opaque glass brick without metal shell

Fig.11 Opaque glass brick smoothed by normalizing (additional heating process)

4.3. Aluminium cans as a mould absorbed by glass during fusing

When fusing glass at high temperatures, it was previously considered impossible to use an aluminium can (e.g. a sardine can) as a mould because the melting temperature of aluminium is lower than that of glass. Indeed, earlier tests have shown a disintegration of the aluminium mould at high temperatures which results in molten glass being spilled in the kiln.

Despite this limitation, the primary author has developed a way to produce a waste glass brick or paving stone using a mould made of sardine cans by establishing and carefully regulating the range of temperatures and soaking times for this particular production process. A paving stone made of waste glass fused in a sardine can is shown in Fig.12 in the Appendix. It was melted at 800ºC with a soaking time of 1 hour and subsequent annealing taking place overnight. On cooling, it was discovered that the aluminium mould was absorbed by the glass core, producing an attractive surface finish. This method can be used for the production of paving stones with an opaque surface and a high coefficient of friction.

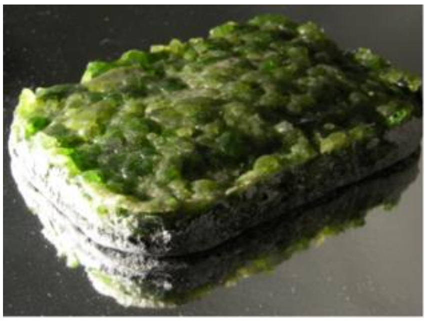


Fig . 12. Rectangular glass brick produced by fusing in a sardines' can mould

4.4 Glass bricks without a permanent mould

All of the instances and cases described above had a metal can – whether made of steel or aluminium – used as a stay-on permanent mould. This section describes a method for the production of waste glass bricks by extracting them from a mould on cooling.

Fusing or melting glass in a metal mould creates a very strong bond between them, and it is practically impossible to extract the glass core from the mould on cooling. This is how the TG concept originated. It is possible, however, to line the mould with ceramic fibre paper prior to heating. This greatly facilitates the extraction of the glass core from the mould after annealing and cooling to room temperature. This method was outlined by Mr David Watson, a British artist in glass (Watson 2001).

Mr Watson's method has been further developed by the primary author. The latter has succeeded in producing glass bricks of rectangular or round shape. Indeed, any reasonable shape can be produced by manufacturing a steel mould of a given shape and lining it with ceramic fibre paper.

The cross-section shape of the brick may be solid or hollow, with a central hole produced by insertion of a steel cylinder wrapped into the ceramic fibre paper (see Fig.13, Fig.14 and Fig.15). Hollow bricks may be incorporated into various structures by stacking them on a steel pole or a similar support mechanism.

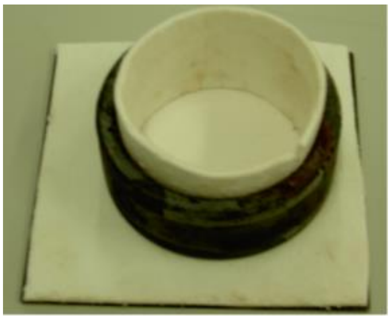


Fig.13 Metal mould lined with ceramic paper prior to fill by glass cullet

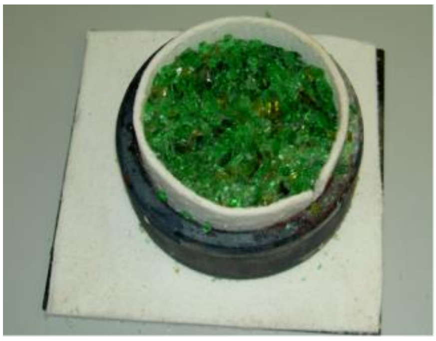


Fig.14 Glass cullet in round steel mould is prepared for the furnace

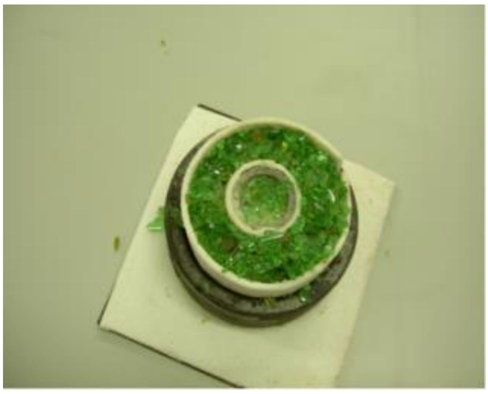


Fig.15 Hollow mould with glass cullet is prepared for placing in the furnace

Sharp edges and corners, combined with matt and grainy surfaces in the areas lined by ceramic fibre paper, present a certain problem for the glass bricks produced by this method. The primary author has addressed this problem by testing and implementing a normalising method for glass bricks.

Description of normalizing method: After cooling the glass bricks to room temperature and extracting them from the mould, the surface layers are re-heated and re-melted by placing the brick into a very hot kiln (900°C) for 30 minutes of soaking time, then it undergoes annealing overnight. This procedure makes the surface much smoother and gives it a more shiny appearance than before.

5.0 Conclusions

This paper outlines the potential usefulness and application of a series of innovative products made from recycled waste glass (TG units). It postulates that these innovative products can be used as structural and finishing materials in the construction industry.

The paper also demonstrates that several problems inherent in the production process of TG and in achieving an even surface on the top of the TG unit can be solved by using waste glass fragments (granules) of the same size and by placing a cover (a cylindrical dick) of 150g in weight and 67mm in diameter on the top of the TG unit.

A central feature of the paper is its intention to reinforce the sustainability message – namely, that making new products from recyclable material not only has the value of increasing the life span of waste material, this recycled waste material can be further recycled in the future – creating a virtuous circle of recyclability. The benefits of this approach – in terms of economic prosperity, the creative use of waste material and the huge potential savings made in relation to our use of prime materials – cannot be under-valued.

The ultimate message of the paper is that the development and design of TG units illustrates how creativity, innovation and sustainability can be brought together to benefit the ever-increasing needs of the construction industry

References

1. Bataineh, A.M., 2006. *Innovative recycling and cooling solutions*. MSc Thesis. University of Brighton.

2. Bugas, V. Afentouli, L. Manzanares, E. Sazhina, and E. Harder, M., 2008. *Producing wealth from waste glass: ecological, commercial and social dimension*, SB08 MED International Conference on Sustainable Building, 2008, Athens, Greece.

3. Bugas, V. Gidado, K. Manzanares, E. Pearce, and D. Sazhina, E., 2009. *Recycling Glass as Construction Material,* SET FOR BRITAIN Presenters and Posters Engineering, 2009, London, UK.

4. The British Standard BS EN 12390-1:2001. *Testing hardened Concrete. Shape, dimensions and other requirements for specimens and moulds*

5. The British Standard BS EN 12390-3:2002. *Testing hardened concrete. Compressive strength of test specimens*

6. The British Standard BS 1881-125:1986. *Testing concrete. Methods for mixing and sampling fresh concrete in the laboratory*

7. The British Standard B.S. 8110: Part 1:1985. *Structural use of Concrete*

8. CES Selector™ software, 2010. Available from: http://www.grantadesign.com, Cambridge, UK [Accessed 11/02/12]

9. Gere, G., 2001. *Mechanics of Materials* 5th edition. USA: Brooks/Cole

10. Watson, D., 2001. *Windows and Turning Point*. In: *Art in the Open: Public Art in Basingstoke and Deane*. Available from: http://www.basingstoke.gov.uk/NR/rdonlyres/AC40DA7F-E2F3-44A3-98A5-B099FD79A69E/0/public_art_brochure.pdf [Accessed 21 June 08]

Appendix 2.5

Investigation of TGCU – concrete bond by X-ray diffraction methods using PANalytical X-pert PRO X-ray diffractomer

Miss L Ojomo, Final Year project, School of SET

Dr M. Smith, School of SET, Private Communication

University of Brighton

2010

Acknowledgements : The XRD experiment is set and supervised by

Dr M Smith of School of Environment and Technology, University of Brighton.

The XRF experiment is supervised by Dr Beth Manzanares, WERG, University of Brighton.

An extract from Final Year project by Miss Leah OJOMO,

School of CEM, University of Brighton, 2010

CHAPTER 3

EXPERIMENTAL INVESTIGATION OF THE GLASS-CONCRETE INTERFACE BY X-RAY DIFFRACTION

"The beginning of knowledge is the discovery of something we do not understand".

Frank Herbert

The TinGlass construction units were inserted into concrete moulds at casting stage, and embedded in concrete cubes of volume $1000cm^3$, for compression testing after curing for 28 days. In addition, thermally fused glass bricks, and APC slag pieces from a company called Tetronics (introduced and shown in Appendix 1), were also embedded separately into concrete cubes of volume $1000cm^3$, in the same manner. They too were left to cure for 28 days and naturally dry at room temperature for a further 48hours.

3.1 XRD analysis for the determination of chemical composition across the composites

The embedding of thermally fused waste glass bricks (thermally fused glass, fused within a tin-plated steel can, lined with a heat-resistant ceramic paper) and slag pieces into concrete was done so that an investigation of the chemical processes taking place within the composite material, as well as the nature of the bonds between the different components could be observed.

Each concrete cube which was to be used for this project was cut in half, after curing and drying. This is done to reveal the structure of the glass inserts embedded into the concrete.

A total of 6 test samples were used for the project. Two thermally fused glass bricks, two APC slag pieces and two TinGlass construction units (which had previously undergone compression testing) were used. PANalytical X-pert pro X-ray diffractometer (http://www.panalytical.com/Xray-diffractometers.htm) was used to determine each of the test samples solid phase compositions. High Score Plus software, a full powder pattern analysis tool, was used to interpret the results by matching intensity peaks of minerals found, to already interpreted minerals referenced in a database.

3.2 Thermally fused waste glass brick preparation before insertion into concrete cube

Before the heat treatment process to create a thermally fused waste glass brick could commence, ceramic paper was placed inside the walls of a tin-plated steel tuna can, to ensure a separation of the waste glass and the walls of the tuna can. This was so that the waste glass when undergoing heat treatment would not bond with the walls of the can, but however, form into its shape. Waste glass cullet was then poured up to the edges of the tuna can aligned with ceramic paper. In total, two thermally fused waste glass bricks were made.

3.2.1 Method used to produce thermally fused waste glass bricks

1. In the lab, the power supply of the glass-processing muffle furnace was switched on from the mains.
2. The power switch on the furnace was then pressed; causing the heater display to light up.
3. The specimen prepared was placed into the muffle furnace, making sure gloves worn when placing specimen into furnace.
4. It is important to ensure that the molten glass being heated will not spill on the alumina lining in the furnace. Therefore a ceramic fibre paper, a layer of sand and a steel plate on the furnace floor, was used to prevent any spilt glass from bonding with the alumina surface walls and the furnace floor.
5. The temperature regulator was then set to 350˚C for an hour.
6. After an hour of ramping up to 350˚C, increase the temperature regulator to 550˚C and leave for another hour to further ramp up.

7. Soaking starts when temperature is held at constant level. The temperature regulator was then switched to 950˚C and soaked at this temperature for two hours.
8. After soaking, the temperature regulator was switched down to 550˚C, for one hour.
9. Temperature regulator was again decreased further to 350˚C for another hour. This was to ensure gradual temperature reduction to protect the furnace heating elements.
10. After the hour, the glass-processing muffle furnace was switched off by pressing the power button on the furnace.
11. The furnace was then switched off from the mains on the wall.
12. The specimen was left in the muffle furnace overnight, for a slow rate of annealing, to prevent as much as possible, internal stresses forming.
13. The following day, the specimen was taken out from muffle furnace.

Once the thermally fused glass brick had been produced, it was then inserted into the concrete moulds and left to cure in the same method as described in chapter 2. Figure 15 and figure 16 shows the end results of the thermally fused waste glass

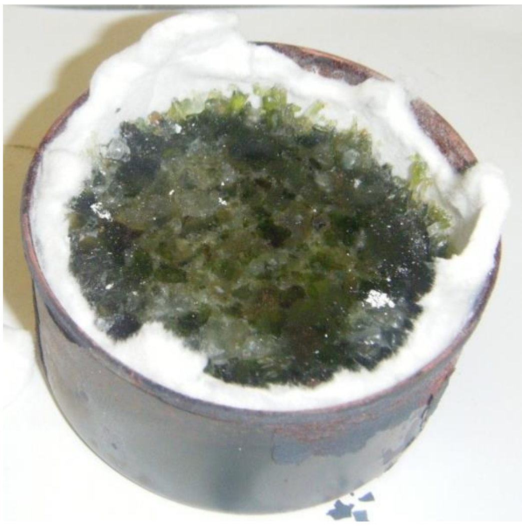


Figure 15. Thermally fused glass bricks within aligned ceramic paper in waste steel can for preserving tuna.

Figure 16. Thermally fused glass bricks before embedding into concrete cube

Once all the concrete cubes had been left for 28 days to cure and a further 48hours to naturally air dry at room temperature, they were then ready for the XRD exploration.

3.5 XRD Sample preparation

Table 8 shows **images of cross-sections** of each glass-concrete cube test samples used for the XRD analysis. Two identical test samples for each case were prepared and analysed in order to get a more accurate statistics for the results.

For each test sample used, the sample was drilled out at set distances of 1cm, 2cm, and 4cm. If the sample margin allowed it, a further 5cm from the concrete glass, slag and Tinglass interface was drilled.

The preparation procedure for one of the cubes (Thermally fused waste glass brick embedded into concrete) is shown below in detail:

1. A small marble bowl to grind minerals was first cleaned with Acetone
2. With a thin pointed pen and a ruler, evenly spaced lines at spacing's of 1cm, 2cm, 4cm (and if space allowed, 5cm) from the interface of the thermally fused glass to the edge of the concrete cube were drawn.

Figure 17. Concrete cube with glass brick embedded inside, cut in half. The lines are marked from the interface of glass brick at 1cm, 2cm, and 4cm

3. Using a specialised drill, small sections were drilled along each marked line; this is to prepare powder- like samples for XRD analysis.

Figure 18. Small sections being drilled within 1cm regions

4. The powder particles were continuously collected and placed into a plastic sleeve which was clearly labelled to identify the block being drilled, and to also show what distance away from the glass interface the particles had come from.
5. In case when not enough powder is available, it was decided to use a Silicon single crystal technique. It is placed into a deep well sample holder (thus changing it to the 'Zero background' sample holder).
6. The powdered samples were placed into the bowl and they were further manually grinded by pestle to form a finer powdered sample. It is important to get the sample in as much of a powdered state as possible to provide as much randomly orientated particles available for diffraction analysis.
7. The powdered sample was then placed into the zero background sample holder as shown below in Figure 26. Using a small spatula, the powdered sample was evened out.

Figure 19. Powdered concrete sample placed into zero background sample holder

8. Opening the doors to the PANalytical X-pert pro X-ray diffractometer, the zero background holder containing the powdered sample was then seated in the diffractometer platform as shown in figure 27.

Figure 20. Powder sample placed in X-pert PRO (PANalytical) diffractometer, ready for analysis

9. The door for the PANalytical X-pert pro X-ray diffractometer was then closed and the diffractometer was set to run to start the analysis (shown in figure 28).

Figure 21. Sample during analysis

Once the analysis was complete, High Score Plus software was used to interpret the findings. The results for each region in each block are shown and discussed in Appendix3.

The experiment was then repeated by the same procedure for the remaining two APC slags, TinGlass cubes and the one remaining fused glass brick.

	Images of cross-sections
APC slag	
Fused Glass Brick	
Tinglass Unit	

Table 8. Images of typical cross-sections of glass-concrete composite cube manufactured and used in the study

The results for all 6 test samples are shown below. Each plot is coloured coded to clearly show the difference in results of the findings within each region. The colour of each plot corresponds to the legend in the top left corner of the plots. The minerals found at each peak are labelled near the corresponding peak.

Results for first APC Slag embedded into concrete

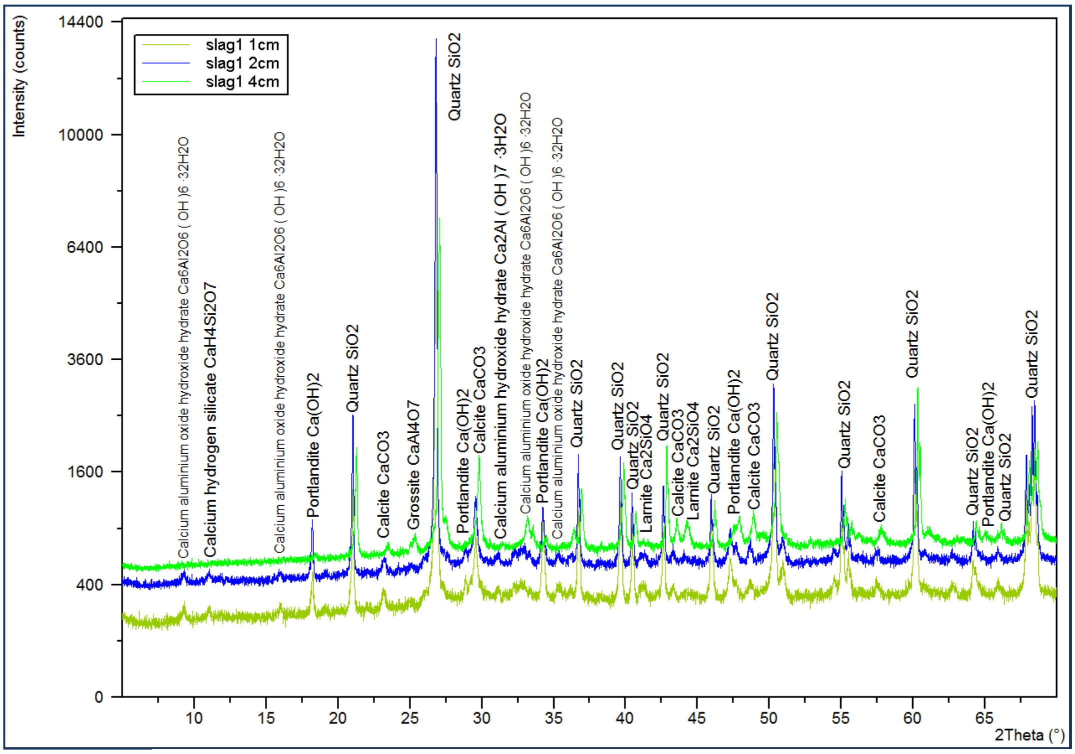


Figure 41. Results for the first APC Slag embedded into concrete

Results for the second APC Slag embedded into concrete

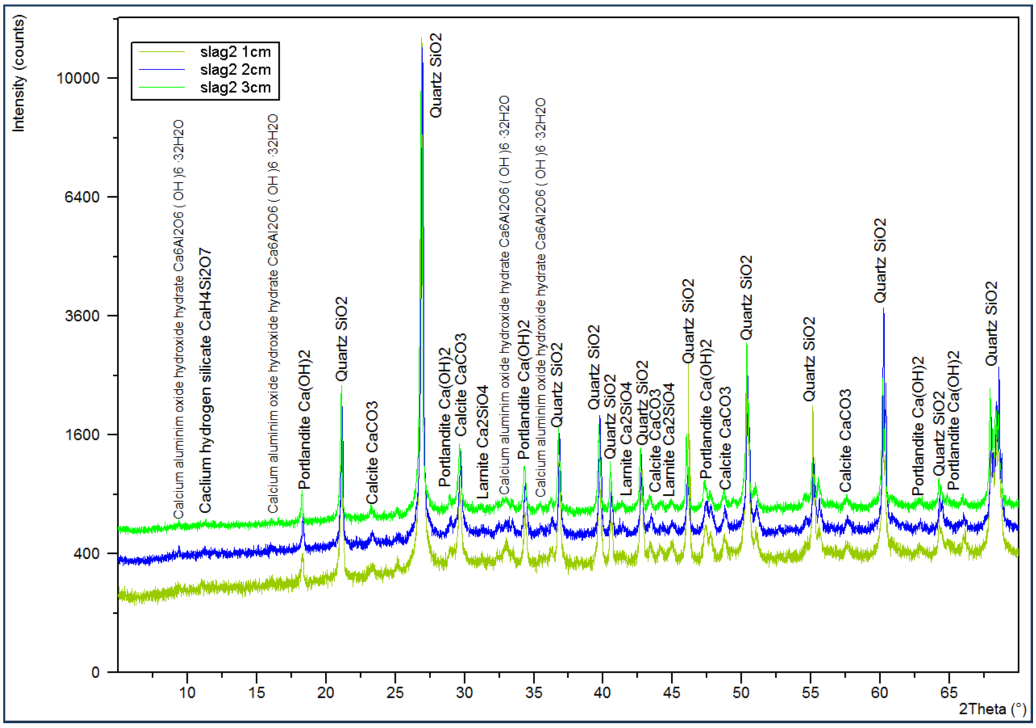


Figure 42. Results for the second APC Slag embedded into concrete

Results for the first TinGlass construction cube

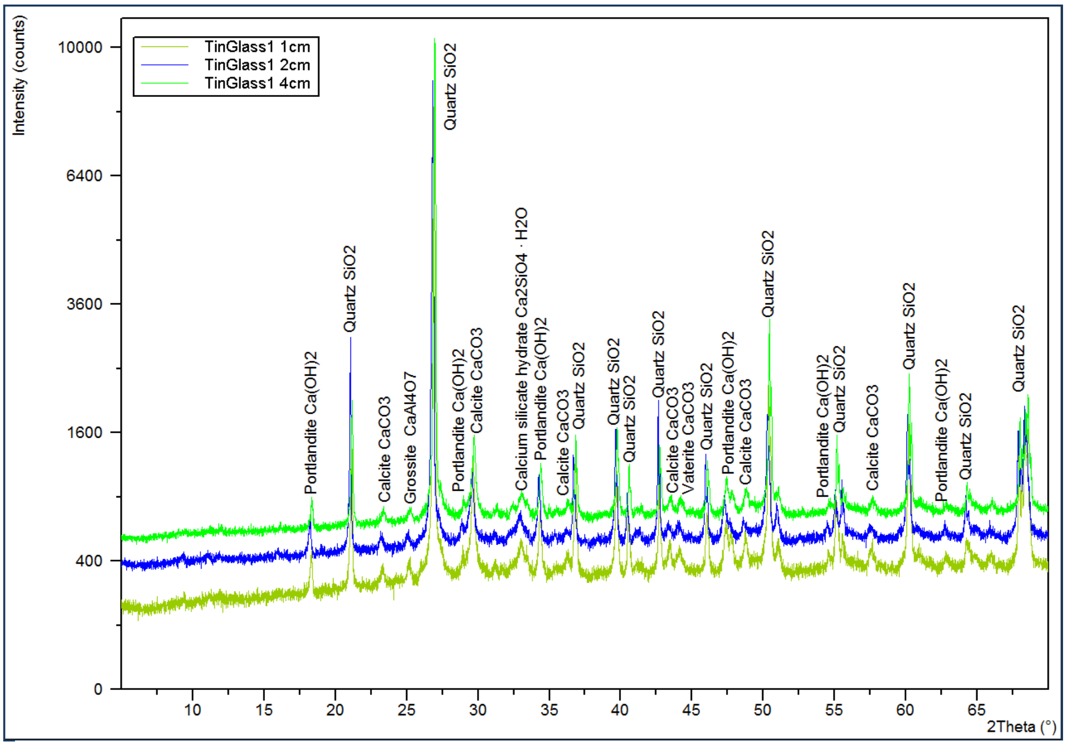


Figure 43. Results for the first TinGlass construction cube. At distances of 1cm, 2cm and 4cm which showed no changes with distance.

5.5.3 Results for the second TinGlass construction cube

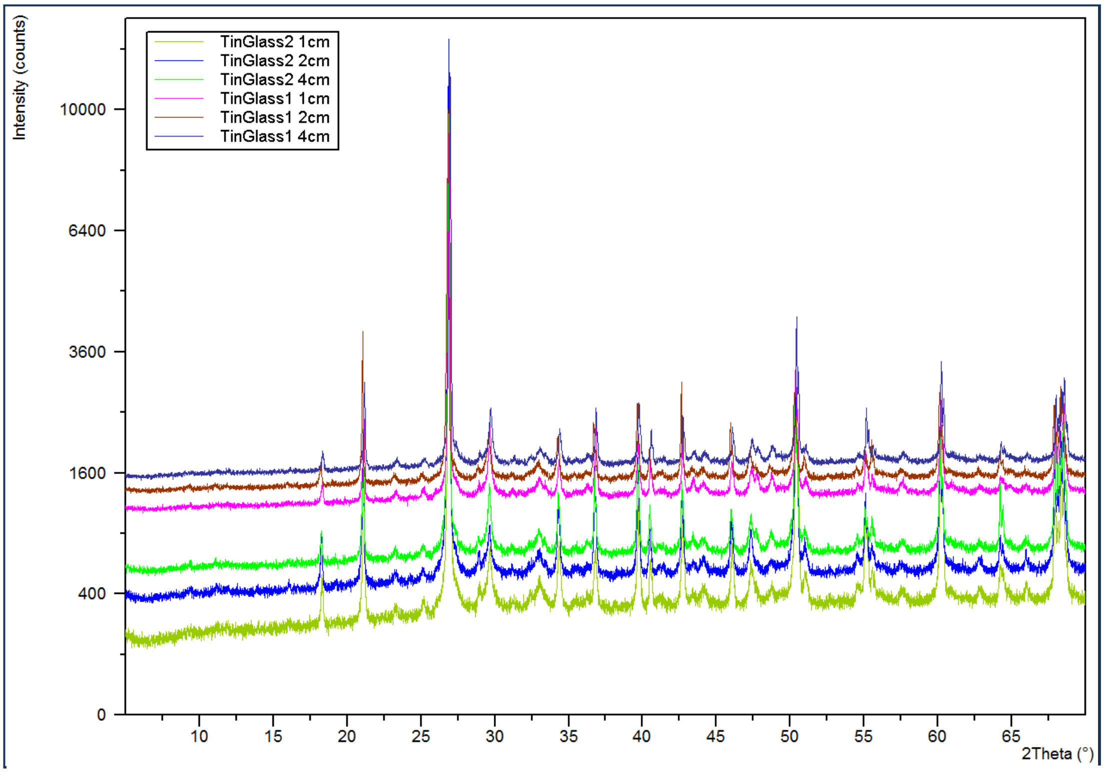


Figure 44. Results for the second and first combined TinGlass construction cube. At distances of 1cm, 2cm and 4cm. Both results highlight that TinGlass embedded into concrete does not affect the chemical composition of the concrete

Results for the first thermally fused brick embedded into concrete

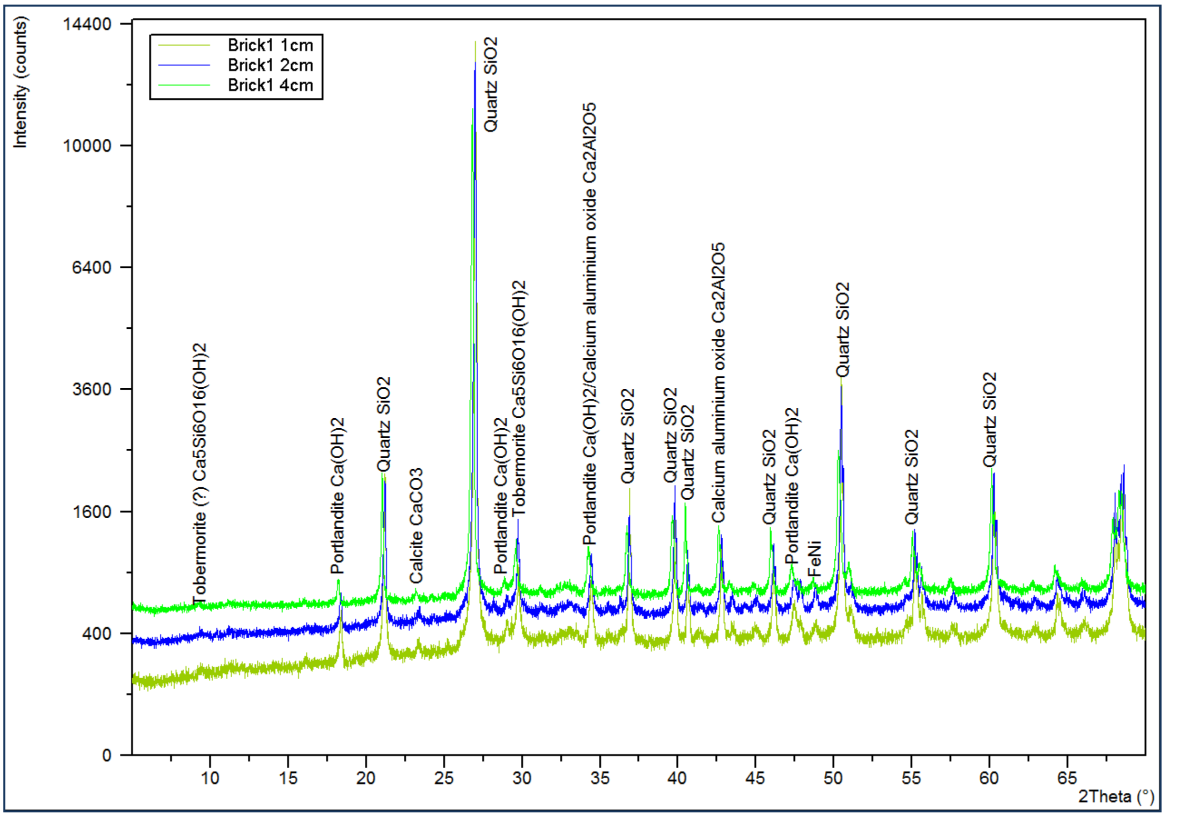


Figure 45. Results for the first thermally fused brick embedded into concrete. At distances of 1cm, 2cm and 4cm, this shows only a slight variation

Results for the second thermally fused brick embedded into concrete

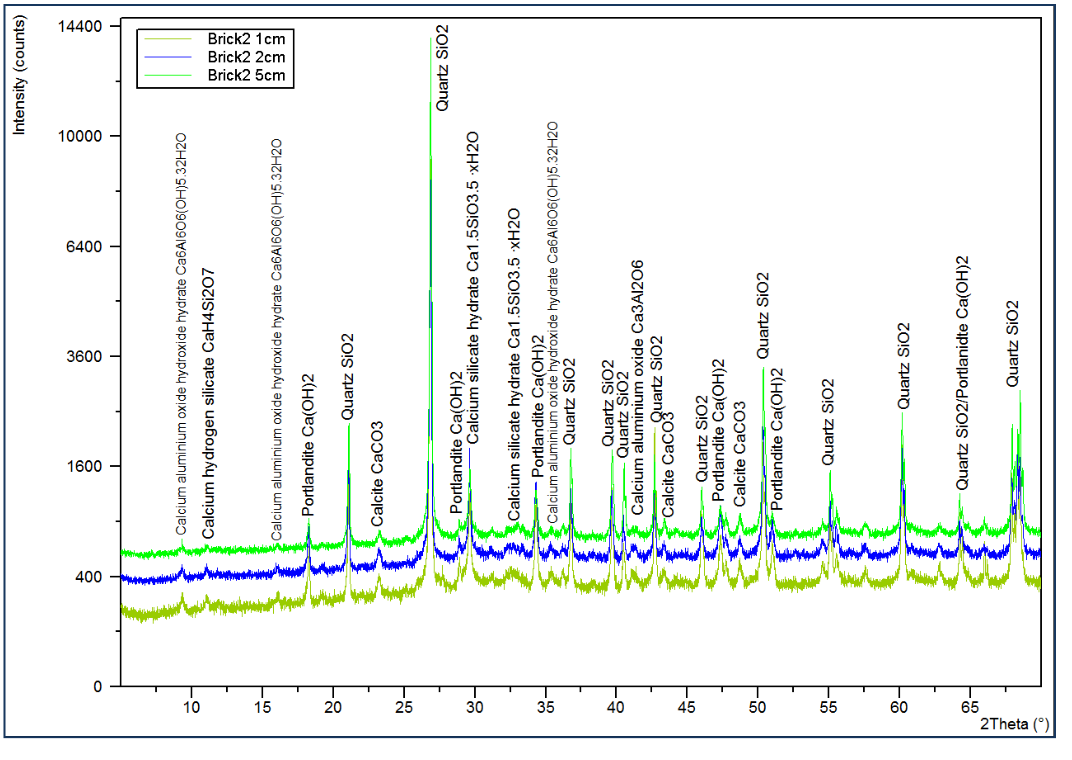


Figure 46. Results for second thermally fused brick embedded into concrete. At distances of 1cm, 2cm and 5cm, this again shows a slight variation with chemical composition at the measured distances

3.6 Analysis of the variation in the crystallinity of amorphous glass and fused glass

Variations of degree of crystallinity in solidifying glass depend of its heat treatment during cooling stage. PANalytical X-pert pro X-ray diffractometer allows to analyse what happens to an amorphous bottle glass after it has undergone thermal fusion and slow annealing in the furnace (thus allowing molten glass to crystallise into opaque glass ceramics rather than transparent glass). An experiment was set using amorphous brown glass cullet (glass 1) and thermally fused glass (glass2) cullet to see how the microstructure of thermally fused waste glass differs from amorphous waste glass. As XRD requires powder specimen samples, both glass 1 and 2 were grinded into a powdered state. The safety precautions followed were the same for that followed in section 5.3

3.6.1 Preparation of amorphous brown glass and thermally fused green glass

1. A bowl to grind minerals was first cleaned with Acetone.
2. Glass 1 (amorphous brown glass) cullet was then placed into the bowl and using a Pestle, it was manually grinded to a fine powder
3. The powdered glass 1 sample was then placed into a deep-well sample holder. Using a very small spatula, the powdered sample was evened out.
4. Opening the doors to the PANalytical X-pert pro X-ray diffractometer, the deep -well sample holder containing the powdered sample was then seated in the diffractometer platform
5. The door for the PANalytical X-pert pro X-ray diffractometer was then closed and the diffractometer was set to run to start the analysis.

The experiment was then repeated in the same manner for Glass 2 (thermally fused and slowly annealed green glass). The results for both samples are shown in section 3.7. Each plot is colour coded to clearly show the difference in result findings. The colours of each plot correspond to the legend in the top right corner.

3.7 XRD results for degree of crystallinity

The degree in crystallinity of fused waste glass from amorphous glass waste bottles, which has been granulated into glass cullet, and then heated to fusing temperatures and slowly annealed to allow the crystallization to proceed, is shown below in Figure 22

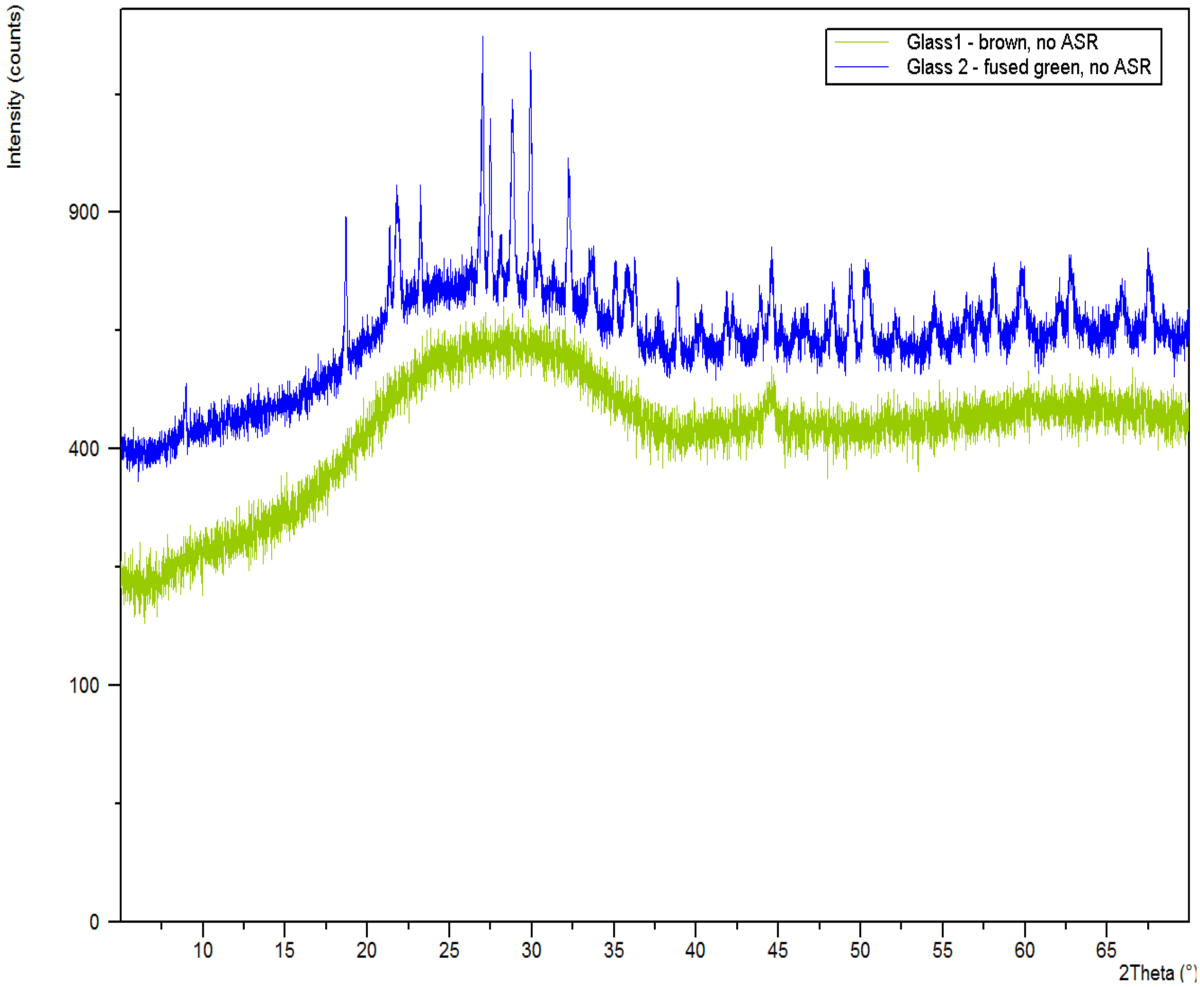


Figure 22. Comparison between thermally fused glass (blue plot) and amorphous glass (green plot)

5.2 Analysis of XRD and PXRF results

The X-ray analysis gives information about chemical composition and crystallinity of the samples. This allows an insight into the microstructure of glass-concrete composites that is linked to mechanical properties, hence the need in the X-ray analysis for exploring the physical and mechanical properties in-depth.

Two X-ray techniques are applied to the study. The XRD gives the mineralogy data via diffraction on crystal structure; whist XRF identifies heavy metal concentration. Monitoring of heavy elements is crucial for preventing the contamination of concrete (and soil when landfilling).

XRF analysis of APC slag: The determination of heavy metal content in the APC slag has been conducted on an APC slag sample provided by Tetronics [1]. The aim was to establish the possibility of immobilisation of heavy metals by vitrifying air-borne pollutant particulates by plasma arc. Portable XRF equipment has been employed for this purpose, under guidance of supervisory team. The results are shown in Table 7.

This is a feasibility study for the determination of toxic waste (heavy metal contents); it paves the way to further work on leakage of toxic waste from landfills into ground waters and soil/

XRD analysis of APC slag - concrete interface: The XRD exploration of the APC samples is summarised in Appendix 1. When APC slag is embedded into concrete the XRD traces taken at several distances from the slag-concrete interface help to trace the change in mineralogy. Some variations in mineral composition are observed for the APC slag.

XRD analysis of the interface between thermally fused waste glass and concrete: Analysis have shown slight variations in mineral composition as shown by the XRD traces taken at several distances from the interface

XRD analysis of the interface between TinGlass and concrete: did not show any significant variations in mineral composition across the interface. This therefore shows that embedding TinGlass into concrete should not cause any changes in the composition of concrete when embedded

Study of the degree of crystallinity by XRD: amorphous glass *vs* thermally fused glass ceramics: The XRD study of glass powder sample (taken from a waste beer bottle), *vs.* fused glass (produced by fusing and slowly annealing the waste glass cullet), has indicated clearly the increased degree of crystallinity for the fused glass. This can be explained as when thermally fusing and annealing waste glass cullet, the atoms reorganise themselves into a crystalline structure. Thus opaque glass ceramics can be formed from transparent waste bottles.

Appendix 1: Determination of heavy metals concentration using XRF for Air Pollution Control (APC) slag

In an effort to reduce waste being sent to Landfill another method called incineration is often used as an alternative method for the disposing of waste. The term incineration describes processes which combust waste and recovers energy. However the downside to this method is that a by-product it produces (APC residue) is hazardous, with approximately 170,000 tonnes of it being created each year in the UK.

Tetronics, a British company well known for their work with plasma technology, has come up with a way of converting the hazardous by-product of incineration into an inert slag material (shown in Figure 31) that can be recycled into various products.

Tetronics have been able to create this conversion by the use of an advanced thermal processing system, Plasma Arc Technology [1]. Plasma Arc Technology operates on principles which are similar to arc welding, where an electrical arc is struck between two electrodes [1].

The high energy arc creates high temperatures ranging from 3000 degrees - 7000 degrees Celsius [2]. Waste material is fed into a chamber and the intense heat of the plasma vitrifies the hazardous by-product of incineration into an inert slag material.

Figure 31. Slag samples provided by Tetronics [1]

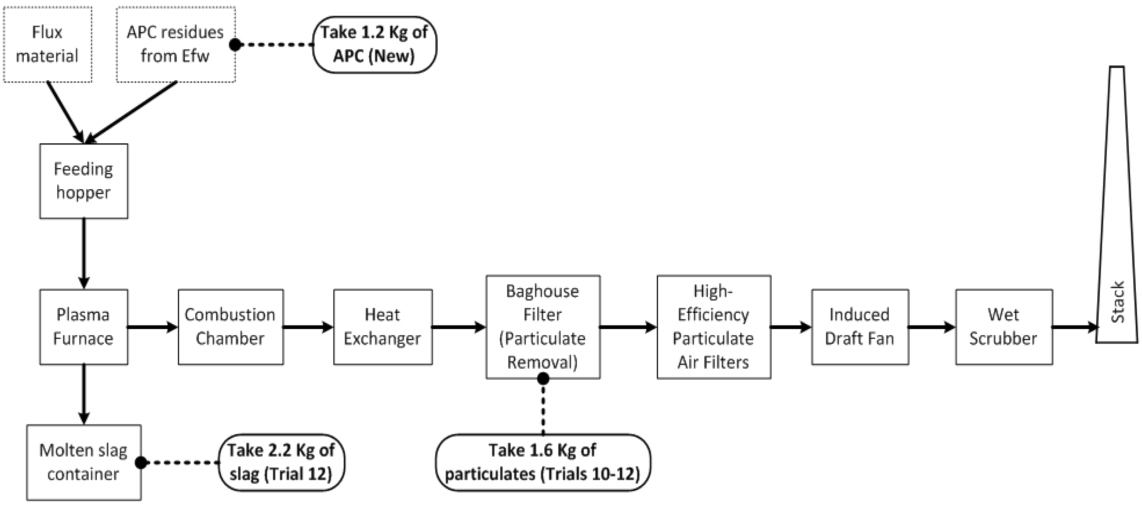


Figure 32. Production of Slag samples

Critical assessment of the Slag produced by Tetronics

Figure 32 shows the process of how the Slag samples were made and the stage of where they were taken. Slag is produced at temperatures as high as 1600C. This means that to produce, it will be more expensive than TinGlass (which is only heated to 950C) as it requires more energy. The Slag samples are not as versatile as TinGlass in the sense that TinGlass is scalable, it can be produced from the back garden to a 'producing energy from waste' power plant, whereas, slag is only produced in a energy from waste power plant [1, 2]

Results for heavy metals in APC slag: Before using the APC slag provided by Tetronics, it was important to know what the concentration of heavy metals which were present. To do this x-ray fluorescent spectroscopy was used. To get better statistics of results, the portable XRF equipment under guidance of supervisory team was used for the same slag sample three times. However the position of the sample was placed in 3 different orientations. The results are shown in Table 7.

To run the experiment, no special preparation of the slag sample was needed. The slag sample was simply placed in the Portable XRF apparatus. The shield of the apparatus was then lowered to shield and contain slag sample whilst under analysis. .

Table 7 shows the elements found in each test run by the same APC slag sample. For each test run, the concentration of the amount of heavy metals found is shown in Parts Per Million (PPP); the error of each result is also shown.

Element	Test 1		Test 2		Test 3	
	PPP mg/kg	±	**PPP mg/kg**	±	**PPP mg/kg**	±
Ti	7830	611	7234	638	8359	643
Cr	284	54	237	56	258	55
Mn	264	37	290	40	381	42
Fe	18722	229	19083	240	19530	242
Zn	153	9	154	9	161	9
Rb	9	2	7	2	8	2
Sr	421	7	445	7	432	7
Zr	168	4	170	4	165	4
Ag	156	16	178	16	182	16
Sn	0	0	118	33	0	0
Pb	0	0	0	0	12	4
Mo	0	0	0	0	11	3
Pt	0	0	0	0	196	53

Table 7.Result showing the concentration of heavy metals found in the APC slag.

References

1. Tetronics: Plasma-enhanced waste recovery technology, n. d. Available from: http://www.tetronics.com/ [Accessed 01/011/2010]
2. Rani, D. et al., (2008) Plasma treatment of air pollution control residues, Waste Management Volume 28, Issue 7, 2008, pp. 1254–1262

Appendix 2.6

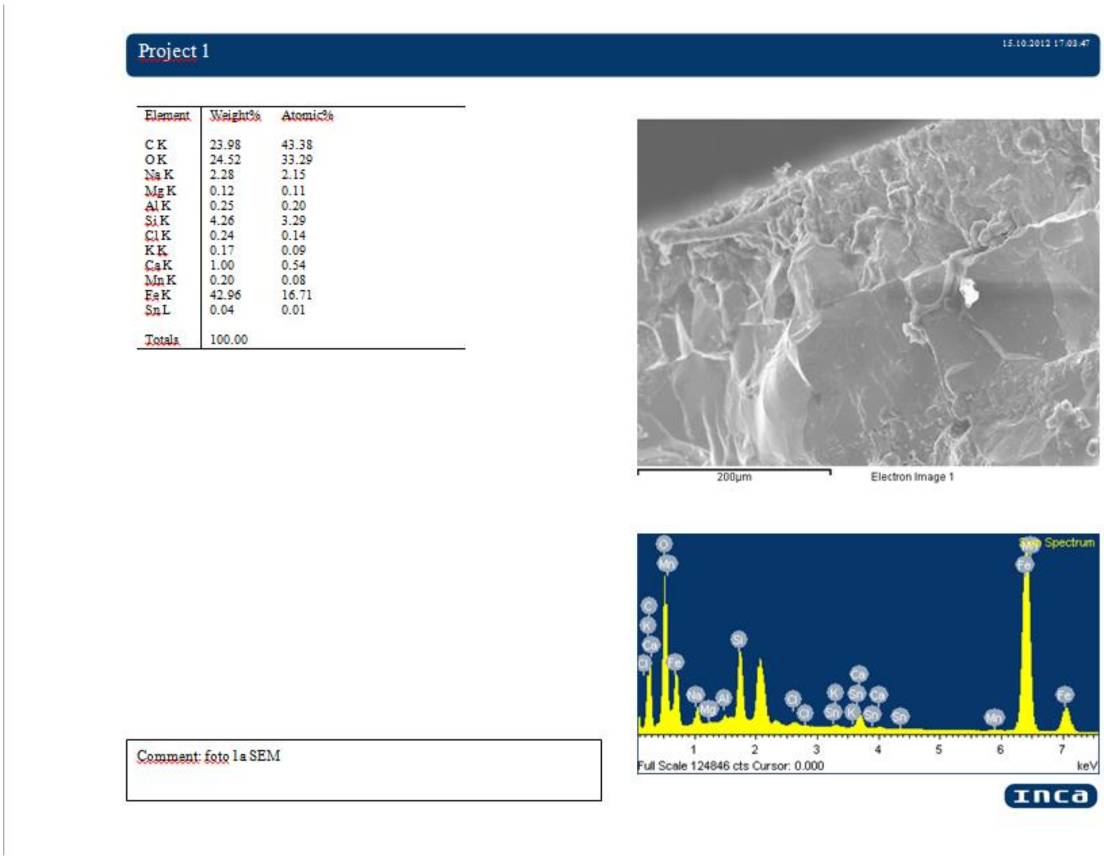
Electron Microscopy investigation of TGCU glass-metal interface

Dr M V Trenikhin

Institute of Hydrocarbons Processing, Siberian Branch Russian Academy of Sciences, Omsk, Russia

FP7 IRSES grant ENSOR project

An electron microscopy investigation of TGCU has been performed by Dr M V Trenikhin, Institute of Hydrocarbons Processing, Siberian Branch RAS, Omsk, Russia under joint project with University of Brighton, *ENSOR*, funded by FP7 IRSES grant. The SEM images below show the interface between the glass core and metal shell (produced by fusing glass cullet in a tin-plated steel waste can for food preserving, such as baked beans can). The fusing process of glass in the tin-plated steel shell causes accelerated corrosion, and the resulting TGCU shell is highly oxidised. The chemical analysis performed under electron microscope investigation shows high content of iron (Fe) and oxygen (O) as it can be expected (Fig 1). A small concentration of tin (Sn) is assumed to originate from the tin-plated surface of the waste steel can forming a fused on mould of TGCU. Other elements such as Si, Ca, K, Al, Mg, Na, Cl, Mn are present in various proportions; it is assumed that they may have originated either from glass, or the steel alloy of the waste can.


Project 1

Element	Weight%	Atomic%
C K	23.98	43.38
O K	24.52	33.29
Na K	2.28	2.15
Mg K	0.12	0.11
Al K	0.25	0.20
Si K	4.26	3.29
Cl K	0.24	0.14
K K	0.17	0.09
Ca K	1.00	0.54
Mn K	0.20	0.08
Fe K	42.96	16.71
Sn L	0.04	0.01
Totals	100.00	

Comment: foto 1a SEM

Fig 1 TGCU glass-metal interface and chemical composition (Trenikhin M. V., 2012, Private Communication)

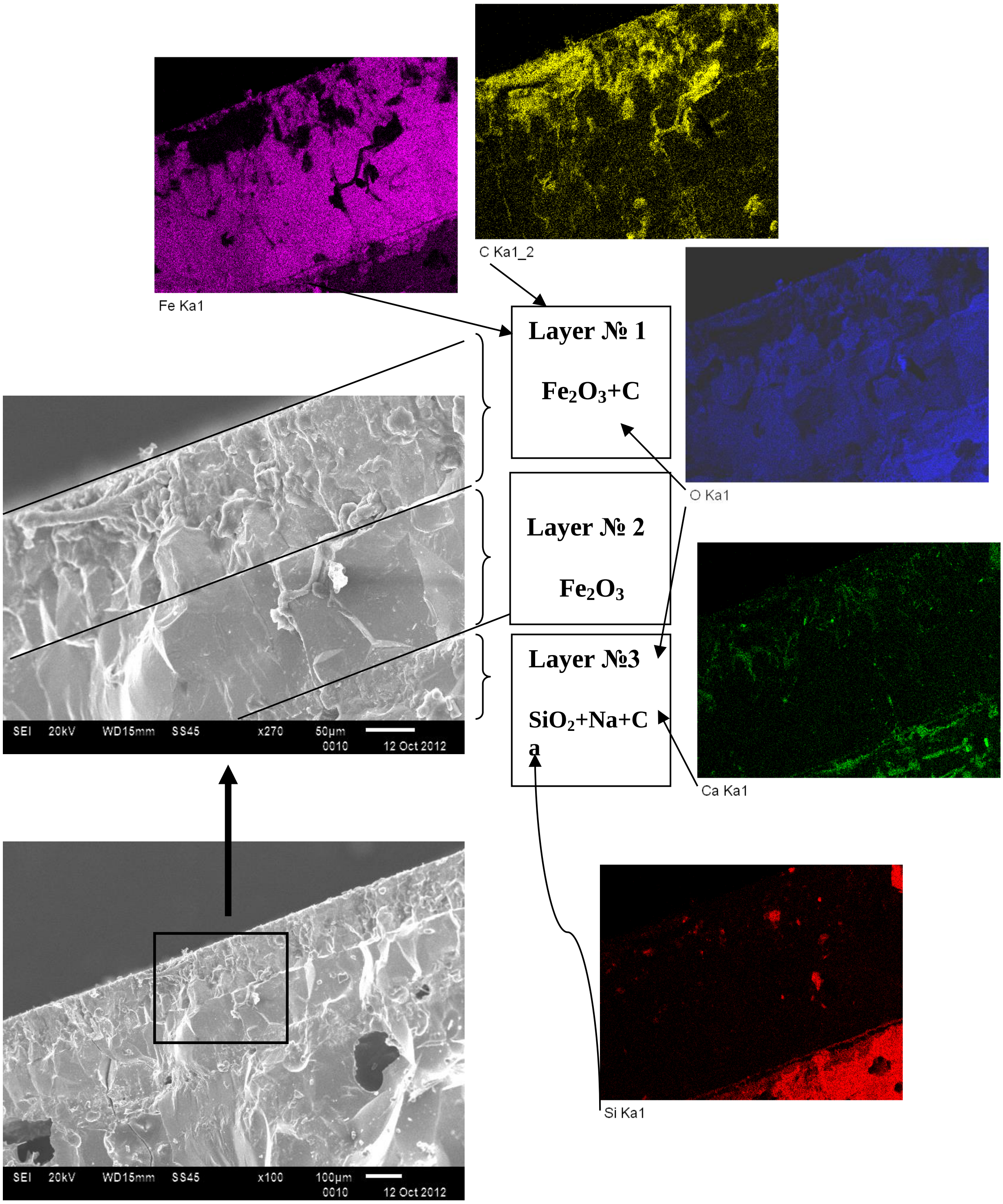


Fig 2. Multilayer structure of TGCU glass-metal interface and distribution of chemical elements (Trenikhin M. V., 2012, Private Communication)

The boundary layer of fused glass has a multilayer structure as shown in Fig 2.

- Outer surface layer has thickness of 120 – 130 μm and analysis of its chemical composition shows presence of Fe, O, C and possibly Ca.

- The next layer No 2 still contains Fe and O but it has much less of carbon C. Its thickness is 120 – 130 μm as well.
- The layer No 3 corresponds to glass core of TGCU, hence the thickness is irrelevant. It contains Si, O and traces of Na and Ca.

The images show that the outer layer No 1 has a rugged and uneven character. This may explain the good bonding observed between concrete and TGCU. Some cavities and pores are observed, mostly at the boundary between layer No2 and layer No 3 (glass core of TGCU) as it is shown in Fig 3.

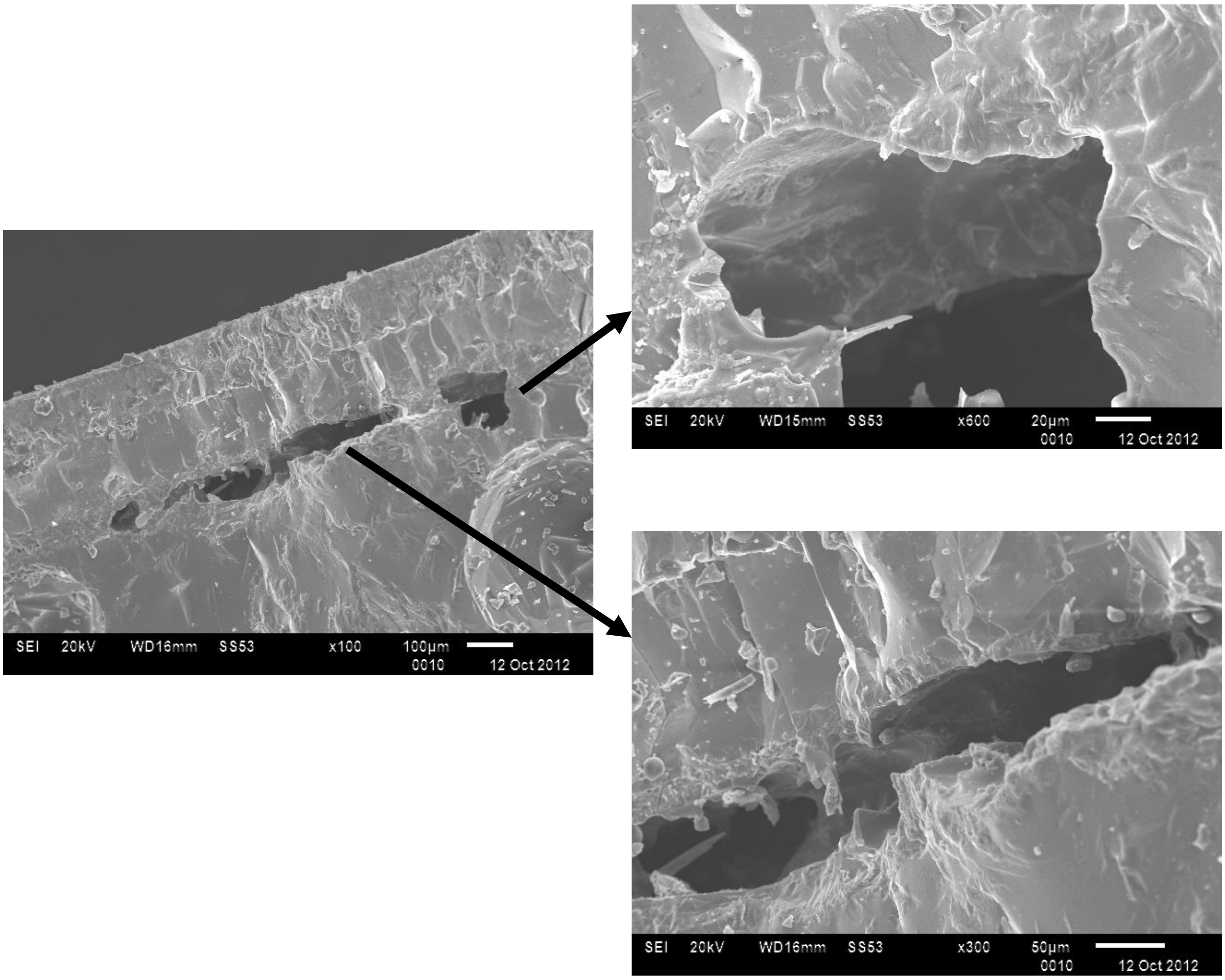


Fig. 3. Cavities and pores between layer No 2 and layer No 3 corresponding to the glass core (Trenikhin M. V., 2012, Private Communication)

Appendix 3.1

Feasibility of industry implementation of TGC

Presentation of research results to industry at the ECOBUILD 2009

University of Brighton has been invited to host a stand at the ECOBUILD exhibition, Earls Court, London, March 2009

The TinGlass innovation has been presented, under guidance of Business Development Manager, Ms Zoe Osmond.

The information sheet (below) has been distributed to industry representatives at ECOBUILD 2009. The response was positive in general.

The industry feedback has been collected and discussed by the author with the colleagues.

Ecobuild/Futurebuild 2009

3-5 March 2009

Earls Court, London

Ecobuild is the world's biggest event dedicated to sustainable design, construction and the built environment.

An excellent place to view innovative sustainable construction products and services.

http://www.bsigroup.com/en/Standards-and-Publications/Exhibitions/Ecobuild-2009/
as seen 12/5/2012

Information sheet: TinGlass Construction Unit

Zoë Osmond

Business Development Manager – Environment

University of Brighton

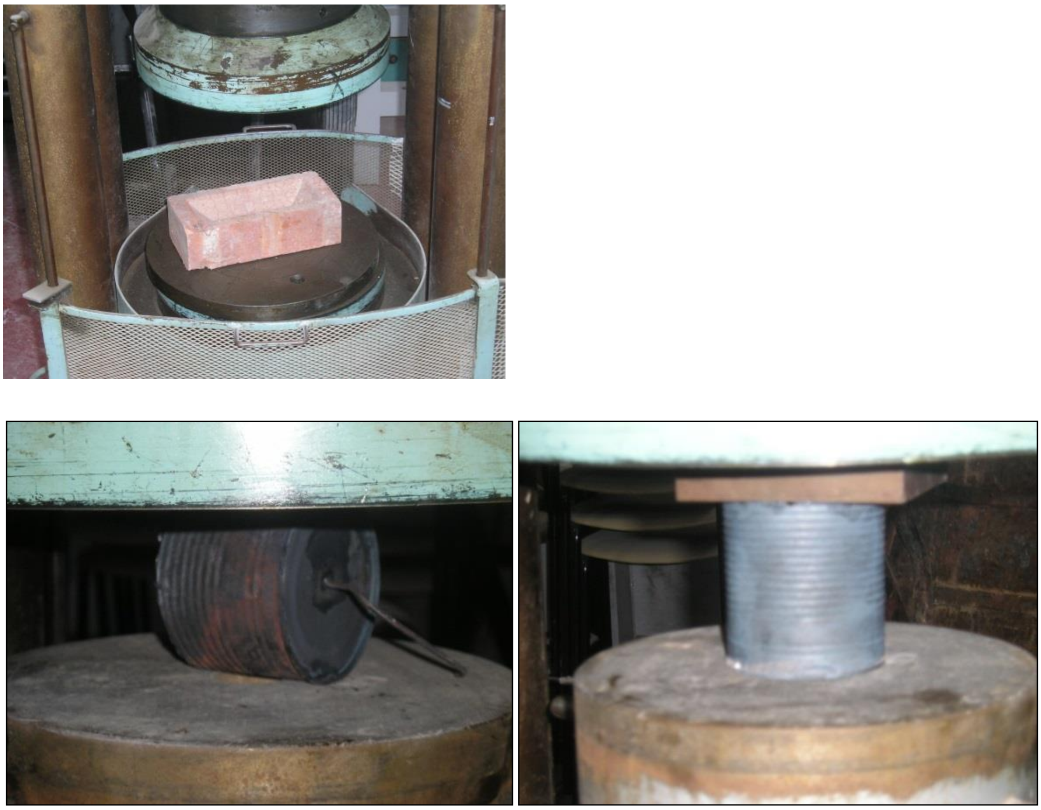
June 2009

Background

The University of Brighton has developed an innovative construction unit using recycled glass and tin cans. The patent pending invention is a metal-glass composite construction unit sourced from recyclable materials. Wine and beer bottles and tin cans are soaked in water and stripped off their labels. The bottles are then granulated and the glass granules are used to fill a waste tin-plated steel can. The assembly is then placed inside an oven to fuse the glass. The result is the TinGlass construction unit.

The university is investigating appropriate applications for the invention. We would welcome input from industry to identify key areas for application and carry out collaborative research and development projects. Possible research and development projects may include precast beams, paving blocks, gabions, foundations, sea defences and crash barriers.

Compressive Strength tests of TinGlass *versus* conventional clay bricks



Clay Brick and TinGlass units under compression testing

The European Standard test method for compressive strength is published as BS EN 772-1. Each brick is placed between steel plates. A compressive load applied until the point of failure is reached. Testing is carried out on a number of bricks in a dry state. Three samples of clay bricks were tested against five TinGlass construction units; the latter were in two orientations to the applied load.

The results show high compression strength of TinGlass units:

	TinGlass Construction Unit	Clay brick produced conventionally
Compressive strength	30 MPa (horizontal direction) 21 MPa (vertical direction)	7 MPa

Potential application - TinGlass Embedded in Concrete (TGMC)

To date the main application the team has investigated is TinGlass Embedded in Concrete (TGMC). The TinGlass unit was embedded in concrete using a standard concrete mixture (ratio of water: cement: sand: aggregate = 0.6:1:2:4). The cement used was Portland cement, the aggregate size was 10mm and the concrete was mixed on site on day of use.

The TinGlass unit was embedded in blocks and beams. It was found that a typical TinGlass unit replaced 0.55 kg of the standard concrete mix.

Tests carried out on TGMC

All tests were carried out in acordance with British Standards.

1. **Compressive Strength tests**

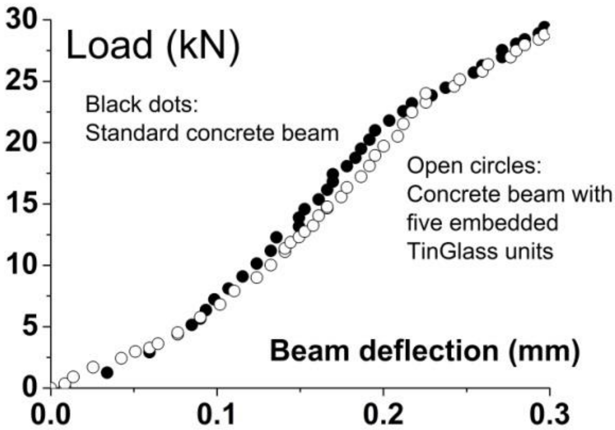
   Mechanical tests on TGMC embedded in blocks and beams were carried out. As illustrated below, compression tests showed that TGMC is stronger than the control concrete beam / block by about 20%.

   Table 1. Compressive strength tests

Cubes	**Description**	**Weight of block (kg)**	**Slump test (mm)**	**Compressive Strength (MPa)**
Standard	Control 100% concrete	2.33	20	64.5
TGMC	Tinglass embedded in concrete	2.35	20	77.4

2. **Bending tests**

Control concrete reinforced beams and TGMC beams were prepared in the same manner. In the case of the TGMC beams an amount of concrete was replaced by TG units. Bending tests on both control and TGMC reinforced beams (71cmx15cm x15cm) were carried out. For these tests 2 parameters were used as variables: the number of TinGlass units embedded and the orientation of the Tinglass units relative to the axis of the beam. All tests showed that the TGMC beam is comparable to or of higher performance than the control specimens. A representative result is shown below for a beam with 5 TinGlass units embedded compared with a control sample.



Figs 1 & 2. Bending test results for control and TGC beams

3. **Alkali-silica reaction (ASR) test**

This test was carried out on 10x10x10 cm^3 blocks using a solution of 1N NaOH at 70°C for 19 days. The TGMC showed better results than the control.

Cost / energy implications for TGMC

The TinGlass units were prepared in the lab using 3kW electric furnaces. Under lab conditions each TinGlass unit required 0.25 KWh of electricity. An estimate of the production cost per unit at residential tariff (9p/ KWh) is 2.25 pence. In terms of CO_2 emissions, this amount of electricity equates to 0.11 kg CO_2 or if gas were to be used of 0.05 kg of CO_2. These costs are high due to small scale lab based production.

Commercialisation (mass production) offers potential reductions in cost and greenhouse gas emissions.

There is further potential for cost / energy savings via the use of energy recovery techniques and use of renewable energy sources.

Other potential applications

These include precast beams, paving blocks, gabions, foundations, sea defence structures and crash barriers.

Potential benefits of TinGlass Construction unit

- potential to reduce the carbon footprint of construction projects by replacing concrete content with recycled materials
- reduces the demand for raw materials for the concrete mix
- diverts materials from waste

One tonne of glass will make approximately 1,470 TinGlass units, potentially replacing 809 kg concrete. There is 1.2 million tonnes of glass in the waste stream.

Collaborative R&D

The research team at the University of Brighton is seeking partners to:

- Assess the suitability of Tinglass Construction Unit for a specific application in the built environment
- Carry out collaborative R&D to further develop, test and prototype the product(s) for commercial applications
- Commercialise the Tinglass Construction Unit

The university has access to a wide range of funding streams to co-finance such work and is highly experienced in identifying suitable funds and writing bids. The university is also experienced in carrying out market research on specific technology areas, and in life-cycle analysis which will help to assess the environmental impact of a new product in comparison to existing ones. Our civil and mechanical engineering laboratories offer a number of relevant testing facilities.

For further information, please contact
Zoë Osmond
Business Development Manager – Environment
z.osmond@brighton.ac.uk / 01273 641949

Industry questionnaire and information sheet

A questionnaire has been sent to a number of companies, via collaboration with Business Services of University of Brighton. The questionnaire reads:

Information Sheet for questionnaire on the project

Innovative solutions for waste glass into construction industry

Mr Vassilios Bugas

School of Environment and Technology, University of Brighton, Brighton, East Sussex

Project description and invitation to participate

The project team would like to invite you to participate in their project by filling in the questionnaire. Before you agree to participate we would like to ensure that you understand why the research is taking place and what it will involve. Please read the following information and ask for clarification if necessary.

Participation

- i) You are chosen to participate because your expertise and practical experience are relevant and valuable for the project
- ii) The participation is voluntary and you may discontinue participation at any time without giving a reason
- iii) If you decide to take part you will be asked to sign a consent form

Confidentiality and anonymity

Confidential information, if any, will be seen by the researchers only.

Contact for further information:

Mr Vassilios Bugas,

School of Environment and Technology, Cockroft Bldg,

University of Brighton, Lewes Road, Brighton BN2 4GJ

Industry feedback and author's response

The environmental not-for-profit company, REMADE, http://www.remade-southeast.co.uk/rse/ as seen on 12/06/2008, has responded for the assessment of the industry implementation of TGC .

A working visit has been made by Dianna Locke of South East Remade; her queries are shown in italic below; the author's comments and replies follow as relevant.

***REMADE* feedback:**

Product application as a replacement for concrete has certain barriers:

- *cost due to high energy requirement*

Reply:
The production energy of TinGlass is lower or comparable with other innovative methods such as plasma treatment of waste for production of aggregate for construction industry, see Rani et al.,2008.

Remelting glass cullet into glass bottles for one-off use in wine industry, can be more energy-intensive than TinGlass production, since melting temperature is higher than that required for fusing glass

- *risk related to use of a new product due to ASR / strength issues*

Comments :
the programme of mechanical testing under accelerated ASR conditions has been carried out; it has shown no deterioration in mechanical properties in compression.

- *has the solution you have identified re. ASR really addressed the issue of potential compromise of strength – e.g. if tin can corrodes or if a hole if made and the glass does come into contact with concrete?*

Comments:

A large number of TinGlass units embedded into concrete have been explored in compression and bending. Some of these have holes or imperfections.

No deterioration in mechanical properties is observed so far when compared with control samples

- *competitor products (e.g. foam glass, pulverised fuel ash) already in use and compliant with BRE / BS standards. How would TGC be better / more cost effective than these?*

Fly ash is a different product and indeed its recycling targets are mostly met.

Recycling of waste glass is still seen as a challenge, as it is illustrated in the further reply below

- *there are already good markets for mixed waste glass so there is no real need to find new uses for this waste stream*

Comments:

Currently, the preferred applications is to send glass cullet abroad for remelting into new bottles by wine producers, thus recycling in closed-loop way. The associated costs of sorting, transportation and remelting are expected to be higher than those for fusing mixed glass cullet into TinGlass units locally.

Using glass as aggregate does not reduce its carbon footprint as it is stated in WRAP recent publications:

http://www.wrap.org.uk/content/collection-recyclable-materials-glass

Landfilling problems is far from being resolved, as a consultation with Bottle Alley Glass, a local company, has confirmed, http://www.bottlealleyglass.co.uk/ accessed 10/10/2008.

The recycling industry figures show that recycling rates are far from 100%; the rest of the glass is continuously streaming into landfills where it does not degrade.

The Government target of glass recycling face difficulties because the applications for waste glass are underdeveloped .This calls for the research on new applications such as TinGlass

- *when production is scaled up under industrial conditions, the CO2 footprint would be high due to high energy requirement of furnace*

Comments :

The output of the product will scale up respectively, hence no increase in the CO2 footprint per unit weight is anticipated. On the contrary significant reductions in cost production of TGs are expected under continuous operation of glass melting furnace.

This is the case with glass remelting bottles for reusing as explored by K. Kostas, MSc Thesis, 2006, UoB for a glass recycling factory *Yioula* in Athens, http://www.newglass.bg/products/Recycling/?lang=en, as seen 20/07/2012

Whilst it is economically viable to produce a new glass bottle by remelting glass cullet, it shall be feasible to fuse glass into TGCU.

The energy requirements for the former process are higher than those for production of TinGlass. The production of TinGlass does not require sorting of mixed galss, to ensure high control over colour and type of glass cullet, whilst it is essential for bottles' remelting and tiles preparation (Bottle alley, 2008, private communication)

Appendix 5.1

Compression testing of the TGCCs of larger sizes

Miss L Ojomo

Final Year project, School of SET

University of Brighton

2010

Appendix 5.1:

Compression testing of the TGCCs of larger size (Ojomo, 2010)

The TGCUs were embedded into concrete cubes of 15x15x15 cm^3 and cured for 28 days following the methodology described in Chapter 3. Compression testing has been performed on the same compression rig and following the methodology described in Chapter 5. The compression testing results for TinGlass concrete cubes (TGCCs) were assessed *versus* those for control cubes. The control cubes were made of the same batch of concrete but they were of smaller size, 10x10x10 cm^3, due to the experimental limitations on the day. The compression test was carried out by Ojomo (2010) for eight TGCCs and three control cubes. The results of compression test are shown below in Table A5.1 and A5.2 adapted from Ojomo, 2010.

TGCC No.	**Orientation of TG**	**Max load (kN)**	**Compression Strength (MPa)**
1	Vertical	792.00	35
2	Vertical	712.00	32
3	Vertical	761.00	34
4	Vertical	834.00	37
5	Horizontal	790.00	35
6	Horizontal	810.00	36
7	Vertical	853.00	38
8	Vertical	872.00	39
		Average	36
		Standard Deviation	2

Table A5.1. Maximum compressive stress for the TGCCs of 15 cm on the side.
Vertical orientation: the axis of TinGlass is along the direction of the applied load.
Horizontal orientation: the axis of TinGlass is perpendicular to the direction of the applied load

The results in Table A5.1 show that changing the orientation of the TinGlass relative to the load, does not affect the compression strength within the observed experimental uncertainty.

Control cube No	Weight (kg)	Max load (kN)	Compression Strength (MPa)
1	2.29	367.4	37
2	2.305	358.2	36
3	2.316	371.5	37
		Average (MPa)	37
		Standard Deviation (MPa)	1

Table A5.2. Maximal compressive stress for the control cubes of 10cm on the side.

As it can be seen from Tables A5.1 and A5.2, the compression strength of TGCCs coincides with that of the control cubes within standard deviation. The compression strength of control cubes is (37 ± 1) MPa whilst it is (36 ± 2) MPa for TGCCs.

This proves the main hypothesis that the mechanical properties of standard concrete can be well reproduced by TGC (the concrete with the insertion of TinGlass construction units).

Appendix 6.1

Vibration control and testing of beams under dynamic loading

Dr D Pearce

Private Communication

University of Brighton

2008

A6.0 Introduction

The scope of a vibration test is the evaluation of the seismic conditions of the novel structure, as the composite material, and a comparison with the standard material. In particular it will give any resonance zone, where large deflection is activated from a small quantity of energy.

This is seen as an important part of the TinGlass concrete beam, TGCB, assessment.
The presence of embedded TGCUs (TinGlass construction units) may influence their resonance properties, and this must be investigated. The result of a vibration test of the new product will be:

- A validation and certification of the new product according to British Standards BS EN 60068-2-6: 1996
- An evaluation of the robust operation properties of the product under shock load

The beams are constructed in the same way that is described in Chapter 3.The three beams are tested in a vibration test to compare the dynamic behavior of the standard beam, SB, and the two composite beams, TGCBs. The reason to do this is to investigate the oscillatory behavior of the two composite beams as new structural material and to compare with the standard beam.

The rig of the test includes:

a) The simply-supported beams using the same supports as of the test in bending
b) A hammer which applies an impulse
c) Transducers of the impact force applied by the hammer, which display the deflection or acceleration of the beam.
d) The equipment that is used is the B&K frequency domain analyzer. It receives the signal with two input channels, one which measures the force applied from the hammer and the other which measures the acceleration of the beam . Four graphs are displayed in real time for the same impact.

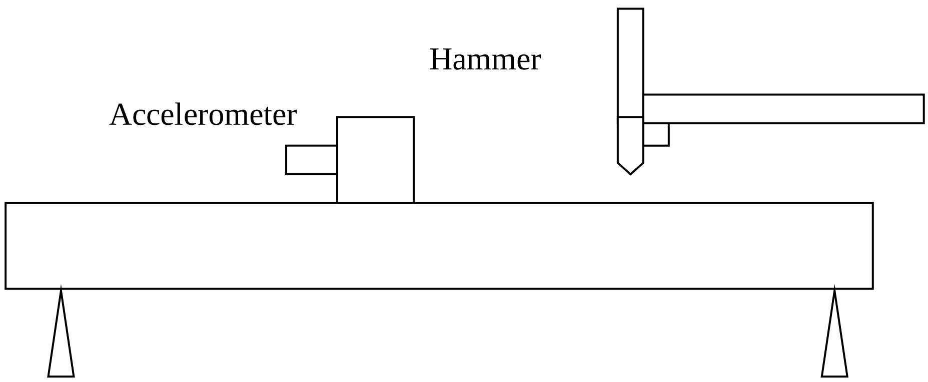


Fig A6.1 Setup of the rig for vibration testing by Dr D Pearce, SET, UoB

A6.1 Vibration Testing

Brüel & Kjær (B&K), is an industrial strength vibration testing analyzer (B&K, 2008). The B&K frequency analyzer has carried out vibration testing of three beams after an impulse excitation. The tests were conducted on 4 June 2008 under guidance of Dr David Pearce, a retired Principal Lecturer of School of Engineering, University of Brighton.

The preparation of the beam is done by gluing a metallic disc on the middle of the top of the beam. The accelerometer is screwed to the metallic disc to measure the acceleration of the beam. (Thomson, 1994)

The results of the action of the hammer and the acceleration are displayed simultaneously. The results can be saved in a Word file and they can be compared after all the different beams have been tested.

An accelerometer is used for measuring the displacement, velocity, or acceleration of the mass of the beam suspended. The results depend on the frequency range used for the activation.

A6.2 Results

The frequency spectra of mobility function for three beams were quite close. This means that no new resonances (that is, structural weaknesses) are emerging for novel beams when compared with conventional concrete beams. This is encouraging finding for using TGCBs in seismic areas and under dynamic loading. Blast resistance (as relevant for a terrorist attack conditions) is an important structural property nowadays. The novel material, TGC, did not show any deterioration under dynamic loading conditions in the experiment.

References:

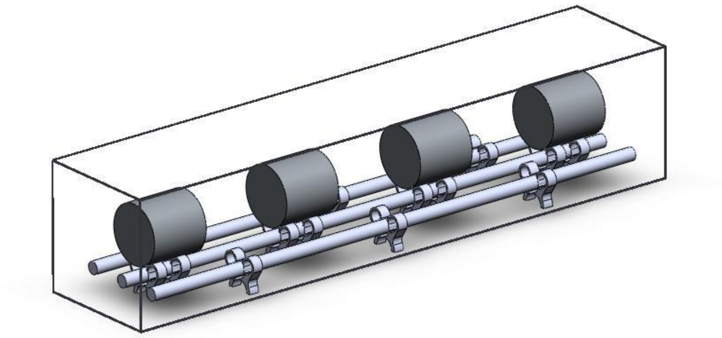
Brüel & Kjær (B&K) http://www.bksv.com/products/vibrationtesting.aspx seen 21/6/08.

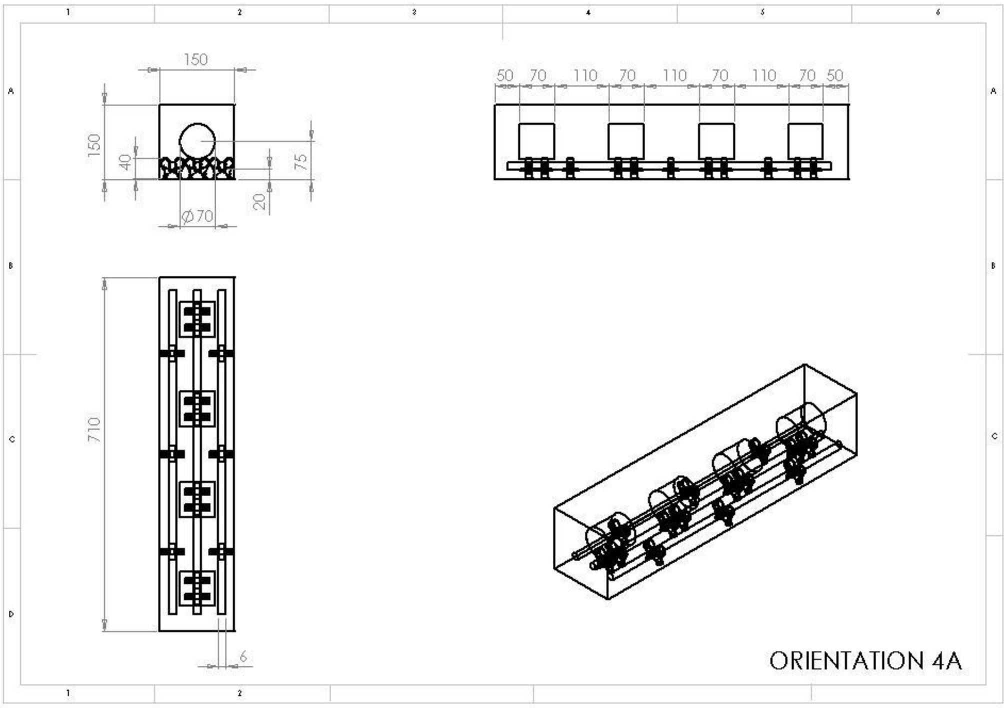
British Standards BS EN 60068-2-6: 1996

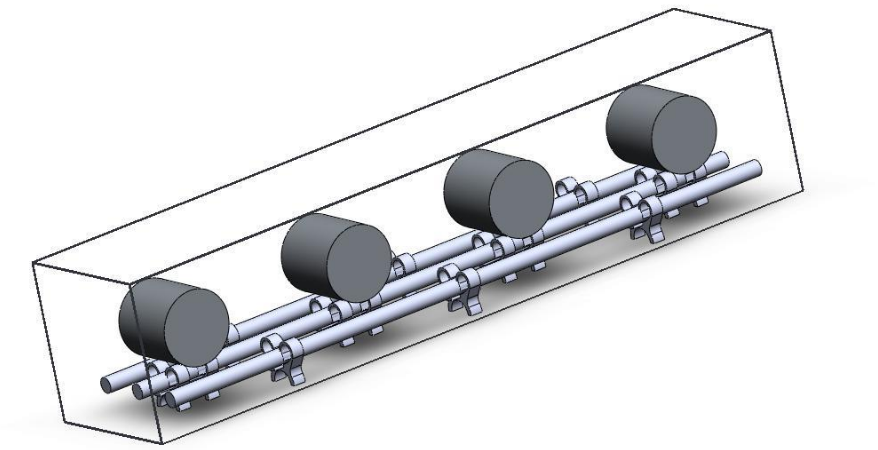
Thomson, W. (1998) Theory of Vibration with Applications 4th edition: Stanley Thornes UK ISBN 0-7487-4380-4

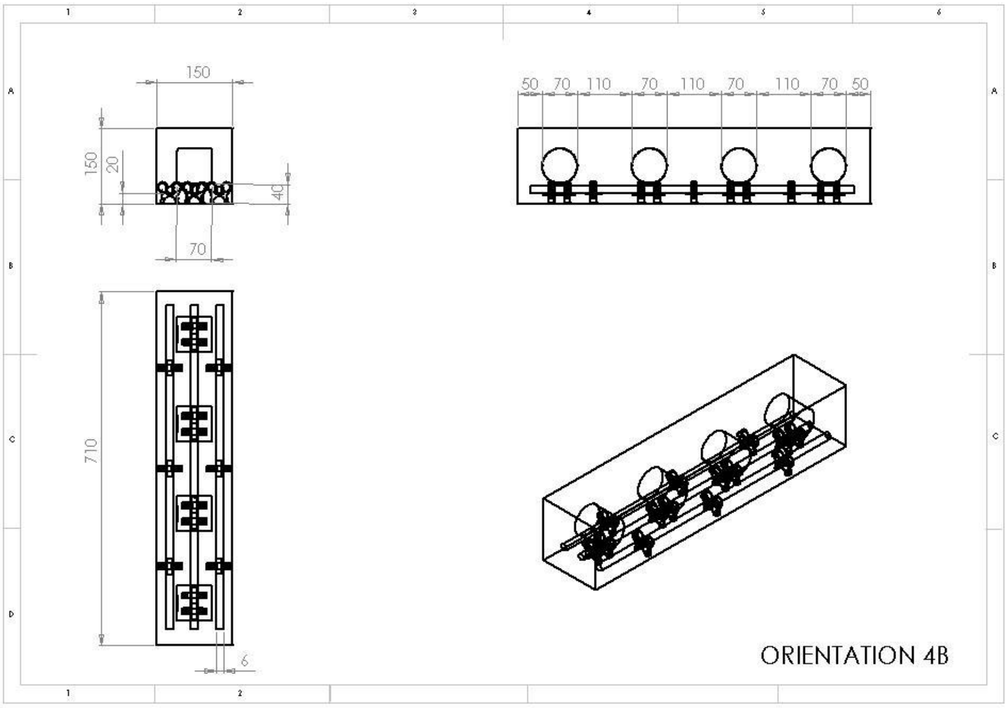
Appendix 6.2

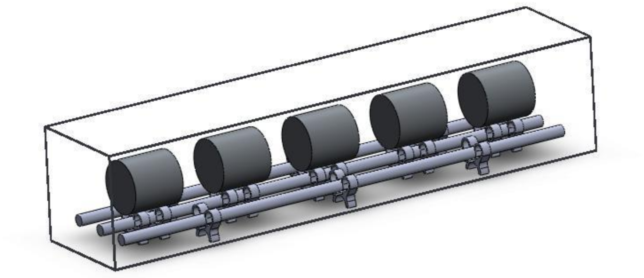
Technical drawings of TGCBs

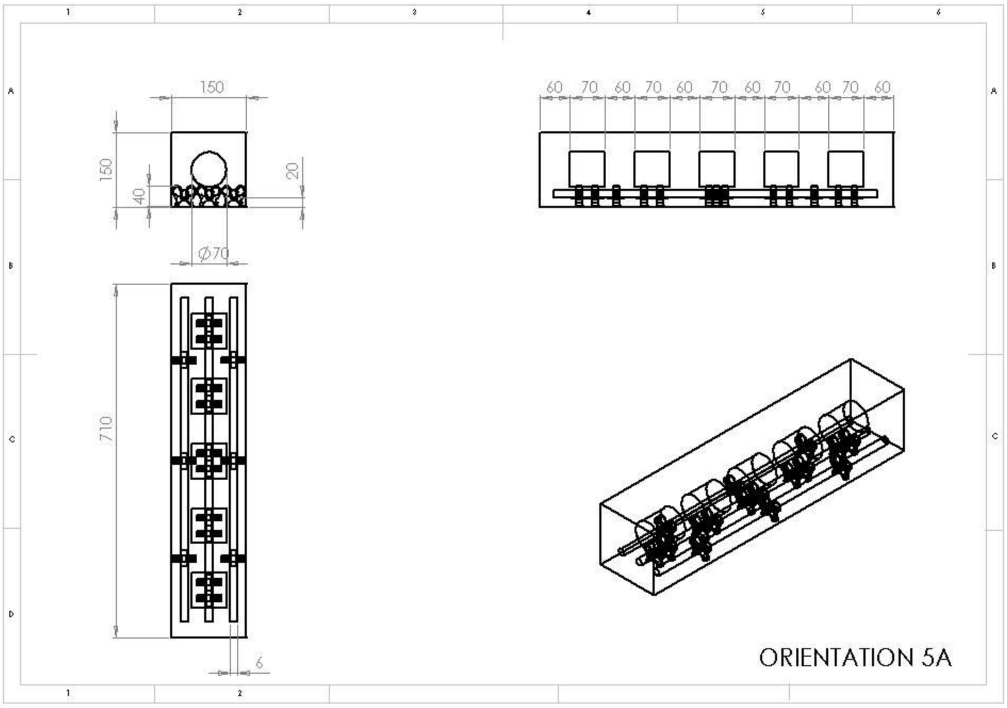



150
150
40
75
20
Ø70
50 70 110 70 110 70 110 70 50
710
6
ORIENTATION 4A

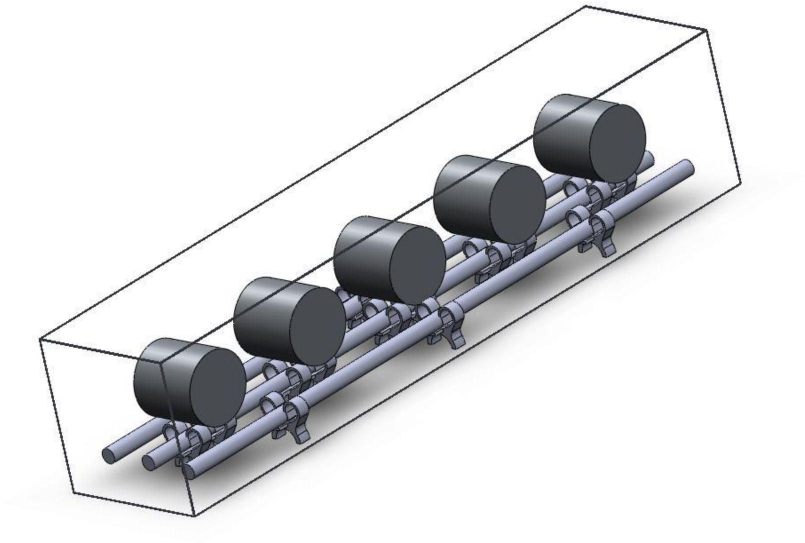


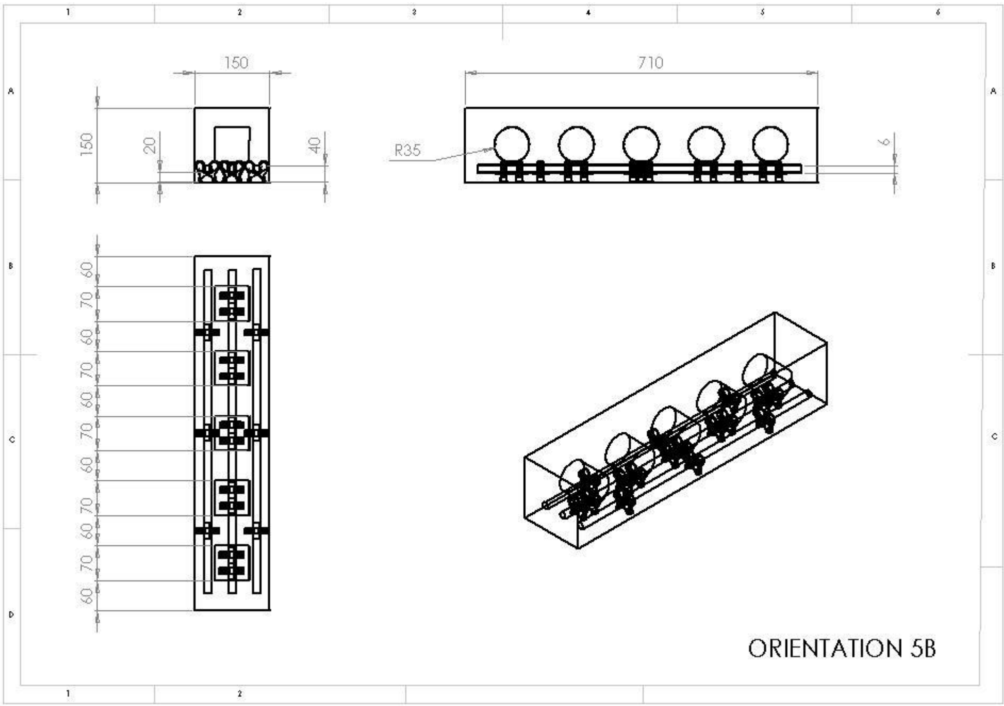

150
150
20
40
70
50 70 110 70 110 70 110 70 50
710
6
ORIENTATION 4B

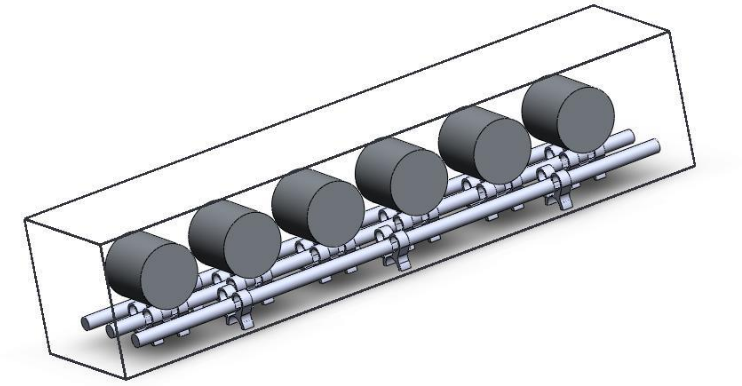


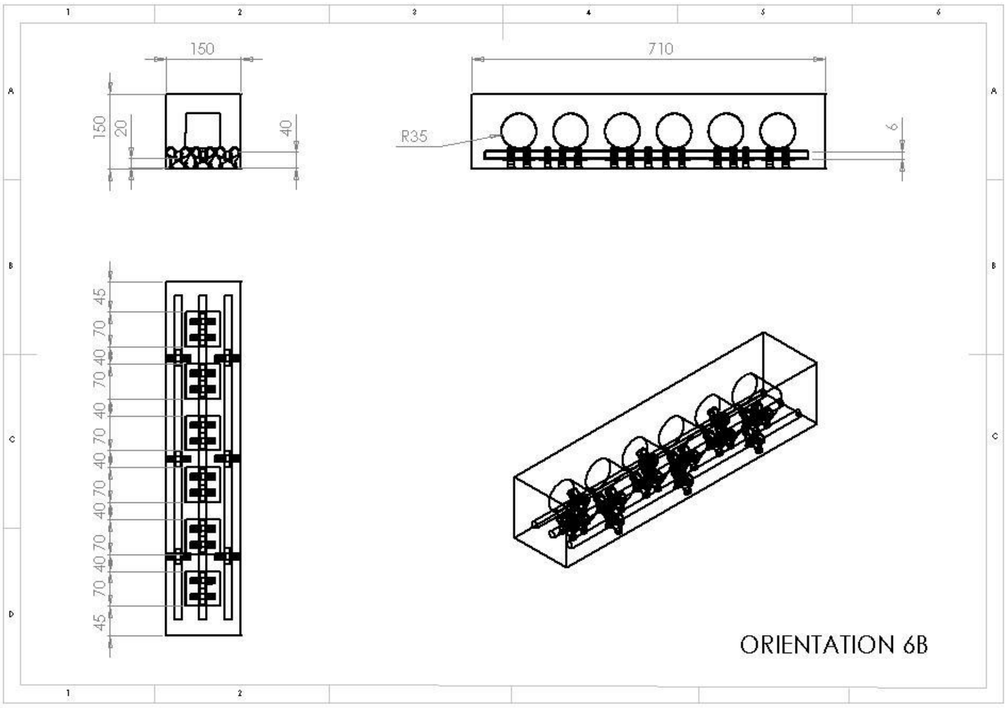


150
150
40
20
Ø70
60 70 60 70 60 70 60 70 60 70 60
710
6
ORIENTATION 5A




150
710
150
20
40
R35
6
60
70
60
70
60
70
60
70
60
70
60
ORIENTATION 5B





150
150
20
40
710
R35
6
45
70
40
70
40
70
40
70
40
70
40
70
45
ORIENTATION 6B

Appendix 8.1

Dissemination of knowledge to postgraduate students of University of Brighton

Dissemination of knowledge to postgraduate students as endorsed by IP experts of University of Brighton

Conditions for giving access to an IP developed by Mr Vassilios Bugas, PhD Student of School of Environment and Technology, University of Brighton, read:

The access will be given to Miss Johanna Salazar White, MSc Product Innovation and Development (PID) student of School of Environment and Technology, University of Brighton

Title of IP: INNOVATIVE METHODOLOGY FOR WASTE GLASS BLOCKS

This document gives access to the IP on a novel methodology developed by Mr V Bugas when working on the environmentally important problem of valorisation of waste glass cullet. The purpose of this document is to set the limitations and conditions when giving an access to the IP developed by Mr Bugas; the IP will be published not earlier than 2009. Miss Salazar needs the methodology for a successful work on her project for a taught MSc PID degree. She works on the project ***Innovative products for home and garden made of recycled materials.*** Her Thesis will be published in October 2008. In what follows she will be referred as the ***MSc PID student***, and Mr Bugas as the ***PhD studen***t.

The MSc PID student will have an access to the INNOVATIVE METHODOLOGY FOR WASTE GLASS BLOCKS developed by the PhD student as described in the accompanying technical note.

The MSc PID student is allowed to use the IP for a specific purpose only, namely, to include it in Thesis to get the MSc award from the University of Brighton. The access to the IP will be given to the internal examiner of the Thesis. The VIVA VOCE is provisionally scheduled on Friday 03/10/08.

Any external members of industry and public will sign a confidentiality form when attending a PID MSc project presentations on Wednesday or Thursday 01-02/10/08 to a public audience; the schedule to be issued nearer the date. This is a seminar given by the MSc PID student as part of the assessment of the project.

The MSc PID student is not allowed to publish the IP in any other way. In case if the IP is used for commercialisation purposes, the remuneration will be due to the University, and possibly to Mr Bugas, as the IP owners.

INNOVATIVE METHODOLOGY FOR WASTE GLASS BLOCKS

By Vassilios Bugas

Dissemination of the Research

School of Environment and Technology

University of Brighton

Introduction and aims

The research work on creation and implementation of a range of attractive and reliable products made of waste glass has many environmental benefits. The progress of this work at the School of Environment and Technology, University of Brighton, and the role of consultations by external experts and contributions of individual team members, is described and acknowledged. This is the aim of current document.

1. Background of research

Recent research in the glass recycling workshop at the School of Environment and Technology (SET) has resulted in a number of prototypes for inexpensive and energy efficient products made from waste glass. An idea for a TinGlass block originated in 2006 and resulted in a patent application filed by the University on behalf of its inventors: M. Bataineh, E. Sazhina and E. Taylor, PCT Patent Application No 0708603.6 filed May 2007. The invention is a metal-glass composite construction unit which may be used in the construction of walls, buildings and other structures. Mr M Bataineh was at the time an MSc PID student.

This dissemination report is to outline the original work of Mr V Bugas, currently a PhD student in the School, and to protect his ideas which may in the future be exploited for commercialisation. The TinGlass construction block unit is produced by fusing waste glass cullet in a waste steel can, the latter serves as a permanent mould for glass. Students following from Mr Bataneih have taken the original concept and made modifications to the processing. In December 2007, Miss Lia Afentouli, described a modification in her MSc Thesis. This modification followed from a meeting with Mr David Watson, an established local glass artist (http://www.davidwatsonworks.com, seen 14/7/08), who suggested a viable way of producing glass tiles made from waste glass. The modification involved using ceramic fibre paper to line the metal mould allowing the production of glass tiles from 100% recycled glass. The preparation of the glass and the melting of the glass follow Mr Bataneih's prescription.

Mr V Bugas has started his research by producing TinGlass blocks following the existing methodology described in the patent. The novelty of his current PhD work involves incorporating these in concrete beams, testing and quantifying the beams' properties to assess their viability for construction industry. Mr Bugas has developed his own methodology that has resulted in a number of novel glass brick prototypes. Whilst the main focus of his research lies in construction, a decision has been made to disseminate the results of his research prior to publishing them in his Thesis.

The immediate beneficiary of the dissemination is an MSc PID student of SET, Miss Johanna Salazar White. The progress of her research on implementation of waste glass prototypes into commercially viable products for the garden environment requires the methodology created by Mr V Bugas. In what follows the novel methodology of Mr V Bugas will be described whilst comparing it to that described in the TinGlass patent.

2. Description of the novel methodology for waste glass bricks

A methodology for producing glass bricks from waste glass has been developed with a view of producing decorative, practical and inexpensive glass bricks as finishing materials for use in pavements, walls, mosaics and others.

2.1 TinGlass surface finish as an eco-friendly alternative to flint wall

The first prototypes produced by Mr V Bugas were based on existing methodology for the TinGlass. Melting and fusing of waste glass cullet in a tin-plated steel waste can is performed at 900°C for a soaking time of 40 min. Subsequent annealing is performed by gradually reducing the temperature to 500°C during a two hour period, then, without opening the kiln, switching off the power and leaving it overnight. The novelty of the approach by Mr V Bugas consists in applying this concept for creating wall finish seen as an eco-friendly alternative to conventional technique of flint walls. A TinGlass block is produced with top surface of glass remaining exposed. It is embedded into mortar mixture thus emulating the flint wall surface.

A sample of the wall finish designed and manufactured by Mr V Bugas is available for viewing in the workshops of SET. Additional guidance has been developed in the course of the work for the boundary between glass and mortar on the wall surface: one is to expose the rough edges of TinGlass brick for a rough surface finish similar to a flint wall surface (see Fig 1 for flint wall photo); and the other, for a flush wall finish, removing the rough ends of TinGlass by polishing them off with a metal file.

The finished wall is a composite material made from concrete and recycled glass. It can replace flint wall whilst it is made without using natural stone. It serves as an example of using material derived from waste stream. This product can be used for a variety of applications, including garden walls, vehicle crush barriers, flood or sea defences. It combines high density and mechanical strength and toughness with an attractive surface finish, allowing the creation of artistic patterns and novel architectural features.

2.2 Method of bonding metal lid to glass core of TinGlass

A metal lid can be placed on the top of TinGlass thus completely encapsulating the glass core within the metal shell. This is seen as beneficial for preventing alkali-silica reaction (ASR) between glass and cement when embedding TinGlass construction units into concrete beams and blocks. Practical steps for achieving good bonding between metal lid and glass core were developed by Mr Bugas in the course of his work on pre-cast concrete beams with TinGlass inserts. A lid is placed on the surface of the glass cullet at room temperature. A weight is placed on the top thus providing a good bond between the lid and the glass during fusion in the kiln.

2.3 Energy recovery and thermal craze of TinGlass brick

Next novel development by Mr Bugas addresses claiming back the energy that was used for glass fusing and melting. This should improve energy efficiency of the production of TinGlass construction units.

Traditional methodology of glass making is based on annealing glass for a much longer time than it takes for the melting process itself. This is necessary to relieve thermal stresses that emerge in a glass object if the cooling process is too fast. Otherwise the glass piece may crack or even fracture into many fragments. This is known as failure by thermal shock, and this stems from the brittleness of glass as a material.

For TinGlass brick, the traditional concept of annealing was applied, as described in the patent. A hot TinGlass block was cooled very gradually, usually overnight, in a kiln with a closed door. Hence the energy that went into fusing glass was not recoverable.

This notion was challenged by Mr V Bugas. He suggested to quench the hot TinGlass bricks in water, straight from the kiln, rather than annealing it. Thus thermal energy of TinGlass could be used up to heat up the water. This method of energy recovery is potentially attractive for implementation into an industrial production of TinGlass. Water heated up by the residual heat of TinGlass blocks can be used for heating of buildings, or for steam production in a steam generator.

A series of experiments were undertaken by Mr Bugas when establishing an optimal regime of quenching of hot TinGlass blocks in water. It has been proved that it is possible to quench a TinGlass brick in water whilst keeping the TinGlass structural integrity on cooling, even with TinGlass at temperatures as high as 850°C on the exit from the kiln.

Analysis of this result should start from the observation that a piece of glass of comparable size and temperature is bound to break into many fragments when quenched in water. It is understood that the outer metal shell of the TinGlass prevents its fragmentation. Ductility of metal shell keeps together the TinGlass in spite of the intrinsic brittleness of the glass core.

Results of the dissemination of research based on TGCU concept

By V. Bugas, SET, University of Brighton

Whilst the main focus of current research is seen as focusing on pre-cast beams with embedded TinGlass construction units, the decision has been made to disseminate the results for a broader research to the MSc students of SET and SoCEM, UoB. The author has originated the ideas for the students' research that led to the results below. In most cases the author has made a direct contribution into manufacturing of prototypes. This is seen as a spin-off from the main topic of this Thesis; nevertheless it is relevant for construction industry.

Wall finishing materials: Wall finishing by TinGlass Constriction units (TGCUs) with exposed glass surface is an eco-alternative to flint wall technique. A number of prototypes of glass bricks, and a wall fragment, have been designed and manufactured by the author. The benefits include replacement of prime materials (such as flint) by the waste materials comprising TinGlass unit, namely waste pubglass and waste steel cans

A methodology for producing glass bricks from waste glass have been developed by the author with a view of decorative, practical and cheap glass bricks as finishing materials for using in pavements, walls, mosaics. A range of attractive glass bricks and wall finishes emulating conventional flint walls is designed and manufactured by the author.

TinGlass surface finish as an eco-friendly alternative to flint wall.

The novelty of approach by the author consists in applying this concept for creating wall finish seen as an eco-friendly alternative to conventional technique of flint walls as shown in Fig.1, photo of Mr H Hills, SET, UoB).

Fig 1. A fragment of Cockroft building wall, and the magnified view.

A fragment of the wall finish is designed and manufactured by the author as shown in Fig 2. The boundary between glass and mortar on the wall surface can be either exposed, with rough edges of TinGlass brick protruding similar to a flint wall. On other hand, for a flush wall finish, removing rough ends of TinGlass by polishing them off with a metal file, will achieve this aim. A TinGlass block is produced with top surface of glass remaining exposed. It is embedded into mortar mixture thus emulating the flint wall surface as shown in Fig 2.

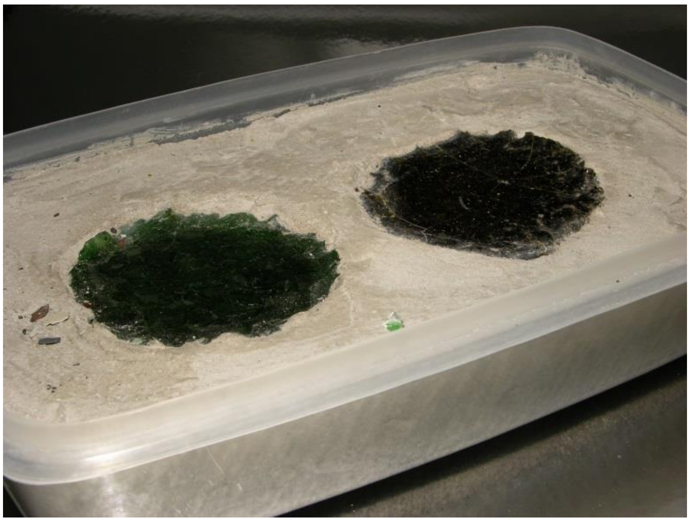


Fig 2. A prototype of eco-alternative to flint wall based on TGCUs prepared by the author

The wall-finish prototype is made from concrete and waste materials. Thus the use of non-renewable flint material is eliminated. TinGlass bricks are placed in the concrete whilst leaving a glass visible. It can be used for reproducing flint wall effect but using recycled glass instead of flint. This product can be used for a variety of applications, including garden walls, vehicle crush barriers, flood or sea defences. It combines high density and mechanical strength and toughness with an attractive surface finish, allowing creation of artistic patterns and novel architectural features.

Surface smoothness, opaque appearance and density of TinGlass construction unit

In the course of extensive experimentation with various production regimes for TinGlass bricks it has been established by the author , that significant variations in surface roughness and density of the Tinglass unit can be achieved by varying length of soaking time in the kiln. Under the standard regime of soaking time 40 min at 900 C, the surface of the fused glass is rough. Increasing soaking time up to 2 hours at this temperature will create a smooth opaque surface and reduced volume of glass core (hence higher density). This is because glass granules have melted under this regime rather than fused at 40min soaking time. Heat transfer inside glass core is by heat conduction, and longer soaking times are raising temperatures inside glass cullet. Sufficient energy is supplied for glass phase change from solid to liquid state.

TinGlass resembles a natural stone under the production regime with longer soak. This is desired result for some of the applications where higher density and enhanced mechanical toughness is needed.

It has been observed by the author that the size of glass cullet granules bears much influence on the appearance of the final product. Large size of glass cullet granules gives a brighter and more translucent appearance to TinGlass than a glass powder .

Aluminium cans as a mould absorbed by glass during fusing

When fusing glass at high temperatures it was previously considered impossible to use an aluminium can (eg sardines can) as a mould since melting temperature of aluminium is lower than that of glass. Indeed earlier tests have shown a disintegration of aluminium mould and spilling molten glass in the kiln.

The author has developed a way to produce a waste glass brick or paving stone, with a mould made of sardines' can, by establishing the range of temperatures and soaking times for this. A paving stone made of waste glass by fusing it in a sardines can. It was processed at 800ºC with 1 hour soaking time and subsequent annealing overnight. On cooling, it was discovered that the aluminium mould is absorbed by the glass core, producing an attractive surface finish as the result. This method can be used for production of paving stones with opaque surface with high coefficient of friction.

Fig. 3 Glass brick produced by the author, by fusing glass cullet in a sardines' can mould

Glass bricks without a permanent mould

All cases described above had a metal can, whether a steel or an aluminium can, as a stay-on permanent mould. This section describes a method of production of waste glass bricks by extracting them from a mould on cooling. Fusing or melting glass in a metal mould creates a very strong bond between them, and it is practically impossible to extract the glass core out of the mould on cooling. This is how the TinGlass concept has originated.

It is possible however to line the mould by ceramic fibre paper prior to heating. This greatly facilitates the extraction of glass core from the mould after annealing and cooling to room temperature. This method was advised by Mr D Watson, a local artist in glass, during his visit in summer 2007. This method has been further developed by the author when working with MSc students of SET, UoB. They have succeeded in producing glass bricks of rectangular or round shape.

Actually any reasonable shape can be produced by manufacturing a steel mould of given shape and lining it up with ceramic fibre paper. The cross-section shape of the brick may be solid or hollow, with a central hole produced by insertion of a steel cylinder wrapped into ceramic fibre paper. Hollow bricks may be incorporated into various structures by stacking them on a steel pole or similar support. Sharp edges and corners, combined with matt and grainy surfaces in the areas lined by ceramic fibre paper, present a certain problem for the glass bricks produced by this method. The author has addressed this problem by testing and implementing a normalising method for glass bricks.

Description of normalizing method: After cooling glass bricks to room temperature and extracting them from the mould, re-heating and re-melting of surface layers is performed by placing the brick into a very hot kiln (900°C) for 30 mins of soaking time, then annealing it overnight. This procedure makes the surface much smoother and gives it more shiny appearance than before. Whilst the main focus of current research is seen as focusing on pre-cast beams with embedded TinGlass construction units, the decision has been made to disseminate the results of the research prior to publishing them in the Thesis. This led to the new products developed by the MSc students such as a brick with a hole provided by the insertion of tuna can into glass cullet prior to fusing. Thus the same idea and methodology of TinGlass was used whilst the development of the researcher goes along its dissemination.

A recent take on the concept of TinGlass for production of a glass brick with a hole without drilling, is shown in Fig 4. A neat and precisely-formed hole is produced without residual stresses by this method. This method can be used for assembly into a structure, by stacking hollow galls bricks onto steel rods. This is similar to the exhibit in V&A Glass gallery by Danny Lane, *The Balustrade*.The methodology of a cheap and efficient construction of an innovative TinGlass Brick with a central hole formed during the heating procedure, is outlined below. It has been originated by the author and refined by K Dikis, MSc student, SCEM, UoB, 2010.

The glass cullet is placed outside the tin-plated steel can. When fused in a mould lined by fireproof ceramic fibre paper, glass cullet forms a brick with central hole. The conventional technique for making a hole in a glass-ceramic brick, involves the operation of drilling it through. Glass is a brittle material, and hence this method requires high control of chemical composition, thermal processing and mechanical properties of glass brick, in order to prevent fracture when drilling it.

Novelty: Under proposed technique, a hole with smooth inside surface is produced without drilling. It is manufactured in a cheap and efficient way, from any mixed waste glass cullet.

The Figure 5 shows the TinGlass Brick with the central hole, produced by fusing the glass cullet in the mould shown in Fig 4.

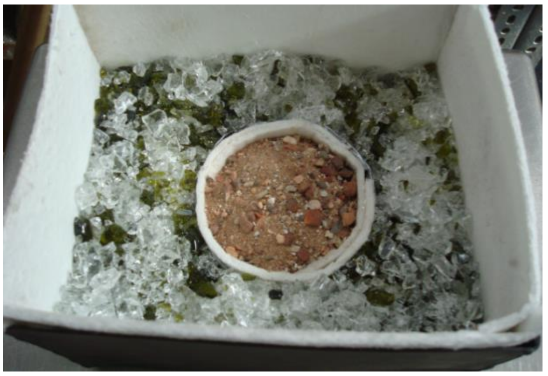


Figure 4. Mould preparation stage for the prototype of hollow TinGlass brick

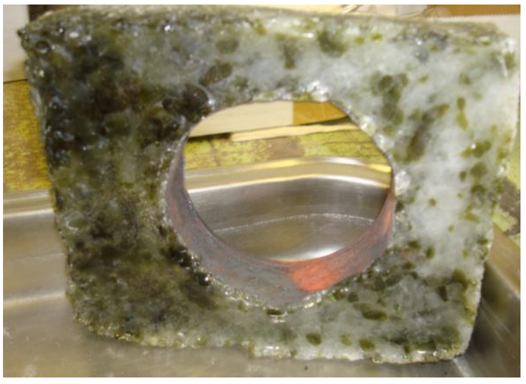


Figure 5. Hollow TinGlass Brick

Appendix 8.2

Corrosion testing of TGCU.

Charpy test of TGCU under dynamic loading

C Filippatos, SoCEM, UoB, 2011

MECHANICAL PROPERTIES OF THERMALLY PROCESSED WASTE GLASS IN MARINE ENVIRONMENT

Extract from Final Year project by C. Filippatos, 2011

Charpy test for corroded and non-corroded TinGlass

In this chapter the Charpy test on TinGlass is going to be presented. It is the first time that a realistic TinGlass sample is tested for absorption of energy. In the past, it has only been tested for compression, and bending when embedded in concrete beams.

The Charpy test was performed on three batches of TinGlass samples. The first batch was non-corroded TinGlass samles, the second batch consisted of samples corroded in tap water, and the last one contained TinGlass samples corroded in sea water.

The failure under Charpy test will tend to happen by crack propagation; this is a random process and a high experimental uncertainty is expected. Because of this, a larger number of samples was processed, to obtain good averaging and reasonable uncertainty as measured by standard deviation.

Experiment Aims

- Measure impact energy for TinGlass samples across all batches
- Study how impact energy varies between the batches
- Discuss how corrosion influences impact energy

3.1 Experimental Design

In this experiment TinGlass will be tested under dynamic load, in order to measure the impact energy absorbed. It is expected that TinGlass will have higher fracture toughness than soda-lime glass brick, due to its structure, namely the presence of fused-on metal shell, as provided by a tin-plated steel waste can, *e g* baked beans can.

Because the corrosion weakens the metal shell, the variations in impact energy will indirectly outline the role of metal shell in resistance to crack propagation. .

3.2 Hypothesis

The hypothesis is that the impact energy absorbed will be higher for TinGlass with a thicker metal shell. It is well know that steel is much tougher than glass, and hence the thickness of the steel shell can be crucial in preventing failure under dynamic load.

In the present set up, where the first batch of specimens are not corroded, the energy absorbed is expected to be higher than that for the other two groups, which have been corroded in tap water and seawater, batch 2 and batch 3 respectively.

The degree of corrosion is expected to play an important role in the toughness of each group. Since the TinGlass samples used for the current experiment were of the same properties, the effect of corrosion on metal shell will be explored and illustrated clearly. Thus the importance of the metal envelope of the TinGlass will be valued.

3.3 Experimental Procedure

Fifteen TinGlass specimens with the same dimensions were selected for the experiment. Three groups (batches) were formed, each containing 4 to 6 samples.

The corrosion experiment was devised for two other groups by the author.

The first group was control samples (without corrosion).Six samples formed the first batch, labeled 1 to 6. The TinGlass samples of the first batch were used without any further corrosion treatment. Moreover, TinGlasses were inspected for corrosion marks. Samples that were intact were approved for the first batch. The first batch of TinGlass was taken as the control batch.

The second TinGlass batch was corroded in tap water. In corrosion process the TinGlass samples were placed in a container full of tap water. The plastic container was filed with 5 litres of tab water in room temperature approx. 19^{o} C to 20^{o}C. The samples were left in the water for 72 hours. Five TinGlass samples were chosen in this batch labeled 1WT, 2WT, 3WT, 4WT and 5 WT. The fourth sample (4WT) was later on removed from the dataset as it was found to be defective.

Figure 3.1 TinGlass samples immersed in tap water

The third TinGlass batch was corroded in sea water. Similar process took place as for the second batch, with the only difference was that TinGlass samples were placed in sea water instead of tap water. The sea water was simulated by salt brine prepared in the lab. Five liters of tab water were poured in the plastic container and then pure sea salt was added in the water, in a proportion of 35 grams of sea salt per litre. So for five litres of tab water 175 grams of sea salt were used. Water in the container was stirred until the mixture became homogeneous. Then the samples of the third batch were placed in the container and were left in room temperature (approx. 19^oC to 20^oC) for 72 hours. This group contained five samples labeled 1SW, 2SW, 3SW, 4SW and 5SW.

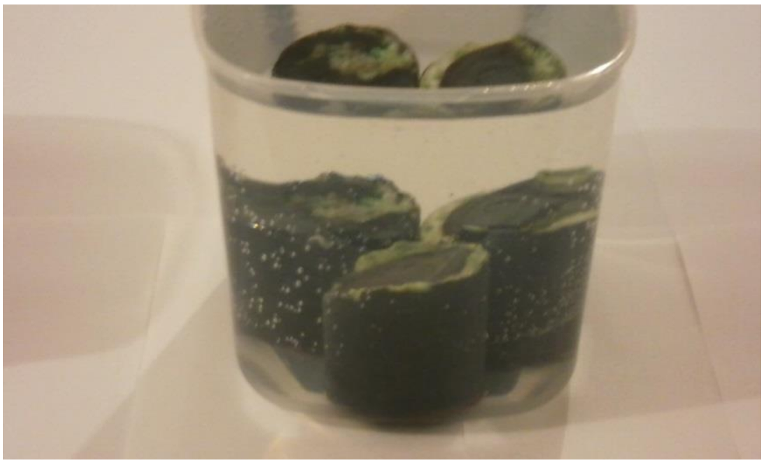


Figure 3.2 TinGlass samples immersed in sea water

After the corrosion experiment an informal visual inspection take place. The experiment was shown that the thin metal shell of TinGlass became corroded both in tap water and sea water.

TinGlass samples number 4wt and 4sw had to be removed. TinGlass number 4sw was completely corroded and started to falling apart. TinGlass sample number 4wt after corrosion experiment had much smaller dimension than the rest of the batch so it was removed in order to have same dimensions for statistical analysis.

After the corrosion experiments take place the cutting process of TinGlass samples. All three TinGlass batches had to be cut in order to fit in the Charpy impact test machine.

3.3.1 Cutting the TinGlass samples

All three TinGlass batches had to be cut in order to fit in the Charpy machine. The limitation of Charpy machine is 35 millimeters height. The height of TinGlass exceeded the 35 millimeters, so the cutting process had to be applied. For this purpose the standard method for rock samples cutting was used; the rotating blade of the machine was operated by the author after the training. All the three TinGlass batches were marked at 35 millimeters height and were placed in the power saw one by one. The feed rate of the blade had to be set. In the photo below is shown the cutting machine.

The cutting speed has been selected after assessing the TinGlass properties, brittleness of glass, needs slower cutting speed to prevent vibrations and failure by crack propagation, so the cutting speed was set at 10 millimeters / minute. This was necessary in order to prevent vibrations caused during the cutting procedure, which would result in smashing the glass inside the tin instead of cutting it. Optical observation after the cutting process ensured that the surface area of all TinGlass batches were smooth and even for every TinGlass sample as shown in Figure 3.4

Figure 3.3 Cutting machine

Figure 3.4 TinGlass batches after cutting process

Visual observation takes place after the cutting process. The valorizations of three TinGlass batches were obligatory in order to identify and evaluate the texture of the glass in the core of each TinGlass.

3.4 Charpy test

All the three batches of TinGlass samples were prepared for Charpy rig. Each TinGlass was inspected and placed in the Charpy test

Fig 3.5 Charpy test machine, located in E4 of engineering block at Brighton University

Charpy rig is measuring the impact energy. The TinGlass samples were placed at the bottom of the machine, and the hammer blade lifted in upper position. Then the hammer blade makes free fall. When the hammer reaches the bottom of the machine, at this particular moment has maximum kinetic energy, equal to 150 J (joules). The dial at the top of the Charpy machine measures how much energy the sample absorbs when breaking. For example if the sample manages to stop the hammer blade, that means that the impact energy of the sample is higher than 150 J.

On the other hand if the hammer blade smashes the sample and passes through the specimen, that means that the sample had less impact energy absorbed. And the dial at the top is calibrated to show the energy that is absorbed by the sample.

Charpy impact test machine is operated by the technician. For this experiment, a general risk assessment form has been filled in, preceding the experiment.The photo below is showing a sample in Charpy machine.

Fig 3.6 Setup of Charpy test

All three batches were tested one by one in the Charpy impact test. The measurements are placed in a table as discussed in the next section.

3.5 Results of Charpy test

Charpy test has measured the impact energy of each TinGlass batch ; Batch 1 is non-corroded; Batch 2 is corroded in tap water; Batch 3 is corroded in sea water.

The data were placed in the Table 10. It can be seen that the result of the experiment agree with the primary hypothesis. Namely, the corrosion weakens the TinGlass. This is believed to be due to the thinning of the metal envelope around the glass core for corroded samples. Hence the importance of TinGlass concept as the cost-efficient method of toughening waste glass blocks.

Batch	Samples	energy (J)	average (J)	standard deviation (J)
1	1	106,00		
	2	126,00		
	3	128,00		
	4	112,00		
	5	116,00		
	6	113,00		
			117	8
2	1wt	74,00		
	2wt	98,00		
	3wt	76,00		
	5wt	72,00		
			77	6
3	1sw	61,00		
	2sw	65,00		
	3sw	71,00		
	5sw	68,00		
			67	4

Table 10 Impact Energy of TGCUs