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Structural cast glass components manufactured from waste glass: Diverting everyday discarded glass from the landfill to the building industry

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Although in theory glass can be endlessly re-melted without loss in quality, in practice only a small percentage gets recycled, mainly by the packaging industry. Most of the discarded glass fails to pass the high quality standards of the prevailing glass industry – due to coatings, adhesives, other contaminants or incompatibility of the recipe – and ends up in landfill. However, using discarded glass in cast components for building applications can be a good way to reintroduce this waste to the supply chain. Such components can tolerate a higher percentage of inclusions, without necessarily compromising their mechanical or aesthetical properties. This paper explores the potential but also the limitations of recycling glass in order to obtain load-bearing components. First, an overview is provided regarding which types of glass reach the recycling plants and which not, arguing on the reasons behind this selection. Afterwards, a series of experiments is presented, exploring the possibilities of recycling everyday glass waste, from beer bottles and Pyrex trays to mobile phone screens. Each type of glass waste is cast at different temperatures and firing/cooling rates to define its flow capability and risk of crystallization. The above information is linked to the X-ray fluorescence (XRF) analyses of the samples prior to recycling. The results point out the types of glass with potential in structural applications, and the overall feasibility of the concept. This paper is an extension of previously reported work by Bristogianni et al. 2018.

Keywords: Glass waste, glass recycling, cast glass components, kiln-casting, crystallization

1 Introduction

The term glass recycling is almost a synonym to the sole recycling of glass bottles and containers for the purposes of the food packaging industry. The glass packaging industry has significantly invested in the infrastructure for the collection, sorting and processing of glass bottle and container waste, and this has resulted in high percentages of waste recovery and recycling, such as a mean of 73.2% in 2015 in the European Union (Eurostat 2016). Glass waste is however a broader term including overall everyday household waste (ex. tableware, ovenware, lighting), building waste (ex. windows, glass tiles), electronic waste (ex. Liquid Crystal Displays and Cathode Ray Tubes), automotive industry waste (ex. laminated windshields) and industrial/laboratory waste to name a few. The percentages of recovery and recycling of non-packaging glass waste are rather low, effectively zero (ELVIROS 2004). Such glass objects are considered non-recyclable either due to contamination from coatings, adhesives, laminates or even hazardous substances, or due to the labour intensive demounting process required (ex. window panes, computer screens) (Dyer 2014). The food packaging industry does not accept contaminated glass cullet that will affect the taste of the products, same as the float industry rejects such glass, as it is responsible for the creation of stones and other flaws and reduces the transparency of their glass panes while also increasing the risk of failure due to inclusions such as Nickel Sulfide (NiS). Since this glass cannot meet the strict criteria to be reused for the same purpose (close-loop recycling), it either ends up in landfills or gets down-cycled (open-loop recycling) into aggregate in concrete, ceramic or pavement products, into abrasive or into foam insulation (Silva et al. 2017; Dyer 2014). What is more, tons of non-contaminated glass waste are simply discarded or down-cycled due to the mismatch in their recipe with that of glass packaging. In other words, the lack of facilities and automated processes for separation and handling of different types of glass is- at a great extend- responsible for the rejection of this waste from the close-loop recycling.

Cast glass technology for structural applications can be a strategy for tackling the problem of glass waste rejection due to contamination or glass composition. Cast glass has already been applied in load-bearing applications, such as the self-supporting glass façade of the Crystal Houses in Amsterdam (Oikonomopoulou et al. 2017). On the one hand, building

components out of cast glass can tolerate more flaws¹ than a piece of float glass or a drinking bottle, without compromising the strength or aesthetic quality. On the other hand, the relatively smaller scale of the cast glass factories and often lack of automation leave more room for experimentation. In contrast to the giants of glass processing and their strict specifications, cast glass producers have more freedom in altering the firing schedules and the glass recipes.

Scope of this paper, is the categorization of prevailing types of glass waste and the understanding of their value as a raw source for the casting of glass building components. Not only the mechanical properties of the final product are important, but also the suitability and easiness of a waste glass type to be cast in the first place. To elaborate on the aforementioned suitability, it should be noted that for each composition, a different liquidus temperature region and minimum cooling rate apply. These parameters need to be taken into account during casting in order to obtain glass, or in other words, to freeze the amorphous structure of the liquid melt into the solid component. A glass formed at temperatures just below this region and cooled down at slower rates, bears the risk of crystallization (Pye 2005). As a consequence, according to the heating and cooling conditions, a portion or all the material will be structured in crystals, and the end product will have altered properties. Such crystallized materials, for example, lose the property of transparency and become more impact resistant than their amorphous alternative (Cormier 2017). Therefore, the parameters defining each type of glass waste should facilitate the casting process, implying that high liquidus temperatures or extremely fast cooling rates are not realistic for the mass production of building components of a competitive price.

¹ Experimental testing on cast glass components at the TU Delft Glass & Transparency Lab indicate that a few air bubbles or inclusions (ex. ceramic stones) within the bulk of the components- that do not exceed a diameter of a millimeter- are not critical for the structural performance. Similar bubbles or stones in a glass pane of 6/8 mm thickness would significantly reduce the strength of the product, but also its aesthetic quality (a perfectly clear transparent pane is expected). For similar aesthetic reasons, colour shifts are rejected from the industry and consumers, but can be of aesthetic value in cast glass elements.

2 Categorization of everyday glass waste

2.1 Prevailing glass families

By clustering the commercial glass waste into families of similar chemical composition, we can set guidelines on how to handle each piece of glass waste and what to expect from the resulting product. In specific, we can define the working and annealing temperature range, the easiness of crystallization, the coefficient of thermal expansion and the possibility of combination with similar glass waste sources. We can also predict the characteristics of the finished products in terms of mechanical, optical and thermal properties.

Everyday glass waste was therefore categorized in the following six families: soda-lime, soda-potash-lime, lead crystal, lead-free crystal, borosilicate and alkali-aluminosilicate glass. Within the soda-lime category- which is also the most prevailing one- three subcategories were set in relation to the manufacturing process of the glass objects, since the production method fine tunes the basic soda-lime recipe. These subcategories are: automated blown, mouth-blown and float glass. Other types of specialty glasses are not included in this research as their contribution to the problem of glass waste is negligible.



Figure 1: Main families of commercial glasses

Appendix 1 provides a list of properties for each family of commercial glass. This list has been used in this research as a guideline for determining the handling temperatures during the casting of the different glass waste.

2.2 Selection of glass waste samples

According to the above categorization, characteristic samples from each type of glass family were collected and analyzed with a Panalytical Axios Max WD-XRF spectrometer in order to define their glass composition. The Panalytical set of Omnic standards were used for calibration, as well as several NIST SRM standards and pure (p.a.) compounds. The results can be seen in Appendix 2. In short, the following samples were analyzed per category:

- Soda lime/ blown, automated: Beer/ wine/ soda bottles, drinking glasses
 - Soda lime/ mouth-blown: artefacts from the glass blowing studio at Southern Illinois University
 - Soda lime/ float: window glass, waste glass from furnace clean-up
- Soda-potash lime: optical lenses, tableware
- Lead crystal: tableware
- Lead-free crystal: CRT screen (panel)
- Borosilicate: laboratory tubes
- Alkali-aluminosilicate: mobile phone screen

3 Recycling experiments and interpretation of the results

3.1 Experimental set-up

In this section, an explanation of the set-up parameters is provided. Regarding the casting method for the sample production, the two techniques listed below were followed, according to the maximum operating temperature needed:

a) Kiln-casting employing investment silica-plaster moulds. For this method, one kiln is used for the melting and annealing of the glass and therefore, the feeding of the moulds with glass takes place inside the kiln. Three different types of moulds were produced:

- Crystalcast M248, powder to water volume ratio 2.75 : 1. The product consists of cristobalite, quartz and gypsum (Gold Star). For firings above 1000°C, the crystalcast moulds are reinforced by an exterior layer of heat-resistant concrete.

- Ransom & Randolph (R&R) Glass Cast 910, powder to water mass ratio 10 : 2.8. The product consists of cristobalite, quartz, mullite, calcium sulfate and fibrous glass (Ransom & Randolph).
- Heat-resistant concrete coated with a 1mm thick layer of Mold Mix 6 by Zincar, which is a high alumina putty coating with glass reinforcement fibers (ZRCI 2017). Two layers of EKamold® spray are applied as top coating. This product is an ethanolic coating based on hexagonal boron nitride (ESK 2013). This mould was used for a firing at 1250°C.

The glass was introduced in the moulds either directly (“free-set”) or indirectly by being placed in terracotta flowerpots that were positioned above the moulds. The heating ramp was set at 50°C/h. Regarding the quenching applied to prevent the crystallization of the components, the samples are either manually quenched below their softening point, by opening and closing the kiln door in repetition or mechanically by setting the kiln controller at the “As Fast As Possible” (AFAP) function. The later cooling process requires more time versus the manual, abrupt quenching.

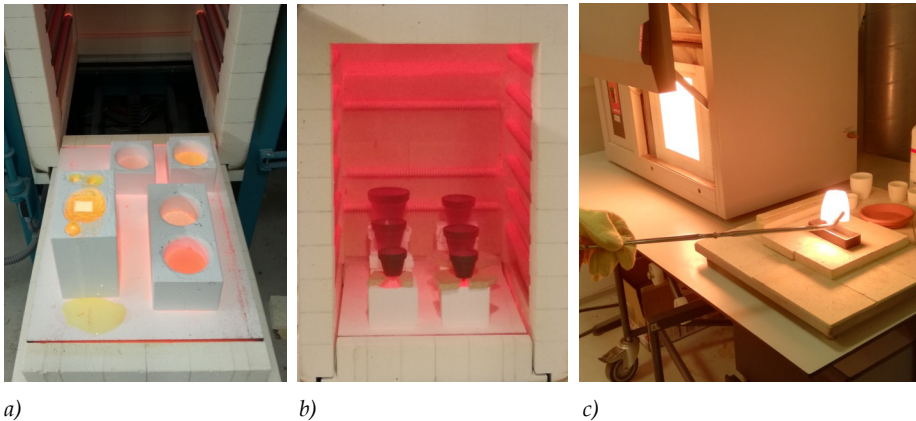


Figure 4: a) Kiln-casting in Crystalcast moulds with glass directly placed in the moulds (free-set), b) Kiln-casting in Crystalcast moulds employing the flowerpot technique, and c) Hot pouring in steel mould.

b) Melt-quenching technique employing high-alumina crucibles and steel moulds. This method is preferred in this research for castings above 1250°C, due to the high thermal and chemical resistance of the alumina crucibles. For this method, two kilns are needed for the

melting and annealing of the glass respectively. The glass is molten in Coors™ high-alumina crucibles and poured at atmospheric conditions in steel moulds that are preheated at 500°C. Upon quenching, the samples are placed in the annealing oven together with the steel mould. The heating rate used was 17.5°C/min.

3.2 *Casting experiment of the selected glass waste families*

Samples were cast from six selected glass families at different temperatures. The samples are initially evaluated on their workability. As the collection of samples includes glasses that have been developed for other production techniques (automated-blowing, float line, automated draw etc.), implications are expected when attempting to cast them, especially with the slower method of kiln-casting. Ideally, the glass samples should be able to flow and homogenize at temperatures below 1000°C, both to increase the energy savings but also to simplify the prerequisites of their mould. Aim of the research is thus to identify the glasses that have both lower working temperatures and a resistance to crystallization from the glasses that are difficult to cast and which will need extra attention. For this identification step, each glass is cast individually. The following observations and conclusions can be gathered for each glass family:

- *Soda lime/blown, automated (Container glass such as beer/wine/soda bottles, drinking glasses)*

These glasses are developed for the automated blowing process, therefore they need to be stiff enough to keep their shape once blown in a mould. Although this prerequisite decreases the workability of the glass, this fact is counteracted by the mechanically applied air pressure for the moulding. This attribute was prevailing during the casting of these glasses, since the samples needed temperatures higher than 1000°C in order to flow and homogenize. Moreover, all samples were very susceptible to crystallization below the liquidus temperature. Abrupt quenching was necessary to avoid full crystallization and to confine the problem only to the top surface. More specifically, samples cast at 860°C would not flow but only partially fuse, and would appear fully crystallized with mechanical quenching. At 950°C the drinking glass sample failed to homogenize and crystallized despite its fast cooling. Likewise, the samples cast at 970°C and mechanically quenched were crystallized and incomplete, as the glass could not easily flow from the flowerpot down to the mould. It should be noted, however, that samples appearing to be fully crystallized, proved to contain glassy zones within their body, when sliced in two and observed along their cross section. Only when cast at 1120/1200°C and abruptly cooled down to 600°C were the resulting samples transparent. This transparency was evident after

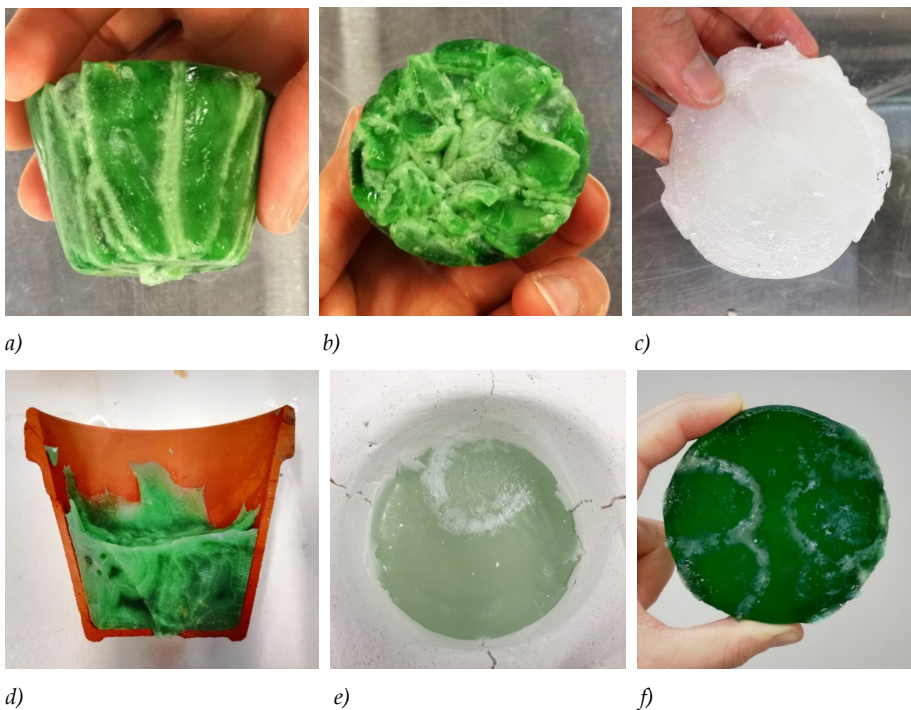


Figure 6: a), b) Beer bottle starting to fuse inside the flowerpot, at 860°C, c) drinking glass, crystallized at 950°C, d) beer bottle fused inside the flowerpot and partially crystallized, e) clear bottle cast at 1200°C with top surface crystallization linked to the contact of the glass to the mould, f) beer bottle cast at 1200°C.

the top crystallized surface² and the bottom surface in contact with the investment mould were polished.

From the XRF data obtained, we can observe that all above tested glasses have a similar composition. Mainly we see a range of 71.12 – 73.99 per weight percentage (wt%) of SiO_2 , 10.95 – 12.90 wt% Na_2O , and 9.74 – 11.88 wt% CaO . Calcium oxide (CaO , lime) is increasing the softening point and the sagging temperature, thus the observed high viscosity of the samples (Zschimmer 2013). Although this is required for the automated

² Unless a nucleating agent is added in the glass melt to promote bulk crystallization, usually crystallization starts from the glass surface. Airborne dust is often the main trigger. In addition, volatilization of various components from the glass melt alters the composition at the outer layer. Particles from the mould found on that altered surface could also act as nucleating sites (Müller 2000).

blowing process, the increased softening point impediments the casting. The high percentage of lime is also responsible for the susceptibility to crystallization. According to Zschimmer, lime percentages above 10% promote devitrification. This is to be taken into account when working with this glass sub-family.

It should be also mentioned that although the tested glasses have almost the same composition and viscosity, their colour is affecting their setting time. Kitaigorodskii et al. (1934) and Burch et al. (1938) proved that glasses with identical basic composition and viscosity characteristics, differ regarding their working range. In specific, dark coloured glasses, due to their greater heat loss by radiation rate, tend to set much faster than the equivalent transparent or light coloured samples. Holscher et al. (1943) suggest chromium emerald green glasses of basic composition SiO_2 74.0 wt%, Na_2O 16.0 wt%, CaO 10.0 wt%, Fe_2O_3 0.035 wt% and Cr_2O 0.25 wt% to be one of the most rapid cooling systems after dark green Fe-Mn systems. In our tested samples that could be easily verified by the intense luminosity of these samples at 1200°C in comparison to the transparent ones. The fast setting of darker colours should be considered when the hot-pouring method is employed.



Figure 7: Kiln-casting experiment at 1120°C , portraying the differences in luminosity among the various coloured samples

Experiments with mixing different container samples together were also conducted in order to define their compatibility. The glass recycling industry separates soda-lime containers from numerous different producers into similar colours. The segregated cullet is then successfully recycled together with new raw material. In that sense, casting two

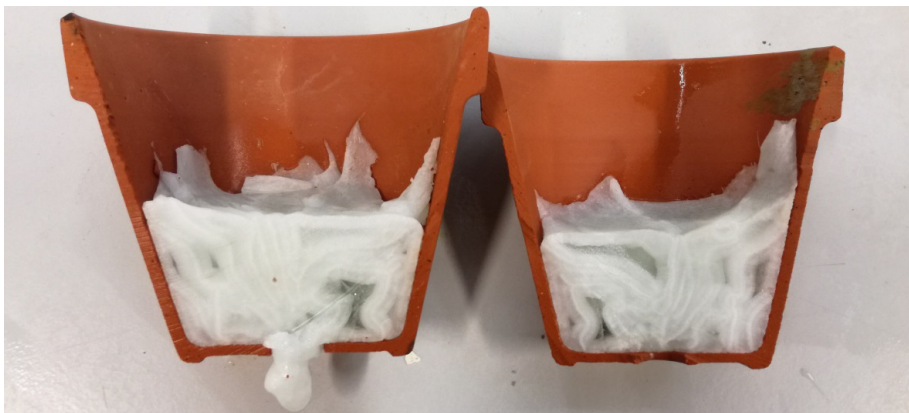
different clear bottles together was expected to work well at temperatures corresponding to viscosities of $10^{1.5-2.5}$ poise, which are achieved in the melting tanks. For typical soda-lime silica glasses (Kimble R-6 used as reference), a $10^{2.5}$ viscosity would correspond to 1254°C (Martlew 2005). Therefore it was opted to test the combination at a lower temperature, namely 970°C . The sample, placed in a flowerpot, was kept at top temperature for 2 hours and then mechanically quenched. A small part of the glass mixture flew down the mould and despite the fact that the glass was fully crystallized, it was homogenized and did not crack during annealing. Regarding the glass mass that remained in the flowerpot, this could be observed by cutting the pot in half. There, zones of crystallized glass of almost same thickness (similar to the thickness of the bottles) are fused



a) Droplets that flowed from the flowerpot down to the mould



b) Glass part that fused inside the flowerpot. In this picture, the surface in contact with the flowerpot is seen



c) Flowerpot cut in half, showing the layering of the fused glass and the glassy areas within the crystallized mass.

Figure 8: Results of the kiln-casting of two different types of clear bottles at 970°C

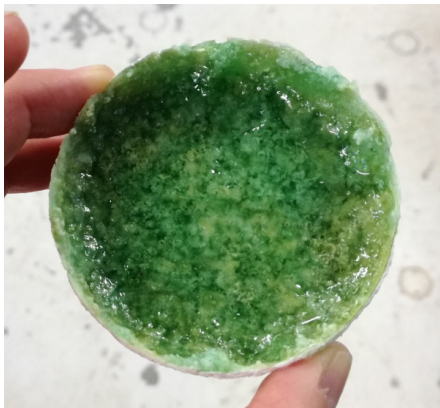
together. A few glassy regions are also observed. It is interesting to see that the zone of glass in contact with the flowerpot – which heats up and cools down faster – is more homogeneous and has a different micro-pattern of crystallization.³ Regardless of the



a) 970°C (small shards)



b) 970°C (powder)



c) 940°C (powder + flux)



d) 1250°C (powder)

Figure 9: Samples of different coloured glass bottles kiln-cast

³ In comparison to the previously described high temperature tests at 1200-1250°C, in this case the glass shards reach a state just above the softening point that allows them to compact within the flowerpot. Moreover, there is a difference observed within the bulk of each individual shard and its exterior surface. The bulk is overall cooler than the exterior surface and has a high viscosity that acts as a kinetic barrier for the formation of crystals. The exterior, however, heats up first and has a reduced viscosity that allows the fusion with the adjacent shards. This viscosity simultaneously allows the formation of crystals, thus the crystallization observed in these areas.

above, none of the glass masses cracked, proving that this combination is also feasible at temperatures below 1250°C.

The mixing of different colours of container glass (wine bottles) was also tested, in various sizes from powder to small and medium sized shards. The XRF analysis of 4 different samples showed strong compositional similarity despite the colour shifts. The mix of wine bottles was fired at various temperatures between 940°C – 1450°C. At 970°C the sample would partially fuse and still keep the integrity and colours of the individual pieces. This comes in antithesis with the above mixture of clear bottles (similar recipes to the wine bottles) that homogenized at the same temperature. In this case, the differences in colour/exact recipe, seem to require higher temperatures. Nonetheless, the sample did not crack upon annealing. Adding 10% of fluxing agent (in this case CNa_2O_3) in the powdered mix and firing it at 940°C helped the melting of the top surface but did not result in a homogenized sample. The sample was homogenized at the tests conducted from 1200°C and above. Higher temperatures are required for the homogenization of this combination.

In general, despite the challenges to cast this sub-family described in this chapter, glass container waste is still the most prevailing one. In that sense, it is worth exploring the derailing of sorted – yet discarded by the packaging industry – glass waste, from the landfill to the building sector. As an advantage, the iron in the green and amber (combined with Sulfur) glasses can provide excellent UV-radiation protection (Shelby 2005) and should thus be considered for use in facades.

- *Soda lime/ mouth-blown (artefacts from the glass blowing studio at Southern Illinois University)*

Glass studios, either commercial or academic, produce quite some glass waste during their trial and error explorations. Especially the discarded pieces by the glassblowing hotshop containing colour are not reused for blown objects, as this would imply the contamination of the clear transparent batch in the furnace.

In contrast to the above glass category, these glasses are meant to be processed according to the power of the human lung, therefore they cannot be as stiff. Also, the artists require a prolonged working time to process their piece, thus a glass that will not set as fast as the container glass. Correspondingly, the content of lime (CaO) in this composition is found around 6.8-7.1 wt% and of sodium oxide (Na_2O) at 14.3-15.4 wt%. The glass samples thus could slowly flow down from the flowerpots to the moulds at 860°C, a temperature

considerably lower than the one necessary for the machine-blown glass objects of the same glass family. However, the lack of abrupt quenching can still induce extended crystallization in the samples. The differences in the working range between the various colour variations are valid also here. Overall though, these coloured glasses are usually engineered to be compatible and as a result beautiful colour patterns can emerge from their combination. Crystallized samples can lead as well to interesting marble-like smooth components. Since the mechanical properties of these objects are expected to be improved during the devitrification, experimental testing of their strength is required in follow-on research, in order to explore their potential value as building components.



Figure 10: Set-up of the kiln and glass ceramic samples resulting from the mouth-blown glass waste



Figure 11: Glass samples cast employing Sprucepine clear and blue glass waste (top and bottom) and lead crystal (middle element). The figure shows the effect of casting temperature to the structure of the glass component. Although the top and bottom sample are cast using the same glass, the one below, cast at 860°C crystallized, in comparison to the clear blue component on top, cast at 950°C.

Further investigation on the crystallization issue of these samples showed that a relatively slow cooling rate is not as decisive as the choice of top temperature for kiln-casting. Using transparent clear and blue Sprucepine shards, two elements were cast, one at 860°C and one at 950°C, kept at top temperature for 10 hours and then cooled down to annealing point with a rate of 120°C/h. The sample cast at a lower temperature appeared fully crystallized in comparison to the one cast at a higher temperature, which resulted in a transparent blue glass.

In order to explain this observation and define the dangerous crystallization zone of this glass, a comprehensive glass thermal analysis (Differential Scanning Calorimetry DSC) was performed to a sample of transparent clear Sprucepine glass, employing a STA 449 F3 Jupiter® apparatus.

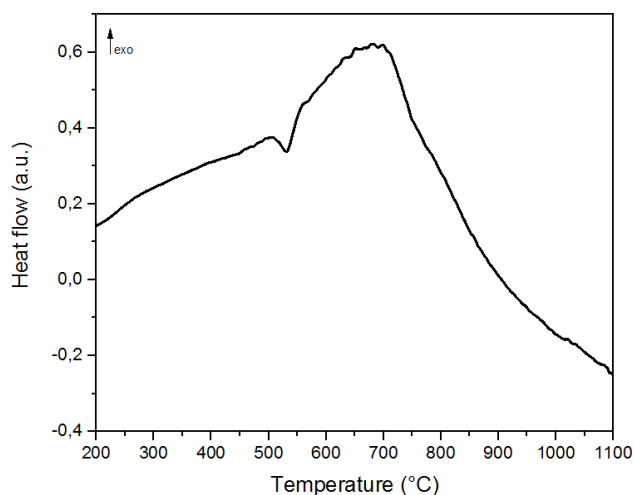


Figure 12: DSC analysis pointing out the glass transition temperature and crystallization peak temperature of Spruce Pine transparent clear glass

The DSC analysis defines the crystallization peak at around 700°C. Observing the endothermic process after this point, we can notice the drastically fall of the DSC curve. This proves that there is a significant difference between casting this glass at 860°C and 950°C.

Regarding the crystallized sample cast at 860°C, the extent of crystallization was also questioned, especially after observing the remaining glass mass in the flowerpot used for

its casting. There, the existence of both crystalline and glassy phases is evident. Therefore, an X-ray diffraction (XRD) test was conducted, employing a Bruker D8 Advance diffractometer Bragg-Brentano geometry and a Lynxeye position sensitive detector.



Figure 13: Glass sample from the flowerpot used during the 860°C casting experiment, showing the formation of crystals

Table 1: Results of the XRD analyses for samples cast at 950 and 860°C. The samples are taken from the top surface of the components and not from the remaining glass in the flower pots.

Sample		Top temp. *)	Transparency	Crystalline phases	Compound	%
1		A 950°C	Transparent	No	-	0
2a		B 860°C	Transparent with opaque zones	Sodium Calcium Silicate	$\text{Na}_2\text{Ca}_3\text{Si}_6\text{O}_{16}$	≈ 3
2b		B 860°C	Opaque	Sodium Calcium Silicate	$\text{Na}_2\text{Ca}_3\text{Si}_6\text{O}_{16}$	≈ 10

*) The firing quench ramp was 120°C/h

The XRD analyses identified the presence of crystalline phases in the sample cast at 860°C. In specific, the sodium calcium silicate component $\text{Na}_2\text{O} \cdot 0.3\text{CaO} \cdot 0.6\text{SiO}_2$ was found, also known as devitrite. Devitrite is a common crystallization product of soda-lime-silica glasses (Clark-Monks et al., 1980). Interestingly enough, although the sample appeared as

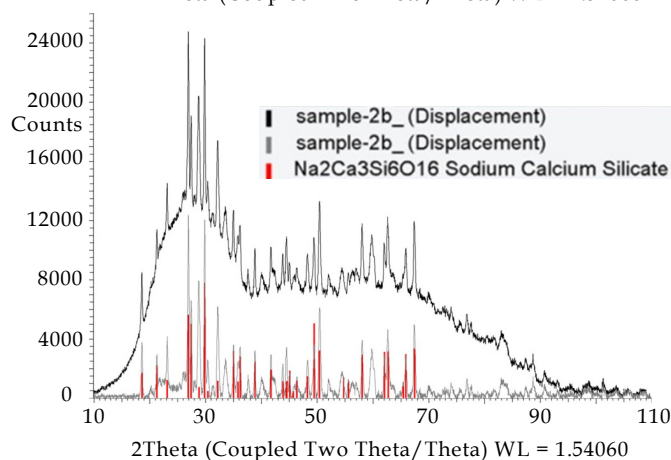
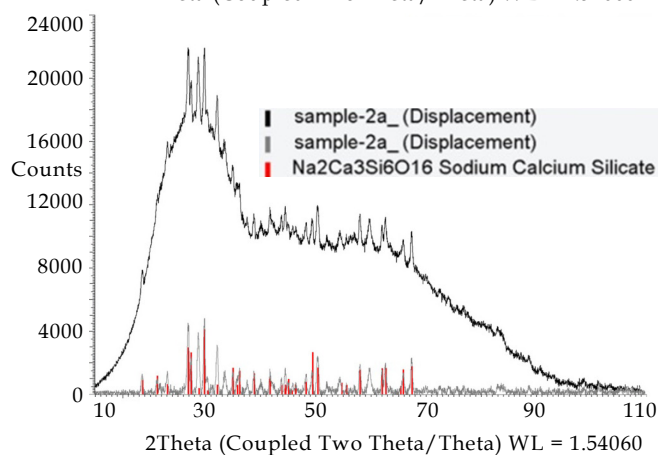
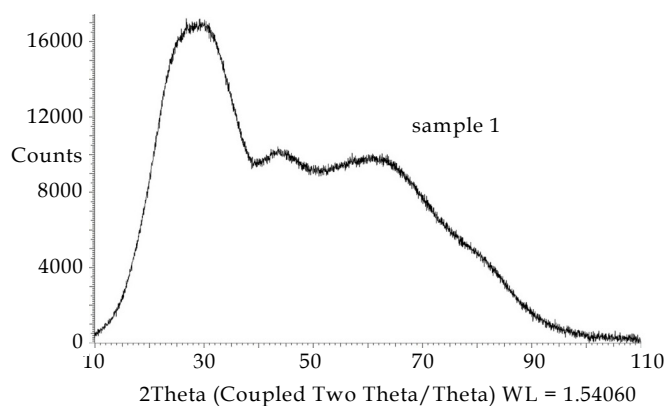


Figure 15: The XRD graph shows the measured patterns in black, after background subtraction. The coloured bars give the peak positions and intensities of the possibly present identified phases, using the ICDD pdf4 database. All samples are amorphous but some have a small fraction of crystalline phases.

fully crystallized (the exterior surface is completely opaque and clusters of crystal patterns are visible), not more than 10% of its structure was crystalline. The sample taken from the 950°C specimen, was entirely amorphous. Further experiments need to be conducted to determine how the crystalline percentage can be controlled and what the effects are of these percentages on the structural strength of the components.

- *Soda lime/ float (window glass, waste glass from furnace clean-up)*

The float glass samples present a bit higher weight percentages of SiO₂ 74, 21-74, 56 and Na₂O 12, 44-13, 32 and lower CaO percentage of 8.91-10.03 in comparison to the automated-blown glass. Magnesium Oxide (MgO) levels are also higher by 1-1.5 wt%. The XRF analysis was conducted at only one surface of the samples which is assumed to be the top surface since no contamination by the tin bed is observed. The glass would be very viscous at 860°C, flowing very slowly. Full crystallization occurred by mechanical quenching at the extra clear sample (PPG Starphire). These glasses could be cast homogeneously at 1200°C and presented only surface crystallization with abrupt cooling.

Here the difference in the crystallization pattern between the clear and the extra clear float samples should be mentioned. The clear sample presented a subtle translucent finishing at the top surface and a couple of local areas of mild crystal formations. The extra clear (PPG Starphire) glass however, showed a more intense crystallization pattern at the top surface, with visible crystal clusters.

It is not clear – when comparing the two glass compositions – why the extra clear sample is more prone to crystallization, but this could also be related to a possible contamination of the top surface from the tin bath. An XRF analysis of the cast sample should be conducted to further investigate this. To better define the extra clear glass, a comprehensive glass thermal analysis (DSC) was performed. The test showed a stable glass, but with a crystallization peak at around 740°C. The glass transition temperature was found at the region of 570°C. With proper cooling- fast enough to avoid the crystallization at the above mentioned peak- this glass can result into very clear and transparent castings.

Regarding the waste from the float production furnace clean-up, this refers to glass that may be located at the bottom of the furnace for years. The glass slowly decays the refractory materials at the base and absorbs part of their elements in its composition. The resulting glass- although in rough lines similar in composition to the original soda-lime

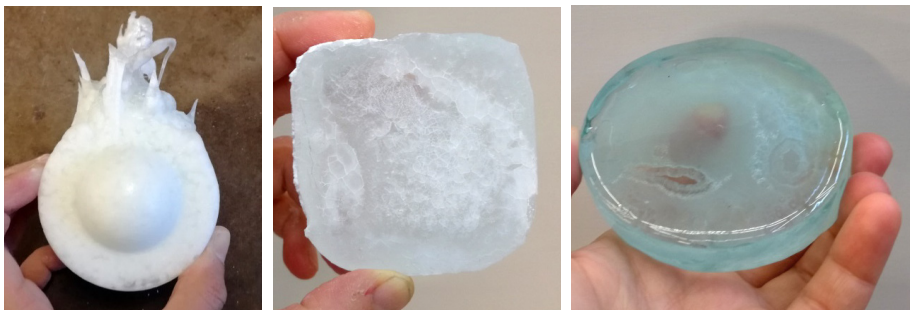


Figure 16: PPG Starphire kiln-cast at 860°C and mechanically quenched (left), PPG Starphire sample kiln-cast at 1200°C with top surface crystallization (middle), PPG clear float sample kiln-cast at 1200°C (right)



Figure 17: PPG furnace waste aquamarine cast at 1120°C (left) and at 860°C (middle). PPG Starphire cast at 1120°C (right)

one, can be quite unpredictable in its exact composition and therefore in its casting behavior. For example, the “PPG light green waste glass” was a very viscous glass (could not flow at 860°C) but also extremely resistant to crystallization. The increased viscosity can be explained by the high content of alumina (8.8 wt%). According to Zschimmer (2013), although alumina reduces the melting point of soda-lime-silica glasses when introduced in small amounts, in weight percentages of more than 7% it has the opposite effect. The increased alumina content in combination with the relatively low percentage of lime (5.94 wt%) is what makes this glass so resistant to crystallization. It is also interesting to point out the content of 2.98 wt% of zirconia (ZrO_2) in combination with traces of hafnia (HfO_2). Zirconia is a refractory material found as paving on the furnace bottom (Clark-

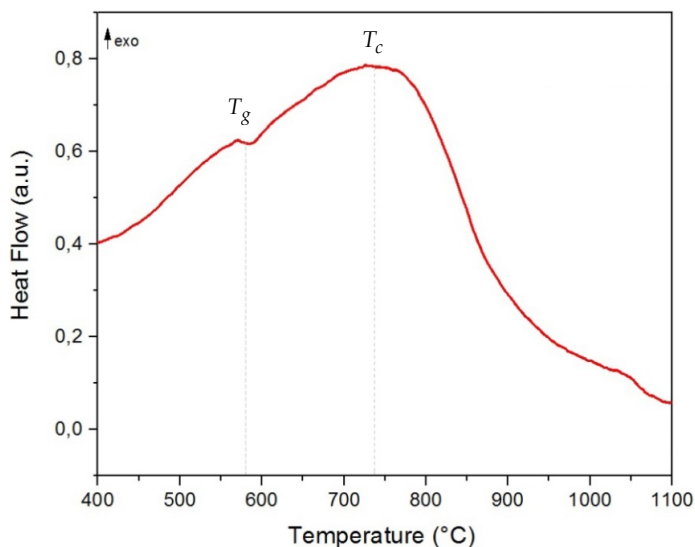


Figure 18: DSC analysis pointing out the glass transition temperature and crystallization peak temperature of PPG Starphire

Monks et al. 1980), especially in cases where very corrosive glasses are melted (Bray et al. 2001). Moreover, Alumina-Zirconia-Silica (AZS) refractories are often used by the glass industry in favour of high-alumina refractories, which tend to more easily corrode and release alumina in the molten glass (Bray et al. 2001). The usage of such refractory products can explain the high content of this glass in alumina and zirconia. Zirconium minerals contain hafnium, in a range of 1.5 - 2.5% Hf/Zr+Hf or more (Nielsen 2000), justifying the traces of hafnia in this glass. Karell et al. (2007) mention that zirconia increases the viscosity of the melt- as observed- but is also used as a substitute to PbO in lead-free crystal glasses, as it increases the refractive index of the glass and thus the light dispersion. The later information can be linked with the high optical quality of the cast sample.

The “PPG furnace waste aquamarine” sample did not exhibit serious contamination from the refractory materials and had a composition very close to that of standard float glass. At 860°C the sample was viscous but could only flow slowly. By inducing mechanical cooling, partial crystallization occurred, with some glassy amorphous regions still preserved within its mass. The same glass could be cast homogeneously at 1120 and 1200°C and presented minor surface crystallization as did sample “PPG clear”.



Green glass before and after casting at 860°C



Aquamarine glass cast at 860°C and 1200°C respectively

Figure 19: PPG furnace waste glass

Despite the unpredictable character of this type of glass waste, interesting colours and patterns can emerge from the casting of these – enriched through their prolonged contact with the furnace – glasses.

- *Soda-potash lime (optical lenses, tableware)*

Potassium oxide (K_2O) is often added in soda-lime-silica systems to achieve extra white clear glass (Zschimmer 2013). K_2O lowers the melting point of the glass yet increases the thermal expansion coefficient. Such alkali-lime silica systems containing considerable amounts of soda and potash and reduced amounts of lime are preferred for hand-pressing, since these glasses are soft and easy to adapt to the shape of the steel mould while still viscous (Rosenhain 1908). In this category, the optical glass B270 by Schott is used as a reference, since the authors have continuously experimented with this glass due

to its good optical qualities and workability at 950°C (Bristogianni et al. 2017). A complete replacement of soda by potassium oxide is found in the pressed historical Bohemian crystal artefacts (Rosenhain 1908). Contemporary Czech (or formerly Czechoslovakian) glass pressed objects however- like the one tested in the scope of this research, may contain considerably less percentages of K_2O , and more soda and silica. The glass obtained after firing at 950°C was transparent and extra clear, yet presented intense creasing at the top surface. Possibly, a small increase in temperature would result in a better quality casting.



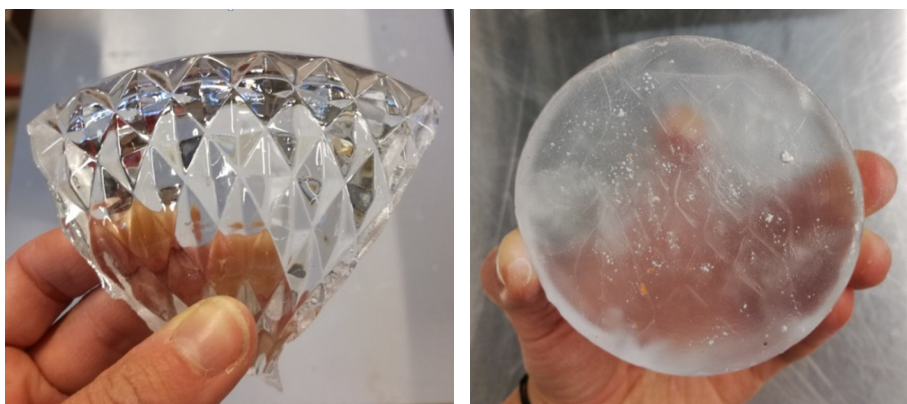
Figure 20: Czech glass cast at 950°C. Post-processing is required to remove the shrinkage of the top surface and reveal the actual transparent glass.

- *Lead crystal (tableware)*

Lead silica glass was a glass type commonly used for high quality table and ornamental ware before the use of lead (II) oxide (PbO) was restricted due to its toxicity. This composition was preferred by the manufacturers because of the high refractiveness that the PbO would attribute to the glass, adding brilliancy to the glass artefacts (Rosenhain 1908). Shelby (2005) explains that due to the relatively weakness of the $Pb-O$ bonds caused by the low field strength of the large Pb^{2+} ions, the lead-silicate network can be easily disrupted. This justifies the low glass transformation temperature of this glasses. As these glasses are relatively soft, they are selected by manufacturers, when complicated manipulations during production are required (Rosenhain 1908). Lead glasses also have X-ray protective properties, which increase with the increase of lead content, and are independent from the radiation quality (Singer 1936). Yet, PbO lowers the Young modulus and the hardness of the glass and significantly increases the density (Zschimmer 2013),

factors that should be seriously considered when evaluating the use of such glasses for structural applications.

In this category, Schott LF5 (≈ 36 wt% PbO) and Gaffer G210 (≈ 44 wt% PbO) lead crystal are used as a reference in the XRF analyses, as the authors have previously conducted successful castings at 860°C , achieving extra clear glass without crystallization upon mechanical cooling. The tested sample was a pressed crystal bowl of lower lead content (≈ 24 wt%), which is a typical percentage for such tableware. The glass was successfully cast at 950°C to a clear glass without crystallization (upon abrupt quenching). At this temperature, the sample is expected to have a much lower viscosity in comparison to soda-lime glass. Yet it is interesting to mention that patterns from the initial design of the bowl were preserved at the bottom of the sample in combination with creasing at the top surface. More experiments are required to determine the flowability of this glass at this temperature, but nonetheless this glass can result to very transparent castings.



a) Before casting

b) After casting

Figure 21: Pressed crystal glass cast at 950°C . The pattern of the glass remained as a trace at the bottom surface of the sample. Upon post-processing, the glass will be transparent.

- *Lead-free crystal (CRT screen/panel)*

Due to the health and environmental concerns linked with the toxicity of lead and other heavy metals, various protocols have been issued around the world with the aim to reduce its use. Regarding glass manufacturers, they would chose PbO either to increase the refractive index adding brilliance to the glass, or to provide radiation protection in nuclear plants, hospitals, TV-tubes etc. Currently, lead is replaced with barium, strontium and

zirconium, although some of the alternative elements (barium in particular) can be quite toxic themselves, only less than lead (Scoullou et al. 2001). The resulting glasses present good optical quality, lower density than lead crystal, and x-ray shielding capacity which is however reduced and dependent on the X-ray quality (Singer 1936).

In this section, the casting of the panel of a colour display Cathode Ray Tube (CRT) is attempted. CRT tubes have been used in TV and computer screens before the emergence and dominance of Liquid-Crystal Display (LCD) technology. Although currently scarcely in use, CRT glass waste constitutes an accountable percentage of the municipal waste in the European Union (Hreglich et al. 2001; Bernardo et al. 2005). Since CRTs are not in production anymore, the route of their recycling into the same product is closed, leaving a question mark on how and where this glass can be used (Edgar et al. 2008). Nonetheless,

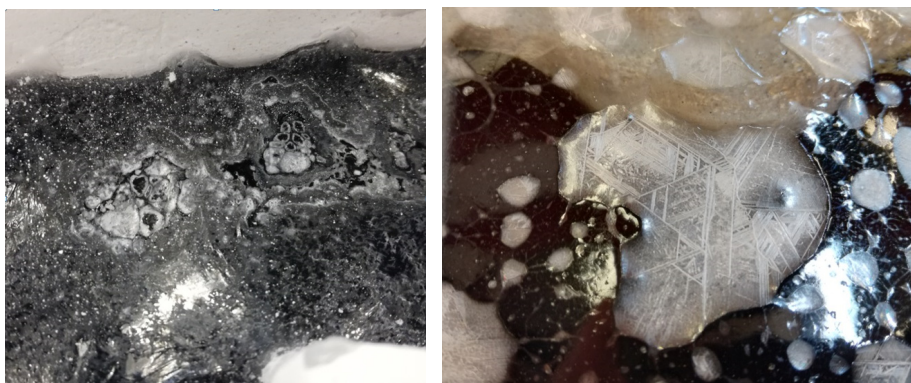


a) Screen shard

*b) Top surface crystallization
of the sample cast at 950°C*

*c) Transparent grey glass after
being post-processed*

Figure 22: CRT panel as retrieved from a computer screen



a) Kiln-cast at 1120°C

b) Kiln-cast at 970°C

Figure 23: Surface crystallization of CRT panel glass

the glass formulation for the CRTs is of fine quality, employing – among others – expensive barium (Ba) and strontium (Sr) oxides (Compton 2003; Bernando et al. 2005). More specifically, a typical CRT tube consists of three parts: the faceplate (panel), funnel, and neck tubing. The panel, in specific, is a lead-free barium–strontium glass that protects the viewers from the harmful X-rays (Compton 2003).

A sample of a CRT panel was successfully cast at 950°C, resulting in a clear, homogeneous glass of grey hue that did not crystallize upon abrupt quenching. Indeed, this glass composition, rich in Ba and Sr, is expected to be very resistant against crystallization (Kosmal et al. 2017). Of particular interest is however the white dotted pattern that was observed at the sample's top surface. The white substance – linked to surface crystallization was easily removed by submerging the sample into water.

A DSC analysis was conducted employing a STA 449 F3 Jupiter® apparatus. The test showed a stable glass with a shallow crystallization peak at around 700°C. Its glass transition temperature was found at the region of 550°C - 580°C. The stability of the glass and its high visual resulting quality prove the potential of this glass for casting glass building components.

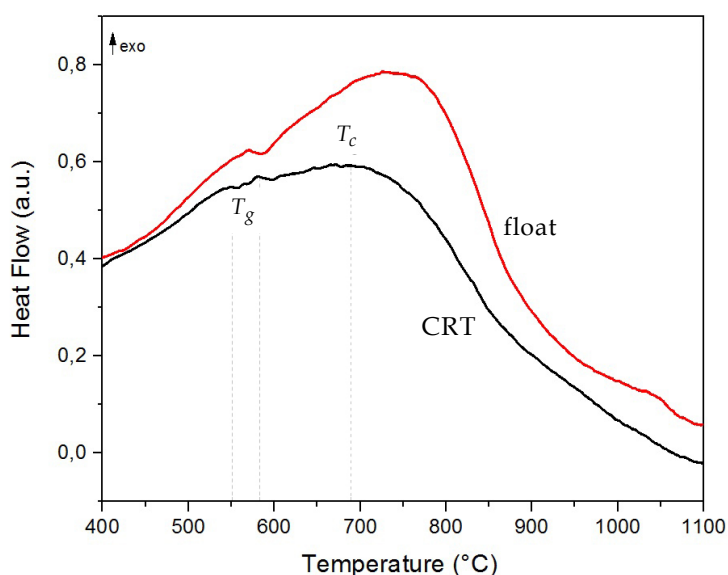


Figure 24. DSC analysis pointing out the glass transition temperature and crystallization peak temperature of the CRT sample. The temperature to heat flow curve of PPG Starphire float glass is included in the diagram as a point of reference.

The crystal traces on the top surface of the CRT sample kiln-cast at 970°C were isolated and XRF and XRD analyses were conducted. The XRF analysis showed a prevalence of sulfide, followed by alkali. The top surface crystallization can be therefore linked with the precipitation of these compounds during casting, in combination with the temperature occurring around the top surface. This crystallization is mainly considered as a flaw of the kiln-casting technique and is not expected in the melt-quenching casting process that takes place in atmospheric conditions. The XRD analysis showed four different crystalline phases, with Barium sulfate and the apththitalite having the sharpest peaks. Aphthitalite, like other K-salts, is water soluble, explaining the easy removal of the crystallization skin from the sample, when immersed in water.

*Table 2: XRF analysis of surface crystallization appearing on
CRT panel glass sample kiln-cast at 970°C*

Compound name	Content [wt%]
S	52.897
Na ₂ O	20.051
K ₂ O	17.43
BaO	4.832
SrO	4.162
SiO ₂	0.177
Cl	0.146
CaO	0.110
MgO	0.067
Al ₂ O ₃	0.052
Fe ₂ O ₃	0.044
P ₂ O ₅	0.032

*Table 3: XRD analysis of surface crystallization appearing on
CRT panel glass sample kiln-cast at 970°C*

Crystalline phases	Compound
Barium sulphate (IV) sulphate (VI)	Ba(SO ₃) _{0.3} (SO ₄) _{0.7}
Aphthitalite	KNa(SO ₄)
Disodium sulfate (VI)	Na ₂ (SO ₄)
Kalistrontite	K ₂ Sr(SO ₄) ₂

Firing set-up: Top temperature 970°C; Quench ramp 160°C/h

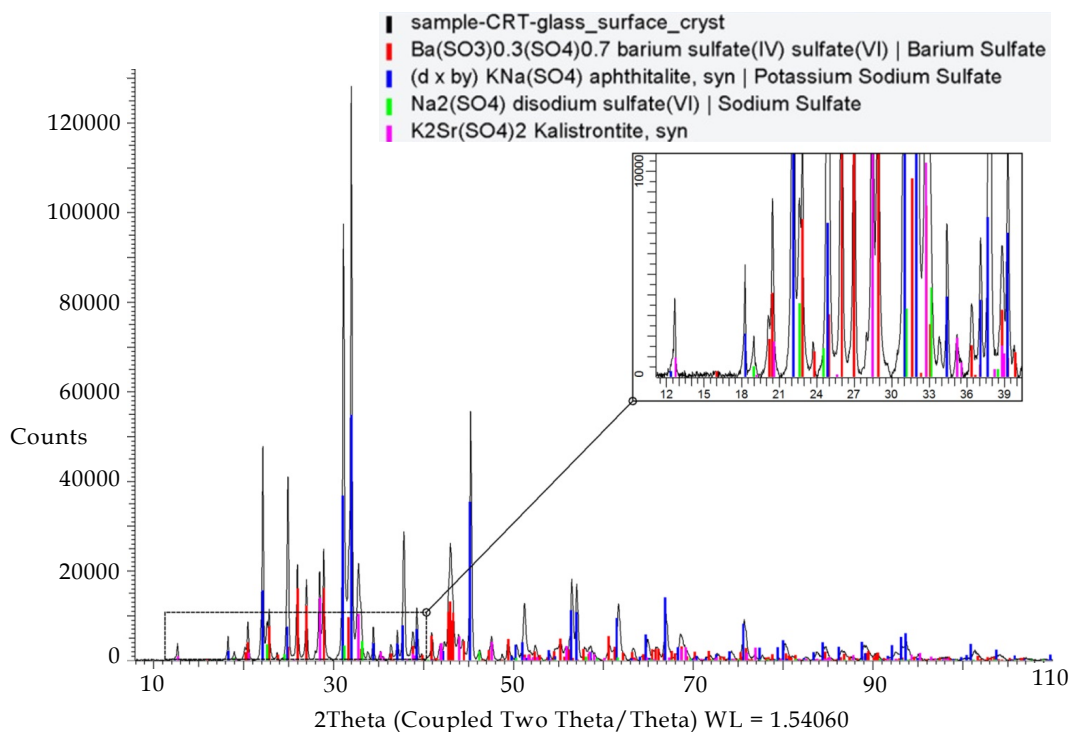


Figure 26: The XRD graph shows the measured patterns in black, after background subtraction. The coloured bars give the peak positions and intensities of the possibly present identified phases, using the ICDD pdf4 database

- *Borosilicate (laboratory tubes)*

Borosilicate glass can be attractive for structural applications at demanding environmental conditions, due to its good optical properties and its high thermal and chemical durability (Schott 2014b). It is commonly found in thermal shock resistant cookware and laboratory equipment. Its higher working temperature in comparison to that of soda-lime adds implications to its processing. Guidelines regarding recycling commonly advise not to discard borosilicate objects together with container glass. Unless chemically contaminated and thus hazardous, this good quality glass often ends up in landfills. Investigations for its downcycling into micro-filler for concrete (Korjamins et al. 2012), glass foams (Chinnam et al. 2014) and other ceramic material applications are currently conducted.

A piece of DURAN® laboratory glass produced by Schott was re-cast at 1200°C and resulted into a clear homogeneous glass after being abruptly cooled. The top surface was



Figure 27: Borosilicate labtube before and after casting at 1200°C



Figure 28: Borosilicate extruded rods successfully re-cast at 1120°C

completely flat and showed some local crystallization. DURAN® extruded solid rods by Schott were also successfully re-cast at 1120°C, using Crystalcast moulds within a heat-resistant concrete case. Despite the minimum surface crystallization appearing on this sample as well, the result was transparent and bubble free.

- *Alkali-aluminosilicate (mobile phone screen)*

Alkali-aluminosilicate glasses are characterized by high glass transition temperatures and excellent mechanical properties such as increased hardness, and scratch and sharp contact damage resistance (Corning 2017; Schott 2014b). Their high alkali content (>10%) enables the ion exchange with bigger alkali ions (ex. potassium bath) that results in a considerably improved surface compressive strength (Schott 2014b). This glass can be drawn via an automated process into very thin sheets of glass (0.4–2 mm) that find applications in the

screens of smartphones, laptops, tablets and other similar devices (Corning 2015). Due to its outstanding mechanical properties and the fact that touchscreens of that kind are an increasing upcoming source of glass waste, the recycling of alkali-aluminosilicate glass into building components becomes interesting. Yet, their extremely high working temperatures create challenges for hot-pouring and kiln-casting.

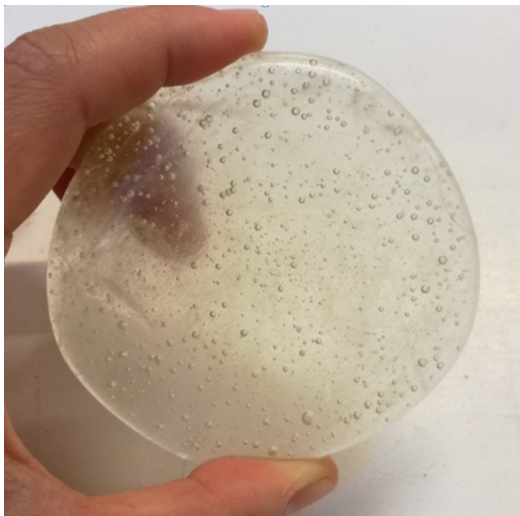
An initial test was conducted by melting a mobile phone screen glass in a high-alumina crucible. At 1500°C the sample still presented a very high viscosity, but some glass drops



a) Before firing



b) After firing at 1250°C



c) Kiln cast at 970°C



d) Melted at 1500°C in a high-alumina crucible and poured into a steel mould

Figure 29: Alkali-aluminosilicate glass retrieved from a mobile phone screen

managed to flow and resulted in a glass of high air-bubble content. The results of the kiln-casting test at 1250°C were quite unexpected as the glass partially corroded the silica-plaster mould and formed – probably as a reaction to the mould – a three-dimensional sponge structure of opaque white colour. Further testing is required to understand the reasons behind this foam formation. On the contrary, the sample kiln-cast at 970°C successfully formed a glass, although of high air-bubble content. Despite the air-bubbles, the formation of this glass at lower than 1000°C temperatures is very promising.

4 Conclusions and further research

The results of this research highlight the vast potential for recycling different types of discarded glass into cast glass building components. Products that are currently almost entirely excluded from the glass-to-glass recycling loop such as CRT panels or crystal tableware- both containing a considerable percentage of heavy metals- proved to be an excellent source of glass that can be kiln-cast at temperatures between 900°C - 1000°C. Soda-lime float, mouth-blown and container glasses, in comparison, needed higher

working temperatures ($\approx 1200^\circ\text{C}$) and faster cooling rates to homogenize into transparent glass samples. Also, glasses from the same family and of similar colours are considered compatible for cast-recycling. The casting of glasses of the above family at temperatures below 1000°C combined with a slow cooling, showed an aesthetically and structurally interesting alternative route, that of glass ceramics. In this case, more investigation is required in order to control the desired percentage of crystalline phases within the material. The recycling of borosilicate laboratory glassware can result into very clear glass, and is worth considering despite of the higher than soda-lime required working temperatures. More investigation is required for the successful kiln-casting of Aluminosilicate glass. Initially, the difficulty to flow even at 1500°C renders this glass unsustainable for recycling through casting. Yet, the ability to form it at 970°C, even with a high content of gas-bubbles, seems promising and requires further testing.

The authors also suggest further research on the mixing of different glass recipes with the aim of simplifying the initial, meticulous stage of segregation of the cullet in fewer glass categories. Towards this step, a method should be developed for controlling the quality of the segregated cullet and thus the quality of the final product in terms of strength and aesthetic homogeneity. Future work will be conducted on the mechanical testing of the



Figure 30: The fundamental differences between various types of glass regarding viscosity, thermal expansion and susceptibility to crystallization, introduce challenges to their mixing. Further research should be conducted to overcome the posed obstacles.

resulting recycled glass components to define their strength and validate their suitability as building components. Research should also address the recycling of glass contaminated by coatings, laminates, and adhesives, which nowadays constitute a considerable amount of our glass waste. The above steps are necessary for diverting the path of waste glass from the landfills to safe and beautiful structures.



Figure 31: Successful casting of pieces of (from left to right) float glass, bottle, laboratory tube, computer screen panel, lens, and mouth blown glass, demonstrating the numerous possibilities that arise in creating unique building components

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Appendix 1. Properties of various types of commercial glasses

Glass family	Lead crystal	Lead-free barium strontium		Soda-lime (mouth-blown)
Glass name	Scott LFS	CRT colour panel	Corning 9068 (Colour TV panel)	Cristalica, Spruce Pine
Young's modulus E in kN/mm^2	59			
Thermal expansion coefficient α (20°C ; 300°C) in 10^{-6} K^{-1}	10,6	9,7-10,9	9,9	10
Density in g/cm^3	3,22	2,75-2,79	2,69	
Forming temperature (viscosity = $\log 4$ in dPas) in $^\circ\text{C}$				995
Forming temperature (viscosity = $\log 5$ in dPas) in $^\circ\text{C}$				879
Forming temperature (viscosity = $\log 6$ in dPas) in $^\circ\text{C}$				792
Forming temperature (viscosity = $\log 7,6$ in dPas) in $^\circ\text{C}$	585		688	692
Annealing point (viscosity = $\log 13$ in dPas) in $^\circ\text{C}$	411	501	503	515
Strain point (viscosity = $\log 14,5$ in dPas) in $^\circ\text{C}$			462	486
Sources	Schott 2014b	Mear et al. 2006 Shelby 2005	Campbell et al. 1990 Seward III et al. 2001	Spruce Pine Batch

Glass family		Soda lime (float)		Soda lime (glass bottles)	Soda-potash-lime
		PPG Starphire	Kimble R6		
Glass name				Common glass container	Scott B270
Young's modulus E in kN/mm ²		73.1		70-75	71.5
Thermal expansion coefficient α (20°C; 300°C) in 10 ⁻⁶ K ⁻¹		9.03	9.3	9	9.4
Density in g/cm ³		2.5		2.52	2.55
Forming temperature (viscosity = log4 in dPas) in °C			984		1033
Forming temperature (viscosity = log5 in dPas) in °C			871		915
Forming temperature (viscosity = log6 in dPas) in °C			789		827
Forming temperature (viscosity = log7,6 in dPas) in °C		710	694		724
Annealing point(viscosity = log13 in dPas) in °C		547	527	548	541
Strain point (viscosity = log14,5 in dPas) in °C		513	486		511
Sources		Precision Glass and Optics	Martiew 2005	Shelby 2005	Knight Optical
		Speciality Glass Products	Brockway 1981		

Glass family	Borosilicate		Alkali-Aluminosilicate	Alkaline Earth
Glass name	Schott Duran*	"Pyrex"	Corning Gorilla Glass 5	Aluminosilicate EZ-1
		KG-33		
Young's modulus E in kN/mm ²	64		76.7	
Thermal expansion coefficient α (20°C; 300°C) in 10 ⁻⁶ K ⁻¹	3.3	3.3	7.88	4.2
Density in g/cm ³	2.23	2.23	2.43	2.52
Forming temperature (viscosity = log4 in dPas) in °C	1260	1248		1204
Forming temperature (viscosity = log5 in dPas) in °C		1072		1094
Forming temperature (viscosity = log6 in dPas) in °C		946		1010
Forming temperature (viscosity = log7/6 in dPas) in °C	825	805	884	915
Annealing point(viscosity = log13 in dPas) in °C	560	565	623 (13.2 poises)	715
Strain point (viscosity = log14,5 in dPas) in °C	518	513	571 (14.7 poises)	670
Sources	Schott 2017	Doremus 1994	Corning 2017	Doremus 1994
	Abrisa	Martlew		
	Technologies	2005		Martlew 2005
	2014			

Appendix 2: Composition of selected waste glass by category (XRF analysis)

<i>Blown, automated Green beer bottle (Stella)</i>		<i>Blown, automated Green beer bottle (Heineken)</i>		<i>Blown, automated Light green wine bottle (from USA)</i>	
Compound name	Content [wt%]	Compound name	Content [wt%]	Compound name	Content [wt%]
SiO ₂	73.34	SiO ₂	72.094	SiO ₂	73.360
Na ₂ O	12.41	Na ₂ O	12.039	Na ₂ O	12.704
CaO	9.925	CaO	10.704	CaO	11.313
Al ₂ O ₃	1.598	MgO	2.24	Al ₂ O ₃	1.220
MgO	1.454	Al ₂ O ₃	1.514	K ₂ O	0.455
K ₂ O	0.517	K ₂ O	0.419	MgO	0.382
Fe ₂ O ₃	0.341	Fe ₂ O ₃	0.368	Fe ₂ O ₃	0.323
Cr ₂ O ₃	0.175	Cr ₂ O ₃	0.208	Cr ₂ O ₃	0.051
BaO	0.055	MnO	0.169	TiO ₂	0.047
TiO ₂	0.051	S	0.056	S	0.043
S	0.029	TiO ₂	0.047	BaO	0.021
MnO	0.026	Cl	0.039	Cl	0.017
PbO	0.018	BaO	0.029	ZrO ₂	0.015
SrO	0.016	SrO	0.019	P ₂ O ₅	0.015
P ₂ O ₅	0.015	ZrO ₂	0.018	MnO	0.012
ZrO ₂	0.014	PbO	0.013	SrO	0.011
ZnO	0.006	P ₂ O ₅	0.011	PbO	0.005
CuO	0.005	ZnO	0.010	ZnO	0.004
NiO	0.003	Rb ₂ O	0.002	Rb ₂ O	0.001
Rb ₂ O	0.002				

<i>Blown, automated</i> <i>Clear wine bottle</i> <i>(Riesling)</i>		<i>Blown, automated</i> <i>Clear</i> <i>(Coca cola)</i>		<i>Blown, automated</i> <i>Clear</i> <i>(Spa)</i>	
Compound	Content	Compound	Content	Compound	Content
name	[wt%]	name	[wt%]	name	[wt%]
SiO ₂	72.543	SiO ₂	73.529	SiO ₂	73.994
CaO	11.266	Na ₂ O	12.008	Na ₂ O	11.255
Na ₂ O	10.953	CaO	10.813	CaO	10.934
MgO	2.030	MgO	1.899	MgO	1.917
Al ₂ O ₃	1.683	Al ₂ O ₃	1.184	Al ₂ O ₃	1.300
K ₂ O	0.689	K ₂ O	0.211	K ₂ O	0.225
P ₂ O ₅	0.244	S	0.168	S	0.121
S	0.163	Fe ₂ O ₃	0.062	Fe ₂ O ₃	0.090
CeO ₂	0.114	BaO	0.027	Cl	0.034
Fe ₂ O ₃	0.071	Cl	0.027	TiO ₂	0.033
TiO ₂	0.065	P ₂ O ₅	0.021	BaO	0.028
BaO	0.048	PbO	0.020	SrO	0.015
MnO	0.034	SrO	0.013	P ₂ O ₅	0.015
Cl	0.030	ZrO ₂	0.010	ZrO ₂	0.013
SrO	0.021	ZnO	0.008	PbO	0.011
ZrO ₂	0.020			ZnO	0.006
PbO	0.017				
ZnO	0.012				

<i>Blown, automated</i>		<i>Blown, automated</i>		<i>Blown, automated</i>	
<i>Wine bottle mix</i>		<i>Wine bottle mix</i>		<i>Wine bottle mix</i>	
<i>Clear</i>		<i>Light blue</i>		<i>Light green</i>	
Compound	Content	Compound	Content	Compound	Content
name	[wt%]	name	[wt%]	name	[wt%]
SiO ₂	73.356	SiO ₂	72.628	SiO ₂	73.358
Na ₂ O	11.882	Na ₂ O	11.761	CaO	11.888
CaO	9.878	CaO	9.746	Na ₂ O	11.477
MgO	2.165	MgO	3.129	Al ₂ O ₃	1.305
Al ₂ O ₃	1.261	Al ₂ O ₃	1.603	MgO	1.013
K ₂ O	0.639	K ₂ O	0.661	K ₂ O	0.397
SrO	0.203	S	0.190	Fe ₂ O ₃	0.257
BaO	0.184	Fe ₂ O ₃	0.144	TiO ₂	0.073
S	0.143	TiO ₂	0.049	Cr ₂ O ₃	0.062
ZrO ₂	0.085	Cl	0.026	BaO	0.047
Fe ₂ O ₃	0.069	P ₂ O ₅	0.022	S	0.025
TiO ₂	0.045	ZrO ₂	0.017	SrO	0.021
Cl	0.031	ZnO	0.009	ZrO ₂	0.020
ZnO	0.024	PbO	0.008	Cl	0.018
P ₂ O ₅	0.021	SrO	0.006	PbO	0.016
PbO	0.013			ZnO	0.011
				P ₂ O ₅	0.010
				Rb ₂ O	0.003

<i>Blown, automated</i>		<i>Blown, automated</i>		<i>Mouth-blown</i>	
<i>Wine bottle mix</i>		<i>Champagne glass</i>		<i>Spruce Pine</i>	
<i>Green</i>				<i>Transparent blue</i>	
Compound	Content	Compound	Content	Compound	Content
name	[wt%]	name	[wt%]	name	[wt%]
SiO ₂	71.124	SiO ₂	73.241	SiO ₂	71.768
Na ₂ O	12.903	Na ₂ O	12.862	Na ₂ O	14.288
CaO	11.072	CaO	10.883	CaO	6.834
Al ₂ O ₃	2.875	Al ₂ O ₃	1.621	Al ₂ O ₃	2.306
K ₂ O	0.882	MgO	1.277	CuO	2.038
Fe ₂ O ₃	0.446	S	0.149	Fe ₂ O ₃	0.835
MgO	0.239	TiO ₂	0.052	ZnO	0.759
Cr ₂ O ₃	0.211	Cl	0.027	K ₂ O	0.380
TiO ₂	0.070	K ₂ O	0.025	BaO	0.355
P ₂ O ₅	0.045	P ₂ O ₅	0.022	Sb ₂ O ₃	0.161
Cl	0.044	ZrO ₂	0.013	MgO	0.133
S	0.038	SrO	0.008	ZrO ₂	0.046
BaO	0.025			Co ₃ O ₄	0.040
SrO	0.017			S	0.040
ZrO ₂	0.009			SrO	0.012
				P ₂ O ₅	0.005

<i>Mouth-blown</i>		<i>Mouth-blown</i>		<i>Float glass</i>	
<i>Spruce Pine</i>		<i>Spruce Pine</i>		<i>PPG Starphire</i>	
<i>Transparent orange</i>		<i>Transparent clear</i>		<i>(extra clear)</i>	
Compound	Content	Compound	Content	Compound	Content
name	[wt%]	name	[wt%]	name	[wt%]
SiO ₂	73.144	SiO ₂	74.610	SiO ₂	74.563
Na ₂ O	15.393	Na ₂ O	13.595	Na ₂ O	13.323
CaO	7.093	CaO	7.356	CaO	8.905
Al ₂ O ₃	2.058	Al ₂ O ₃	2.037	MgO	3.006
ZnO	0.886	ZnO	0.908	S	0.105
BaO	0.411	BaO	0.450	Al ₂ O ₃	0.035
K ₂ O	0.411	K ₂ O	0.388	Fe ₂ O ₃	0.015
MgO	0.258	Sb ₂ O ₃	0.218	Cl	0.014
Sb ₂ O ₃	0.223	MgO	0.157	K ₂ O	0.012
Fe ₂ O ₃	0.027	Er ₂ O ₃	0.123	P ₂ O ₅	0.010
ZrO ₂	0.024	S	0.062	ZrO ₂	0.007
S	0.023	Fe ₂ O ₃	0.054	SrO	0.005
PbO	0.021	Cl	0.016		
SrO	0.012	SrO	0.013		
Cl	0.010	P ₂ O ₅	0.007		
P ₂ O ₅	0.005	Ag ₂ O	0.005		

<i>Float glass</i> <i>PPG clear</i>		<i>Float glass</i> <i>PPG furnace waste</i> <i>Aquamarine</i>		<i>Float glass</i> <i>PPG furnace waste</i> <i>Light green</i>	
Compound name	Content [wt%]	Compound name	Content [wt%]	Compound name	Content [wt%]
SiO ₂	74.214	SiO ₂	73.108	SiO ₂	67.410
Na ₂ O	12.438	Na ₂ O	14.346	Na ₂ O	13.676
CaO	10.029	CaO	7.888	Al ₂ O ₃	8.828
MgO	2.859	MgO	3.947	CaO	5.943
Al ₂ O ₃	0.142	Al ₂ O ₃	0.311	ZrO ₂	2.975
Fe ₂ O ₃	0.124	S	0.159	MgO	0.431
S	0.084	Fe ₂ O ₃	0.087	TiO ₂	0.213
K ₂ O	0.043	K ₂ O	0.078	Fe ₂ O ₃	0.171
P ₂ O ₅	0.038	TiO ₂	0.035	S	0.101
Cl	0.024	ZrO ₂	0.014	SrO	0.089
SrO	0.005	Cl	0.013	K ₂ O	0.073
		P ₂ O ₅	0.009	HfO ₂	0.055
		SrO	0.005	P ₂ O ₅	0.020
				Cl	0.015

<i>Potash-soda-lime</i>		<i>Potash-soda-lime</i>		<i>Lead Crystal</i>	
<i>Optical</i>		<i>Optical</i>		<i>Schott LF5</i>	
<i>Schott B270 lenses</i>		<i>Czechoslovakian bowl</i>			
Compound	Content	Compound	Content	Compound	Content
name	[wt%]	name	[wt%]	name	[wt%]
SiO ₂	71.802	SiO ₂	82.632	SiO ₂	53.731
Na ₂ O	10.138	Na ₂ O	6.488	PbO	36.643
K ₂ O	6.275	CaO	4.146	K ₂ O	5.387
CaO	5.168	K ₂ O	3.200	Na ₂ O	3.771
ZnO	2.198	MgO	2.755	Al ₂ O ₃	0.198
Al ₂ O ₃	2.083	SO ₃	0.281	SO ₃	0.134
TiO ₂	1.765	Al ₂ O ₃	0.219	CaO	0.114
Sb ₂ O ₃	0.403	Cl	0.100	NiO	0.018
MgO	0.041	TiO ₂	0.060	P ₂ O ₅	0.005
BaO	0.030	Fe ₂ O ₃	0.045		
Cl	0.022	PbO	0.028		
S	0.018	P ₂ O ₅	0.023		
P ₂ O ₅	0.017	ZnO	0.010		
Fe ₂ O ₃	0.016	ZrO ₂	0.009		
ZrO ₂	0.008	Rb ₂ O	0.004		
SrO	0.006	Br	0.002		
Rb ₂ O	0.005				
PbO	0.005				

<i>Lead Crystal</i> <i>G210</i>		<i>Lead Crystal</i> <i>D'Arques 24% Lead</i> <i>Bowl</i>		<i>Alkali-barium silicate</i> <i>CRT computer screen</i> <i>(panel)</i>	
Compound name	Content [wt%]	Compound name	Content [wt%]	Compound name	Content [wt%]
PbO	47.002	SiO ₂	63.229	SiO ₂	61.505
SiO ₂	44.714	PbO	24.799	SrO	8.056
K ₂ O	3.936	K ₂ O	7.753	BaO	8.039
Na ₂ O	3.296	Na ₂ O	2.842	Na ₂ O	7.210
S	0.231	CaO	1.200	K ₂ O	6.776
Pb ₂ O ₃	0.215	S	0.075	ZrO ₂	3.587
CaO	0.212	Al ₂ O ₃	0.051	Al ₂ O ₃	2.304
Al ₂ O ₃	0.203	ZrO ₂	0.026	CaO	1.109
Cl	0.086	Fe ₂ O ₃	0.024	TiO ₂	0.378
MgO	0.060			Sb ₂ O ₃	0.343
Fe ₂ O ₃	0.046			MgO	0.296
				SO ₃	0.153
				Fe ₂ O ₃	0.095
				CuO	0.055
				Cl	0.028
				ZnO	0.027
				P ₂ O ₅	0.023
				NiO	0.018

*Borosilicate**Schott lab glassware*

Compound name	Content [wt%]
SiO ₂	93.024 *
Na ₂ O	3.548
Al ₂ O ₃	2.725
K ₂ O	0.513
Cl	0.051
ZrO ₂	0.049
Fe ₂ O ₃	0.036
TiO ₂	0.033
P ₂ O ₅	0.012
ZnO	0.005
SrO	0.002
Rb ₂ O	0.002

*Alkali-aluminosilicate**Mobile phone screen**thin glass*

Compound name	Content [wt%]
SiO ₂	63.062
Al ₂ O ₃	12.958
K ₂ O	11.120
MgO	6.235
Na ₂ O	5.603
ZrO ₂	0.843
CaO	0.062
S	0.039
Fe ₂ O ₃	0.027
Cl	0.017
TiO ₂	0.014
HfO ₂	0.013
P ₂ O ₅	0.006
SrO	0.002

* Boron not traced, therefore, the Si content appears high.

Duran composition according to (Heimerl 1999) SiO₂ 80, B₂O₃ 13.