The increased thermal performance of a structural cast glass brick wall

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by

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In partial fulfilment of the requirements for the degree of
Master of Science
in Building Engineering
at the faculty of Civil Engineering,
Delft University of Technology,

Student number:	4371712
Date:	December 10th, 2020
Graduation committee:	prof. ir. Rob Nijsse (chairman) prof. James O'Callaghan dr. ir. Martin Tenpierik ir. Telesilla Bristogianni (supervisor)

Acknowledgements

This thesis is written in partial fulfilment of the Master Building Engineering at the TU Delft. Writing a thesis is an immense task, in which various people have supported and assisted me. Last year has been a rollercoaster, with several lockdowns during my thesis. This thesis could not have been completed without the help of some very important people. Therefore I would like to take a moment to thank all those involved.

First of all, I would like to thank my graduation committee Rob Nijsse, James O'Callaghan, Martin Tenpierik and Telesilla Bristogianni for their knowledge and expertise. I want to thank you all for your enthusiasm, patience and time. I am very grateful for everyone being able to adapt to online tutoring and everyone's compassion in these odd times.

In particular Martin Tenpierk, for the opportunity to perform tests in architecture, knowledge regarding the building physic, for your critical opinion and all the feedback. It was very helpful to have a different point of view, with lots of new insights.

Also, I would like to thank Fred Veer for providing the opportunity to do shear tests in the laboratory. Even though our tests were postponed a lot due to lockdowns, in the end, we managed to do them all. Your experience and input were very helpful and it is always a pleasure working with you.

Most of all, I would like to thanks Telesilla Bristogianni, not only for your help during the completion of this thesis but for all the incredible years we worked together. For over 3 years, you have given me so much enthusiasm, wisdom and time. I would not have achieved what I have today if it wasn't for you. From the endless hours in the Glass laboratory to all the daily conversations and feedback. You were there for every step in the road and for that, I will always be grateful.

Throughout my thesis, some individuals also supported me in various ways.

I would like to thank Sander for discussing and brain-picking for so many years. For taking the effort to read through my whole thesis and always be interested to discuss my progress.

Liza, Ronald, Kelly and Robin, for being my hideaway in all the lockdowns. Thank you for all the laughs and study sessions. It was nice to get out of my house and have a safe and fun place to go to.

Lisa, for all the emotional support and always being there for me. Not only regarding my thesis, but also on a personal level. I tremendously enjoyed all the endless phone calls and 1.5-metre-strolls around the city, to get my mind off writing for a bit. You helped me fight my way through my final deadlines by opening your home to me to work in and you always managed to encourage me to keep going, no matter what.

Dafne, for all her motivational and empowering speeches, critical thinking and for proofreading my thesis. Your opinion really helped me to improve my thesis even further.

Sven, for being a very understanding housemate, going through a lockdown together and providing a safe home workspace.

Puck, for some last-minute proof-reading. Your different background and critical comments improved my writing and allowed me to clarify where needed.

All the other friends, with whom I studied, complained and mostly relaxed. From weekly wake/snow/skateboard sessions to simply getting a drink and sharing a laugh. Thank all of you!

And last of all, my family, for the (financial) support, never losing trust and their patience.

I am proud of my final product, I have learned a lot during the process and I am mostly excited for what is to come. I am excited to continue within the fascinating world of structural glass and am curious what more it will bring me.

Mariska van der Velden
Delft, December 2020

Abstract

In the current built environment, the three main glass elements are glass window blocks, (structural) float glass and (structural) glass bricks. Float glass is the most used type of glass element and it is evolving from a skin material to a structural material. Glass hollow blocks became popular in the 1930s, but have lost their appeal due to little structural capacity and outdated aesthetics. A new and upcoming technique is the usage of cast glass bricks, which provides high structural performance without the use of substructures.

The 21st century is unmistakably characterized by climate change and the effort being put into the battle against it. It is the duty of engineers to design in a sustainable way. 'Sustainable' can be interpreted in many ways; the focus within this paper lies on the usage of recycled materials, the recyclability of the final product and the energy usage during the lifespan of the façade (linked to thermal performance).

When looking at the material itself, glass is a very recyclable material. This is widely done for glass bottles. However, the recyclability of float glass is very limited. Windowpanes and structural glass panes both consists of several layers of glass, combined with a PVB interlayer. Mostly, these combined panes are themselves processed further into insulated glass units, or IGUs. This end product consists of many different materials, that are hard to separate and for this reason, IGUs are seldom recycled at this moment. Additionally, not only the end product is rarely recycled, little recycled material is used for the production of float glass. The tolerances for using waste cullet in the production of float glass is very limited.

Since the lifecycle cannot easily be changed for float glass, it is interesting to look into cast glass. The production technique is different from the production of float glass. Glass is melted into a mould, rather than spread along a bath of tin. The latest research shows the possibilities of using glass cullet and thus casting waste glass. One opportunity that arises from this, is the development of waste glass bricks. One main problem of cast glass bricks is its thermal performance. Due to the lack of cavities, as present in IGUs or hollow glass bricks the thermal performance is not optimal, especially with the increasing need for high-performing facades to meet sustainability demands.

There are several strategies to improve the thermal performance of glass structures. The most simple solution for reducing the thermal transmittance is the introduction of air pockets or cavities. Air is a relatively good insulator, especially in small confined geometries. Convection reduces the thermal resistance of air and the bigger the air pocket, the more convection can occur.

Not only air can provide insulation, this can also be done with other materials. Inert gasses, like argon and krypton, have a lower thermal conductivity than glass, but are more costly and would require a more complex production process to fill the cavity and to ensure complete sealing. Translucent solutions can be achieved with materials like aerogel and glass fibres. Light transmittance is still present, but the result is not transparent. If transparency or translucency is completely ignored, traditional insulation materials, like rock wool and polystyrene, could increase the thermal resistance too.

Improvements can also be made with either reducing the amount of as long-wave, infrared energy going through the glass utilizing coatings or by reducing the conductivity of the glass itself by changing the molecular build-up. The glass recipe influences the thermal conductivity.

This thesis focuses on the thermal performance of cast glass bricks and in specifically the investigation of the impact of cavities on the thermal performance and the development of a relevant production method for cavity cast glass bricks. Air cavities can be added on either system-level or element-level. On a system-level, the design of a singular brick does not change, but the typology in which it is used does. Cavity walls with either a double brick wall or with an additional float glass wall will improve the thermal performance but will utilize a lot more material.

When changing the geometry of the brick itself, one or more cavities can be introduced to improve the performance. Since smaller cavities have a relatively better performance, multiple small cavities will automatically perform better than a singular larger cavity. Several designs are drawn, varying from a single or double cavity to an arrangement of glass shards, providing lots of encapsulated air pockets.

Thermal bridges within a design influence the overall thermal performance. The heat will choose the path with the least resistance, which is via the glass. It is possible to lengthen the path that the heat must undertake, by introducing multiple air chambers and increasing the overall thickness of the brick. This increased thickness will also aid the structural performance.

Creating multiple air pockets is directly linked to many glass-air transitions and thus a more complex geometry and production process. Producing such a brick with current standard manufacturing techniques would require glue. Glueing is not very environmentally friendly. The glue is not easily (if not impossible) to remove and therefore the final product is not recyclable. With experimental research, the potential of tack fusing glass is highlighted. This 'tack fusing' is done at a temperature below the actual fusing temperature, where the glass still creates a permanent bond, without relaxation and shape loss. This temperature lies around the dilatometric softening point of the specific glass type.

The potential of the tack fusing method is explored employing shear tests of fused specimens. Three types of specimens are tested: two different series of tack fused specimens at 650°C (1hr, 3hr dwell at top temperature) and one series of glued samples (DELO 4468) to be used as a reference. DELO4468 is a high-performance glue, which is mostly used for its high strength.

Nine design concepts are drawn, based on a solid brick of 200x200x100 mm. Seven element-based designs are limited within these boundaries since increased thickness (even with only glass) would lead to higher thermal performance. Two system-level alternatives are not in-depth researched but are still examined as reference. These two alternatives cannot be kept within these boundaries and are thus at increased depth of the finished wall. All nine designs are scored in a multi-criteria analysis. The main focus is the thermal performance and therefore the thermal transmittance of each design needs to be analysed.

This is for eight out of nine designs done with TRISCO, a steady-state 3D thermal analysis software. The last design, a fused shard brick, consisting of a random arrangement of random-shaped shards and is not easily modelled in 3D software. For this reason, it is not analysed in TRISCO but analysed through an experimental analysis. This experiment replicates a situation in which one side of the brick is warmer than the other while measuring the temperatures and heat fluxes. With these measurements, the thermal transmittance can be estimated.

The last part of this thesis is the multi-criteria analysis, or MCA, in which all alternatives are scored against several criteria. One of these criteria is the thermal performance, others are sustainability, producibility, aesthetical potential and transparency. The sustainability is scored against several checks, related to the recyclability and the required temperature for production. The producibility and the aesthetical potential is scored utilizing a small expert survey. Both criteria are subjective of nature, but by including the opinion of several experts, the outcome is inter-subjective. The transparency is scored regarding the number of refractive surfaces (because with each air-glass transition visibility is lost due to reflections) and the percentage of non-transparent materials in the cross-section.

The result of this thesis is not a single design, but insights in the potential of each concept. All designs are not ready for direct application but would require further structural verification and thermal optimisation, depending on the governing thermal requirements. There is not one perfect solution since each façade has different performance requirements, but the results do provide insights for an improvement from the current technologies.

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1. Introduction

This chapter will deal with the formation of this thesis. The inducement of the topic will be explained. The centuries-old material glass will collide with the everlasting need to make our buildings more sustainable. The material "glass" in architecture has been around for centuries, but with climate change comes the need for new technologies and changes. Secondly, personal motivation will be given for pursuing this specific topic for this research. Research objectives will be stated, followed by the main research question. The last part will deal with the methodology, in which the method 'Research through Design' is introduced and where the pros and cons of a multi-criteria analysis will be explained.

1.1. Context

1.1.1. Glass in architecture

Glass has been around in the built environment for centuries. The Romans started with 30-centimetre-small windows while nowadays the biggest panel available is around 22 meters long. The fascinating material has evolved from a skin material to a structural material. Traditionally, the windows were small and supported by mullions or frames. With upcoming techniques and knowledge, glass can now be load-bearing without a support structure. Increasingly, glass is being accepted as a structural material. In architecture, glass is often related to openness and lightness, a connection between inside and outside. Glass physically divides the outside from the inside, while visually allowing light to enter the building. This openness is the main reason why glass has become so popular. Glass windows are prevalent among modern architecture.

The three main glass technologies in the built environment are glass window blocks, (structural) float glass and (structural) glass bricks. Float glass is the most used type of glass element and it is evolving from a skin material to a structural material. Before, glass was mostly used to create transparency, to allow light to shine in, while the structure was made out of other materials. Nowadays, full-glass structures are appearing in present-day high-end architecture.

On oceangoing ships, in the age before electricity, glass skylights made from prisms could let natural light shine through, which reduced the risks of fire due to candles or oil lamps. Later, these prisms were widely used as sidewalk-embedded light vaults. In 1907, a German company patented a process in which a glass block was strengthened by fusing two sections into one. The centre was hollow, partially vacuum, which enhanced the insulating properties. In the 1930s, glass block windows became popular. Glass blocks, also known as glass bricks, became an effective architectural element in areas where privacy was desired while still admitting light. These blocks have their structural limitations and from these blocks, the modern-day structural bricks evolved. The hollow glass block is mainly found in older buildings and is not commonly used any more. Mainly because of their aesthetics and their poor structural capacity.

Another rising development within the structural glass field is cast glass bricks. These bricks are capable of transferring loads and are used in high-end architecture. *"Solid cast glass components are a promising solution for engineering pure glass structures of high transparency and load-carrying capacity; a solution that so far has been little explored in architecture."* (Oikonomopoulou et al., 2018) These cast glass bricks have a lot of potentials but are not yet widely used.

Figure 1 Three different glass technologies; hollow glass blocks, float glass and cast glass bricks (*Eckersley O'Callaghan - Engineers - Apple Fifth Avenue*, n.d.; *Glass Block Windows*, 2018; *MVRDV (@mvrdv) • Instagram Photos and Videos*, n.d.)

1.1.2. Glass as a sustainable building material

The 21st century is unmistakably characterized by climate change and its politics. It is the duty of engineers to design in a sustainable way. ‘Sustainable’ can be interpreted in many ways; the usage of renewable materials, designing a flexible building for multiple usages, using recycled materials, reducing the energy used during its lifetime, minimizing and responsibly disposing of waste, reduce the amount of transportation and many more. The number one contributor to climate change is greenhouse gas. By reducing the carbon footprint, the amount of greenhouse gas that is released into the environment can be reduced.

The future of glass structures will depend on the technologies invented to reduce the number of greenhouse gases. To be able to have cast glass brick walls ubiquitous in the future, the development of sustainable ways to build with glass bricks are inescapable. Within glass structures, there are two main strategies to become more sustainable; The lifecycle of the material and the performance of the structure.

When looking at the material itself, glass is a very recyclable material. This is widely done for glass bottles. However, the recyclability of float glass is very limited. The two products might seem very similar, but the chemical composition is different. The two products cannot be recycled together, because of their chemical composition (and melting point, etc.). Glass bottle industry can accept a bit of float glass cullet; however, the float glass industry can accept zero bottle glass cullet. Little recycled material is used for the production of float glass, due to the tolerances for using waste cullet in the production of float glass.

Not only in the production itself, but in the end-of-life stage of float glass, little recycling occurs. Windowpanes and structural glass panes both consists of several layers of glass, combined with a PVB interlayer. Mostly, these combined panes are processed further into insulated glass units (IGUs). This end product consists of many different materials, that are hard to separate and for this reason, IGUs are seldom recycled at this moment. Single float glass panels could be recycled, but recycling float glass into bottles is downcycling, which is unfavourable. Manufacturers creating bottles have invested in the equipment needed to crush bottles and melt them. This infrastructure, combined with the effort put into the collection of bottle glass waste, is vital to make recycling work. Also, float glass comes in a variety of types, like low-iron, ultra-clear, coated, tinted tempered, heat-strengthened. All these different subsets of window glass also cannot all be combined to create a new product. For this reason, the industry is not focused on recycling float glass. Thus, every pane is made from new raw material, and after its lifetime, the glass is going to waste.

Since the lifecycle cannot easily be changed for float glass, it is interesting to look into cast glass. The production technique is different from the production of float glass. Glass is melted into a mould, rather than spread along a bath of tin. The latest research shows the possibilities of using glass cullet and thus casting waste glass. One opportunity that arises from this, is the development of waste glass bricks. Within the research into glass bricks, a trend arises to make the brick interlocking. This interlocking mechanism can resist shear forces, without the usage of glue. This is in terms of sustainability a big improvement. The bricks are replaced more easily when damaged and can be reused.

Another way to improve the sustainability of glass structure is by enhancing the performance and its energy efficiency. The importance of energy consumption of a building cannot be neglected. The EU has established a legislative framework to boost the energy performance of buildings. The European Directive 2010/31/EU, Article 9.1, states that all new buildings will have to become energy neutral by 2020 (2018 for public buildings). The sum of the energy required for the operation of a building must be compensated by the net gain of energy by a building. This has shown positive results on the energy performance of buildings. Since rules on energy efficiency have been introduced in national building codes, buildings of today consume only half as much as typical buildings from the 1980s. (Erban, 2012; Fernbas, 2019)

The biggest issue with cast glass bricks, compared to IGUs, is the lack of thermal insulation. Glass is a fairly good conductor and lets through a lot of heat. Glass brick facades are thus not a sustainable solution when it comes to energy use. To make bricks a candidate for float glass in modern-day society, the thermal performance needs to be improved.

1.2. Motive

The particular interest in glass originates from my bachelor thesis. My topic was *“Design of an all-transparent cast glass column”*. This was my first introduction with structural glass and after that, I knew what I wanted. It combines engineering, designing and a bit of architecture. I have worked in the glass laboratory ever since, became a tutor of the Structural Glass course and did an internship in London at Eckersley O’Callaghan, a marvellous company specialised in glass structures made of float glass. The ingenuity when working in the laboratory is what triggered me most to dive into cast glass for my thesis, and not float glass. I enjoy working with a hands-on approach, where prototyping places a centric role in the design, which also contributed to the choice of subject.

1.3. Scope

The focus of this thesis is the thermal performance and in specifically the investigation of the impact of cavities on the thermal performance and the development of a relevant production method for cavity cast glass bricks. The structural verification lies outside the scope of this thesis, due to a broader exploration in the thermal performance. For sustainability, four aspects are considered:

1. the thermal performance (thermal transmittance or U-value) which influences the energy usage during the lifetime of the building
2. the material usage in the production of the brick (the implementation of recycled materials)
3. the required energy for production
4. the recyclability of the end product

1.4. Research objectives

The main research objective is to understand how the thermal performance of a structural cast glass brick can be improved compared to existing designs while maintaining structural performance and taking into account the producibility and sustainability of the product. In this thesis, the potential of several alternatives will be analysed, employing both prototyping, measurements and computer analyses.

The following objectives can be distinguished:

- Investigate the recyclability of current glass products
- Investigate strategies for improving the sustainability of cast glass bricks
- Generate design alternatives with this improved sustainability
- Investigate the potential of alternatives by assessing the value of each alternative

1.5. Research questions

These objectives can be translated into one main research question, which can be subdivided into sub-questions.

“How can the sustainability of a structural cast glass brick wall be increased, in both thermal performance and production process?”

1. What strategies exist to improve the thermal resistance and thus the overall energy usage of the façade?
2. How do these strategies translate in design concepts and how are these designs produced?
3. Which design concept has the highest potential for improving the sustainability of cast glass brick walls?

1.6. Methodology

For this research, five conventional research strategies exist:

1. survey;
2. experiment;
3. case study;
4. grounded theory approach;
5. desk research.

However, for this research, an upcoming research strategy seems most applicable: research through design.

Table 1 Strategies and key decisions **(Verschuren et al., 2010)**

type	breadth or depth?	quantification or qualification?	empirical or theoretical?	theory-oriented or practice-oriented?
survey	breadth	quantitative	experimental = empirical literature = theoretical	both
experiments	breadth	quantitative	empirical	both
case study	depth	qualitative	empirical	practice-oriented
grounded theory approach		qualitative	empirical	theory-oriented
desk research			theoretical	

1.6.1. Research through design

Design and research were seen as separate endeavours in the past, in which design resides in industrial practice and craft and research is focusing on academic experiments and reflection. However, in recent years, 'research through design' is making its way in the academic field, in which both parts are perfectly balanced and solidify each other.

Table 2 Clarification of terms 'research' and 'design'

	research	design
purpose	general knowledge	specific solution
result	abstracted	situated
orientation	long-term	short-term
outcome	theory	realization

Research and design both aim to create something, yet they differ. Where research aims to develop knowledge in the form of theory that can be transferred onto new minds, design focuses on a more specific solution to a problem, in which the outcome does not lie in the transfer of the knowledge but only in the realization of the product. Lots of information lies within the product, that goes to waste without the literature to understand it. Combining both research and design leads to "new" methodologies that can benefit from both fields. In modern literature, both 'research *for* design' and "research *through* design" exist (Figure 2).

Many design approaches require research, like interviews, literature reviews, measurements etc. Gathering and applying this relevant scientific and technological information aids the design and for this reason, it is referred to as 'research for design'. Studies are conducted in which the research supports merely the design, not the opposite.

The second application is 'research through design', in which design activities play a formative role in the generation of knowledge. 'Design' is used as a tool within the 'research'. Most typically, a prototype is developed (often mistaken for a 'product'), that plays a central role in the knowledge-generating process. The designing act of creating a prototype is in itself a potential generator of knowledge. An important step is that this knowledge does not disappear into the prototypes but is looped back into the platform (e.g. a publication or thesis). The prototype on itself is not a transmitter of knowledge. (Stappers & Giaccardi, 2013)

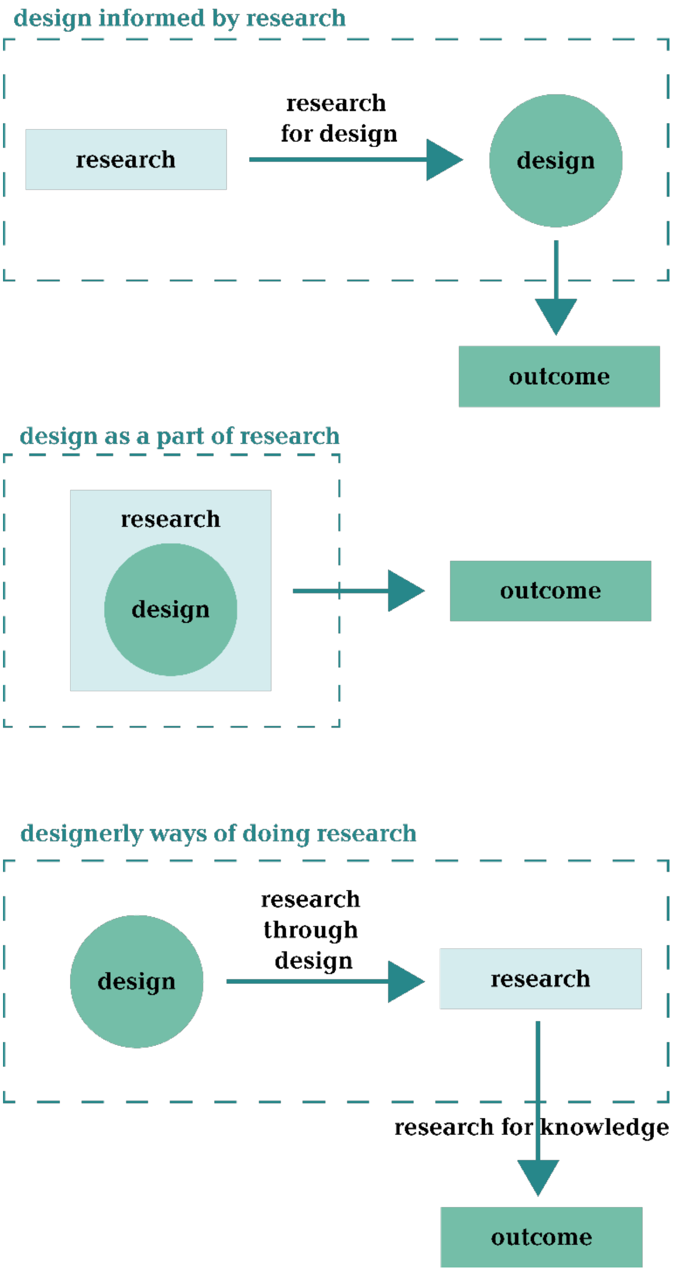


Figure 2 Difference between 3 types of collaboration between research and design, originally from (Stappers & Giaccardi, 2013)

1.6.2. Multi-criteria analyses

An important aspect of the design approach is a multi-criteria analysis (MCA). An MCA is decision procedure, in which first a set of goals or objectives are identified, weights are attached to each objective and the alternatives are scored according these objectives. All steps required in an MCA are:

1. Define the context
2. Identify the design alternatives
3. Set objectives or goals and define criteria
4. Weigh these criteria based on their relative contribution and importance
5. Score alternatives per criteria
6. Calculate the values by multiplying the score by the weight

(Hertogh & Bosch-Rekveldt, 2015)

MCA techniques are used to order alternatives from most desirable to least desirable, based on several criteria. The outcome can be the single most preferred option, to limit the number of options or to simply have the entire list. There are lots of different MCA techniques nowadays, which is mostly due to the:

- many different types of decisions in different circumstances
- variation in the time available to undertake the analyses
- variation in the amount and/or nature of the original data
- influence of the analytical skill level of those making the decisions
- need of administration depending per organisation

A standard feature of multi-criteria analyses is a performance matrix in which each row describes a certain option or alternative and each column represents its score. The individual performance assessments are often in cardinal numbers (numerical, colour coding, percentage), but may also exist as binary terms (ticks, bullet points) or qualitative terms. In the most basic analyses, this performance matrix might prove sufficient and be the final product from which the decision-makers assess which entry will be chosen. This intuitive processing of data is very time-efficient and effective for simpler projects, but for more complex projects it can cause incorrect ranking of options. For this reason, mostly an additional step is required, in which all values are converted to numerical values and each criterion is weighted according to its relative importance.

The scoring is best suited for further analyses when they are a numerical score on a predetermined scale. A numerical scale from 0 to X is the most common scoring. The highest number leads to the most preferred (hypothetical) option. It is not required that the highest score is achieved within the analysis.

Numerical weights are defined to balance the importance/influence of each criterion. Some criteria might be more decisive for the final product than others. The higher the assigned weight, the more impact the score on this criterion will have on the final evaluation.

(Great Britain & Department for Communities and Local Government, 2009)

Multi-criteria analyses and Research through Design as a whole have some pitfalls, to which the researcher must pay attention.

Important in scientific research, and thus also in research through design, is the systematic development of alternatives. This can be recognized by a ‘starting point’ from which (preferable) one variable changes every time. In this way, it can be more clearly concluded which variable has the most influence on the design. If random designs are generated, it would prove impossible to analyse.

Attention must be paid to determining the characteristic criteria. A balance should be ensured because the method lends itself easily to deception. Certain aspects can be unjustly emphasized by an ever-increasing breakdown of criteria and therefore emphasis on certain objectives. In this way, for example, one main aspect can be further broken down and two important criteria can be summarized in one criterion. This results in an unbalanced scoring system, in which the first criteria has a huge advantage over the ones that are combined in a simple criterion. The reverse is of course also possible.

Dominance occurs when one option scores average on all criteria and rigorously better in at least one other criterion. This can lead, in principle, to one option dominating all others. Luckily, this is in practice not very likely. When it does occur, it is helpful to investigate whether or not there is some advantage in the dominated option that is not represented by the criteria. This can result in criteria that were neglected before.

Another problem could be the scoring itself. Some criteria can be distinct, with clear numerical values that followed from calculations or measurements. However, it is also possible and sometimes inevitable that less objective criteria are introduced. These subjective criteria are hard to substantiate with good reasoning and can be prone to inaccurate scoring or ‘guessing’. If the researcher favours a design over others, or if benefits if a certain design is chosen, it could lead to ‘unfair’ scoring. A possible solution for this problem is an ‘inter-subjective’ approach, in which the opinion is gathered from people with expertise in a certain field of study. This relatively small survey, combined with the opinion of the researcher can lead to a more substantiated scoring. This will never reach full objectivity but aims to improve the subjective nature of the criteria.

2. Theoretic framework

To be able to improve the thermal performance, it is important to further deepen the knowledge within building physics, the properties of the material and current technologies. This chapter is divided into six paragraphs. First, the literature will be used to understand all general processes within the building physics and how insulation can improve the thermal performance of buildings. Secondly, this will be supplemented by basic characteristics and the thermal properties of the material glass. The third paragraph shows all current structures and technologies, after which in paragraph four, the thermal performance of these technologies are compared. Fourthly, the focus will be on which applications glass has nowadays and how these different types of glass are produced. This is necessary to be able to understand the sixth paragraph; the recycling opportunities and challenges within the material glass.

2.1. Building physics and insulation

2.1.1. Transfer of energy

Heat is a type of energy. It will flow from areas with a high temperature to areas with a lower temperature, trying to reach an equilibrium. Heat can be transferred in three different ways: convection, conduction and radiation.

Convection is heat flow due to bulk movement of molecules within fluids, both gases and liquids. Convection cannot occur in solids, because molecules are not able to move freely within the material. When looking at the heat transfer of a structural element, convection is mostly characterised by airflow on the surfaces. Air passing a hot surface will absorb some of this heat and carry it with it.

Every object or body with a temperature higher than 0 K (-273 °C) will emit heat through radiation as electromagnetic waves. These waves will be converted to heat when touching another material. The emission of radiation can take place without a medium, i.e. the sun can heat the earth through the vacuum of space. Heat radiation is caused by long-wave electromagnetic waves. When these waves touch a surface, it will partly be reflected and partly absorbed, rarely passing through. Glass is opaque for long-wave radiation, but transparent for short-wave radiation. Short-wave light comes through the glass and once that light is converted to long-wave infrared radiation by materials indoors, it is unable to escape back through the window, causing the inside to heat up. The term ‘greenhouse effect’ originates from the wide usage of this principle in greenhouses, however, it is unfavourable for buildings in hot summers.

Conduction occurs because of internal energy passing through a medium. Heat is translated within a material as the movement of particles. These particles collide with surrounding particles and cause those to vibrate as well. This is called thermal conduction. Conduction takes place in all phases of solids, liquids and gases. The heat transfer coefficient λ is the amount of heat flow transfer through a medium of one meter thick, over an area of one square metre with a temperature difference of 1 Kelvin. The lower this value, the higher the resistance.
(van der Linden et al., 2017)

2.1.2. Climate classification

One of the most widely used climate classifications is the Köppen climate classification, invented by German-Russian climatologist Wladimir Köppen in 1884. The Köppen climate classification divides climates into five main climate groups, with each group being divided based on seasonal precipitation and temperature patterns.

A: **Tropical climates:** the all-year-round monthly average temperature is at least 18°C and with significant precipitation.
B: **Dry climates:** little precipitation, there is a distinction between hot and cold dry climates
C: **Temperate/ mesothermal climate:** the coldest month has an average between 0 °C and 18 °C and at least one month averaging above 10 °C.
D: **Continental/ microthermal climates:** the coldest month has an average below 0 °C and at least one month averaging above 10 °C
E: **Polar and alpine climates:** the all-year-round monthly average temperature is below 10 °C

Generally speaking, the need for insulation changes within these types of climates. The type of insulation needed is dependent on the boundary conditions of the climate.

For example, within a polar climate, buildings benefit from bulky, heat-resistant insulation. Insulation is needed to keep the heat inside the building. The heat loss can be further diminished by using air and moisture barriers and thus ensuring that air gaps are sealed properly. The main focus lies thus on insulation against heat loss, the thermal transmittance of the envelope.

The opposite of this is a very hot climate (tropical and hot dry climates), where the biggest issue is keeping the heat outside, minimizing the solar gain. Reflective insulation and sun shading are needed to prevent the building from heating up like a greenhouse and ventilation can help to cool down the building. The main focus lies on reducing the solar gain, the g-value of the envelope. However, if the building is actively cooled with an A/C system, the thermal transmittance becomes important to keep the cool air inside.

Some areas have a climate between these two, which is a mild climate. A balance has to be found regarding the type of insulation, as part of the year will be spent at keeping the warmth in, whereas the other part at keeping the heat out. Combination-type of insulation will be needed to be able to function within both situations.

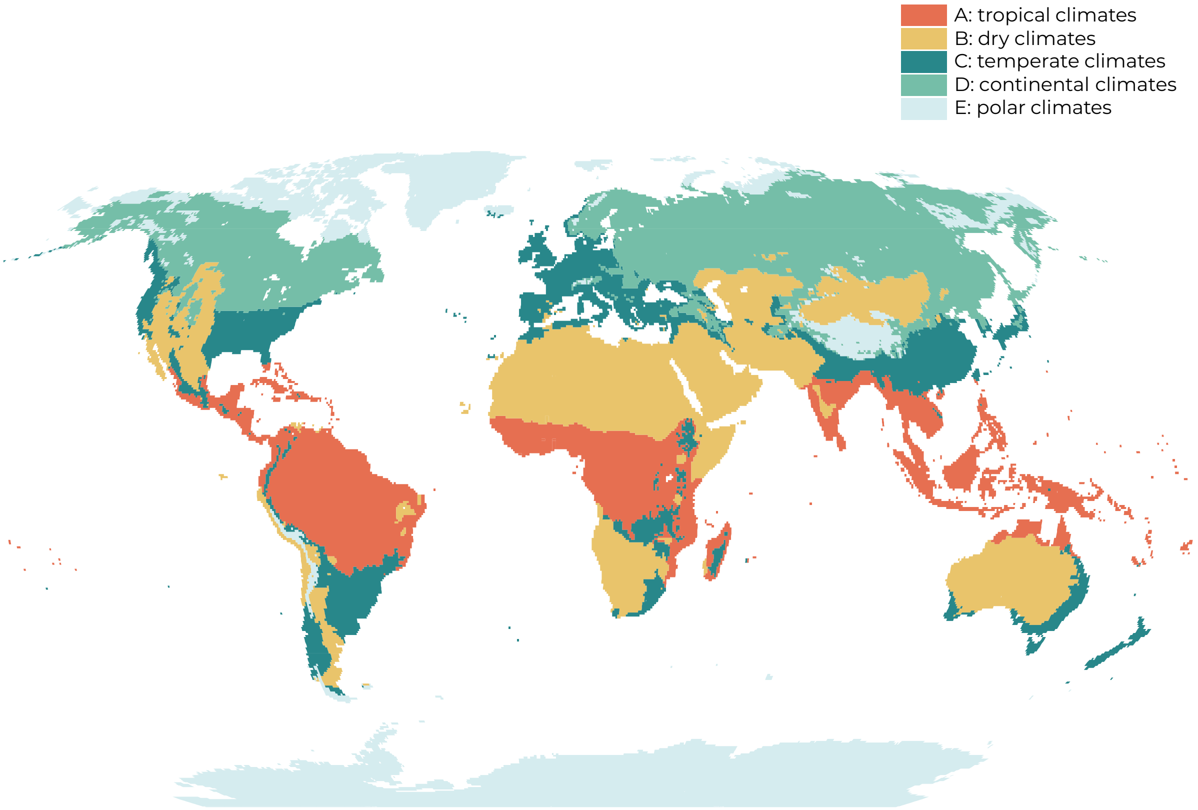


Figure 3 Simplified Koppen-Geiger climate classification map, originally from **(Kottek et al., 2006)**

Figure 3 (Kottek et al., 2006) shows a world map with a simplified version of the Köppen-Geiger classification. The five main groups are normally subdivided into several categories. To illustrate a general overview, this subdivision is not shown. Concerning this thesis, the focus will lie in temperate and continental climates, in which thermal insulation has the upper hand and solar gain in summers is often dealt with shading.

2.1.3. Thermal conductivity

The thermal conductivity λ can be defined by considering a piece of material (in this case: glass) with a thickness L and a cross-sectional area A. One face of the material is exposed to temperature T_1 and the other side to temperature T_2:

$$\boldsymbol{\lambda} = \frac{\boldsymbol{Q * L}}{\boldsymbol{A(T_1 - T_2)}}\ [\boldsymbol{W/mK}]$$

Equation 1

Q	*heat flow*	W
λ	*thermal conductivity*	W/mK
L	*thickness*	m
A	*cross-sectional area*	m^2
T_i	*temperature on one side*	K

Table 3 Thermal conductivity of various materials (Bansal et al., 1986; van der Linden et al., 2017)

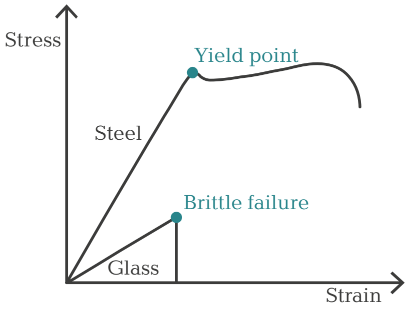
material	**thermal conductivity $\boldsymbol{\lambda}$ $[W/mK]$**	**thickness $\boldsymbol{d}$ $[m]$**	**heat resistance $\boldsymbol{R_m}$ $[m^2K/W]$**
concrete	2.0	0.2	0.1
chipboard	0.2	0.02	0.1
insulation material	0.04	0.1	2.5
glass	0.5-1.0	0.15	0.3-0.15

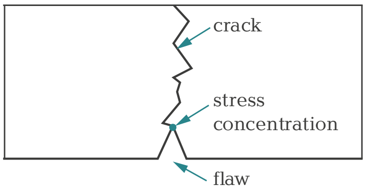
2.2. Glass properties

2.2.1. Mechanical properties

Glass is a brittle material. Brittleness is not a desirable property of a building material. Preferably, a material shows deformation or cracks before it fails, which is a warning signal to prevent accidents. Glass is not able to dissipate local peak stresses through plastic deformation as other materials do, since it does not have the capability of plastic deformation. Because of this, local imperfections lead to cracks and crack propagation.

Thus, the strength of a glass component does not depend on the ultimate compressive strength of the material, but the peak tensile stresses due to imperfections in the component. A relation between the strength of glass and the depth of the crack can be found. This relation is shown in Figure 6. (Schittich et al., 2007).





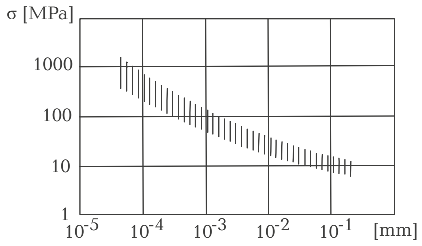


Figure 4 Stress-strain behaviour of glass, originally from (The Institution of Structural Engineers, 1999);
Figure 5 Crack development, self-illustrated;
Figure 6 Relationship between strength and crack depth, originally from (Schittich et al., 2007)

Table 4 Comparison of material properties (Schittich et al., 2007)

Property	Soda-lime silica glass	Concrete C25/30	Steel S355	Aluminium	Units
Density	2500	2500	78	27	kg/m3
Modulus of elasticity	70 000	26 700	210 000	70 000	N/mm2
Yield point	-	-	360	160	N/mm2
Tensile strength	~45	2.6	510	15	N/mm2
Compressive strength	700	25	-	-	N/mm2

Table 5 Comparison of material properties (Schittich et al., 2007)

Property	Soda-lime silica glass	Borosilicate glass	Units
Density (at 18°C)	2500	2200-2500	kg/m^3
Modulus of elasticity	70 000	60 000-70 000	N/mm^2
Poisson's ratio	0.23	0.2	-
Coefficient of thermal expansion	9×10^{-6}	$3.1 - 6.0 \times 10^{-6}$	K^{-1}
Thermal conductivity	1	1	$Wm^{-1}K^{-1}$

2.2.2. Durability

Glass is a durable material since it can withstand influences from its environment, like acid-resistance or scratches. The surface of glass has a scratch hardness of 5 to 6 on the Mohs scale. This is relatively high since gold, for example, has a hardness of 2.5 to 3 or steels 4 to 4.5. Mohs scale is comparing the hardness of a material relative to the hardness of diamond, which is considered to have a hardness of 10. (*Mohs Scale of Mineral Hardness*, 2017)

The definition of corrosion is: "*electrochemical oxidation of metal in reaction with an oxidant such as oxygen or sulphur*" (*Corrosion*, 2017). Glass is much more resistant to corrosion than most materials and almost resistant enough to consider it corrosion-proof. Glass windows can withstand exposure to the elements for years, remaining clear and can appear unaffected. Glass is however not fully corrosion-resistant. The alkali in the glass surface can (after a very long period of time) dissolve in water. A porous surface is left that consists of the silica network with holes where the alkali has been removed. This will result in a dull and less transparent surface, hairline cracks, and eventually crizzling. The porous surface protects the underlying glass for further corrosion and thus slows the rate of corrosion. Chemicals can speed up the corrosion time of glass. Nevertheless, only a few chemicals aggressively attack glass. (*Glass Corrosion*, 2018)

2.3. Current glass structures and technologies

There are many examples of glass structures and each design has its advantages and disadvantages. For this reason, not only glass bricks are examined, but also other design solutions.

2.3.1. Float glass

The most common glass usage in buildings is float glass. The lamination of glass provides a structure with significant load-bearing capacities. The main limitation of float glass structures is their size since production, transportation and installation limit the panel size. The price increases exponentially its increased size. Also, the connections between the panels are very critical and determine the strength of the total structure. This means that the reusability is very low since every panel has its specific size and type and location of connections. Laminated float glass is not very suitable for recycling either.

Characteristics

1. (optionally) insulated
2. When laminated and/or tempered, considerably high load-bearing capacity
3. Size limitations due to manufacturing
4. Need for connections
5. Not easily recyclable or reusable
6. Very transparent

Examples

Three examples are given, in different locations throughout the world, designed by three different engineering firms. Close to home, Octatube designed an all-glass entrance to the parking garage of Provinciehuis Noord-Holland. This structure is executed with steel spiders as connections. Part of the panels are working as a portal and one façade acts as a three-hinged frame.

The second example can be found in a desert climate, in Qatar. The enormous façade for the National Library is executed with corrugated glass panels. Two important aspects that ABT had to deal with was the climate and the earthquake resistance. All panels are heavily insulated and 50% is covered with a reflective silver frit to reduce the solar gain. The seismic load resulted in ingenious details in which all panels can slide through steel to steel oiled connection in both horizontal and vertical direction.

The last example highlighted here is the entrance for the Apple store on Piazza Liberty in Madrid. *"A curtain of water, created by a series of water jets running over eight-metre-tall glass panels, provides both a focal point for the amphitheatre and a striking entrance to the Apple store beneath it.* (*Apple Piazza Liberty*, n.d.) This is an excellent example of a very minimalistic glass structure, bonded with structural silicone. By using structural silicone to bond the glass panels for the two glass structures, the need for fittings and holes was minimized, which ensured a clean aesthetic while also keeping the design cost-effective

Figure 7 National Library of Qatar, ABT (*OMA-Designed Qatar National Library Nears Completion in Doha*, n.d.; *Qatar National Library*, n.d.)

Figure 8 Provinciehuis Noord-Holland by Octatube (*Provinciehuis Noord-Holland*, n.d.)

Figure 9 Apple Piazza Liberty, Milan by Eckersley O'Callaghan (*Apple Piazza Liberty*, n.d.)

2.3.2. Glass hollow blocks

The glass block may be considered out of style by some, but the technique is quite effective when it comes to insulating properties and assembly ease. The light transmittance and transparency are very dependent on surface finishing. Some products have on purpose distorted image formation, to increase privacy. The biggest downside of these blocks is the lack of sufficient load-bearing capacity. Substructures are needed to support these blocks and mortar is needed to glue the bricks together and hide some assembly components. Each brick is only transparent perpendicular to the surface.

Characteristics

1. Considerable insulation value
2. Almost no load-bearing capacity
3. Not easily recyclable
4. Substructure needed
5. Mostly with distorted image, still transparent

Example

Mostly these blocks are used in smaller projects, such as residential buildings. However, Renzo Piano managed to design a skyscraper with hollow glass blocks. The result is a stunning tower with a mesmerizing façade at night. The diffused light creates an interesting pattern, still providing some privacy. The main structure of the building is a steel structure, executed with viscous dampeners to limit horizontal sway. The façade consists of roughly 13.000 blocks, each 450x450x120 mm. This building allows for deformations during an earthquake, to prevent peak stresses in the glass blocks.

2.3.3. Adhesively bonded glass structures

Modern computer-aided calculations allow for the usage of solid cast glass bricks without the need of a (steel) support structure. The glued bricks have some disadvantages regarding sustainability and assembly ease. The glue used for the Crystal House in Amsterdam is UV-curing and leaves room for little tolerances. This makes the installation a tricky and time-consuming process. Since glue cannot be replaced or dismounted, the use of glue is not considered very sustainable.

Characteristics

1. Low insulation value
2. Considerable load-bearing capacity
3. Not easily reusable or recyclable, due to permanent connection type
4. Less clear image formation than windowpanes, but still quite transparent

Examples

The Atocha memorial in Madrid is an 11-metre-high monument with a nearly elliptical plan consisting of approx. 15.600 solid glass bricks joined with adhesives. The geometry of the brick was specially developed for this project and allows for a change in curvature. The thermal shock, induced by rainwater and sun, depends on several factors, including the temperature difference, the thermal expansion coefficient, the heat transfer coefficient between glass and rain and the thickness of the block. To limit the thermal shock, these bricks were fabricated in borosilicate glass, which has a significantly lower thermal expansion than regular soda-lime silicate glass. (Bos et al., 2008)

The P.C. Hooftstraat in Amsterdam is a luxurious shopping street, where the Crystal House is located. Previously housing Chanel, the building is now in use by Hermès. The principle is similar to the Atocha memorial, with bricks glued with UV-curing adhesive. The interesting aspect is the complete transformation of ‘regular’ windows to complete glass windows, including glass frames. This is done to mimic the original façade and building style. Also, a transition is visible from glass to clay bricks.

The last example in adhesively connected glass structures is the Crown Fountain in Chicago. The structure relies for its lateral stability and load transfer on the steel substructure. The frame holds all the glass blocks and transfers the load to the base with a truss-system. 22,500 glass blocks were subdivided into larger segments, later glueing all segments together.

Figure 11 Maison Hermès, Tokyo, by Renzo Piano (Behance, n.d.; Hendel, n.d.; Tokio Sell/Inhabit - Maison Hermès | Area, n.d.)

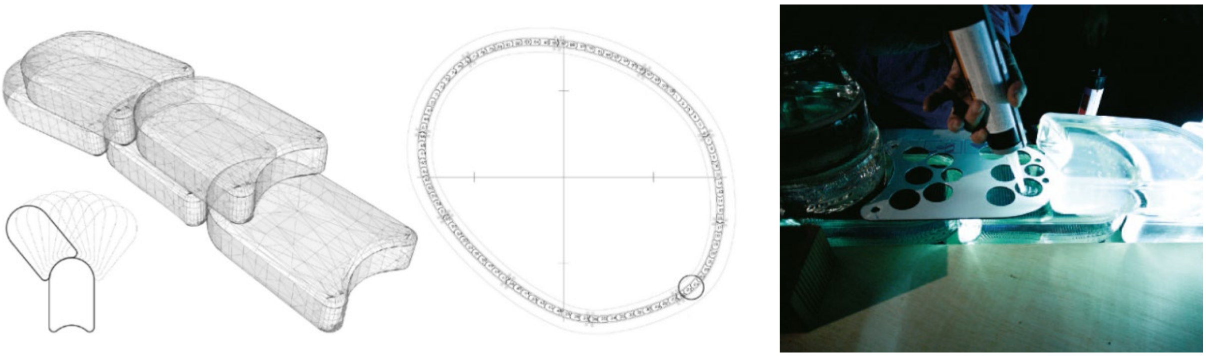


Figure 10 The brick used in the Atocha memorial [left] and the glueing process [right] (Hartman, 2008)

Figure 12 (MVRDV - Crystal Houses, n.d.)

Figure 13 ('Crown Fountain', 2019; *Crown Fountain, Glass Brick Wall, Tower Interior, July 23, 2004*, n.d.; *Gallery of The Crown Fountain / Krueck & Sexton Architects - 5*, n.d.)

2.3.4. Interlocking cast glass bricks

The structures mentioned in the previous paragraph, rely on a colourless adhesive or a steel substructure to keep the blocks together. The solution of a steel substructure is undesirable when it comes to transparency and elegancy. However, the adhesives are permanent, which results in a non-recyclable and a non-reversible structure. Concerning sustainability, this is a major weakness. For this reason, research is being carried out to explore the potential of a novel, reversible system employing dry assembly, interlocking cast glass components that can tackle the in-built limitations of current systems. Since this a relatively new development, these bricks have not been used yet in practice. Nevertheless, some design proposals will be discussed here.

Characteristics

1. Low insulation value
2. Load-bearing capacity considerable and yet to be proven in practice
3. More suitable for reusability and/or recyclability
4. Image distortion due to irregular connection surfaces, but still quite transparent

Examples

In the last couple of years, lots of research has been done in interlocking cast glass bricks and its potentials. Additionally, many designs have been summarized before, in papers and theses. Six examples are shown in Table 6, each designed to tackle the problem of using adhesive in glass bricks. The main principle of interlocking glass bricks is increasing shear resistance by creating non-horizontal contact surfaces. Concentrated peak stresses will occur in sharp corners, which results in organic-like and curved shapes.

The first three examples are designed by Oikonomopoulou and Bristogianni, as part of the research group at the TU Delft. The so-called osteomorphic brick is a flexible design which is applicable as walls, columns and corners. Some weight has been saved by concaving one surface, which results in a less image formation, but an interesting refraction pattern. The second has a bone-like second piece that locks two oval pieces with two recesses together. Their third design has curvature freedom due to the round shape of the interlocking area and round edges. (Oikonomopoulou et al., 2018; Scholtens, 2019)

Jacobs was inspired by the first osteomorphic brick, with curved contact surfaces. Since the geometry of a cast glass interlocking brick influences its mechanical properties, he determined the optimal values for the dimensions to maximize the shear resistance. The Lego-like design of Barou is a very common design principle, also used in concrete building blocks. This design is however less ideal considering the sharp edges and their risk to residual internal stresses and local peak stresses. Similar to the curved Lego-like brick from Oikonomopoulou and Bristogianni, de Vries designed a brick with a spherical interlocking contact area. However, within this design, the spheres are separated and not part of the actual brick. (Barou, 2016; de Vries, 2018; Erwin Jacobs, 2017; Scholtens, 2019)

Table 6 Comparison between the existing studies to interlocking cast glass components (Scholtens, 2019)

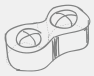
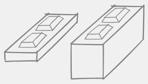
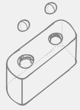
	Oikonomopoulou & Bristogianni 1	Oikonomopoulou & Bristogianni 2	Oikonomopoulou & Bristogianni 3	Jacobs	Barou	De Vries
Shape						
Suitable in external wall configuration	Yes	Maybe	Maybe	Yes	Yes	Yes
Shear force capacity	High	Moderate	Moderate/ high	High	Sufficient	Sufficient/ high
Homogeneous cooling in casting	Effective	Risk of internal residual stress	Effective	Effective	Risk of internal residual stress	Risk of internal residual stress
Redundancy	Yes	Yes	Yes	Yes	Yes	Yes
Ease of (dis)-assembly	High	Medium	High	High	High	Medium

Figure 16 Doggy bone interlocking brick (Oikonomopoulou et al., 2018)

Figure 14 Osteomorphic interlocking bricks (Oikonomopoulou et al., 2018)
Figure 15 Curved lego bricks (Oikonomopoulou et al., 2018)

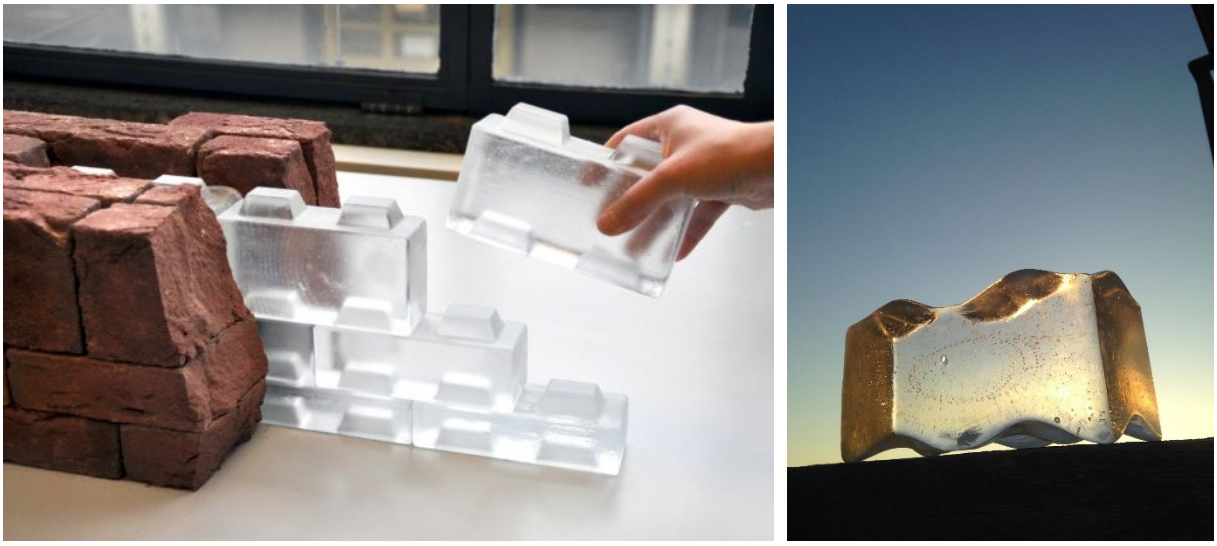


Figure 16 Restorative lego bricks (Barou, n.d.)
Figure 17 Interlocking brick by Jacobs (Erwin Jacobs, 2017)

2.4. Thermal performance of current structures and technologies

The thermal performance of cast glass bricks will be improved. Even though hollow glass blocks might have the reputation of being good insulators, the regular blocks score quite poorly. The argon-filled blocks score significantly better. In current building practice, the requirements increase for thermal performance due to global warming and climate change agreements. This results in stricter building regulations and thus the need for well-performing facades. Insulated glass units with HR++ certification scores the best within the glass facades. Insulated concrete cavity walls can perform even better, due to the lower thermal conductivity of the insulation material, lots of concrete mass and relatively high depth.

Table 7 Thermal transmittance of current technologies

Type	Characteristic dimension	thermal transmittance U [W/m^2K]
concrete cavity wall (not insolated) (1)	50 mm	1.9
concrete cavity wall (insulated) (1)	50 mm	0.6
	100 mm	0.35
solid glass brick	100 mm	2.94 (paragraph 6.3)
single glass pane (1) (2)	4	5.7
IGU (1) (2)	4-12-4	3.0
IGU HR++ (2)	0.5-1.2	1.2
hollow glass block (3) (4) (5)	80 mm	3.0-3.2
hollow glass block with argon (3) (4)	80 mm	1.5

(1) (van der Linden et al., 2017)
(2) (Stichting Kennisbank Bouwfysica, n.d.)
(3) (Betere isolatie voor je glasblokken | Energy Saving, n.d.)
(4) ('Sustainable Building', n.d.)
(5) ('Bouwglas Gesman', n.d.)

2.5. Types of glass and their applications

The term “glass” has no exclusive definition since it describes a wide variety of inorganic materials. Glass materials are amorphous, which is a result of fast cooling and solidification of the originally molten state. The fast cooling prevents crystallization, a process in which atoms, molecules or ions organize in a more thermodynamically favourable crystalline pattern.

2.5.1. Types of glass

In its purest form, glass consists of pure silica (SiO_2) and is called quartz glass. Pure silicate glass requires a melting point up to 1900 degrees Celsius. This highly energy-intensive process can be changed by adding other compounds. Silicon is responsible for forming the networks within the material and alternatives for silicon are boron and germanium. Network modifiers, alkali-oxides, are added as fluxing agents to lower the melting point of glass (i.e. sodium, potassium, lithium, calcium, magnesium, barium, strontium). The main types of glass, according to chemical composition, are soda-lime glass, lead crystal glass, borosilicate glass and electric glass (E-glass).

Soda-lime glass

The most common type of glass is soda-lime silicate. Soda-lime glass is used in the container industry, flat glass and domestic glass sector, which are the biggest contributors in the glass industry. To lower the melting point of silica, sodium carbonate is added. This results in a drop from 1900 to 1500 °C. Sodium decreases the chemical durability of the glass, resulting in glass corrosion. To counteract this corrosion, oxides are added to the recipe (calcium, magnesium and aluminium oxides).

Lead crystal and crystal glass

Characteristic for domestic lead and crystal glass products is its high brilliance and its sonority *(the condition or quality of being resonant or sonorous)*. Lead oxides are incorporated to increase the reflective index and the sorority. Lead oxides are also used, because it eases the workability of handmade glass products, due to the lowered viscosity and working temperature.

Borosilicate glass

Boron can be used to replace silicon, which will result in increased durability and resistance against chemicals, water and heat. The viscosity and liquidity are affected, and the production of fibres is facilitated by the boron. The high durability and resistances make borosilicate glass highly suitable for laboratory equipment and thermo-critical products.

Electric glass, or E glass

Electric glass or E glass is a special type of borosilicate glass where part of the boron trioxide has been replaced by aluminium oxide and is also characterized by a low alkali content (<2%). The specific electrical resistance of E glass is very high and therefore it is mainly used as an insulator for electrical wiring, as a product of continuous filament fibres.

(BREF, 2009; Rodriguez Vieitez et al., 2011)

Table 8 Major components of soda-lime glass, lead crystal glass, borosilicate glass, and E-glass (BREF, 2009; Rodriguez Vieitez et al., 2011)

	Soda-lime glass	Lead/crystal glass	Borosilicate glass	E-glass
Siliceous dioxide (SiO2)	74-75%	54-65%	70-80%	52-56%
Boron trioxide (B2O3)			7-15%	0-10%
Lead oxide (PbO)		25-30%		
Soda (Na2O)	12-16%	13-15%	4-8%	0-2%
or Potassium oxide (K2O)				
Lime (CaO)	10-15%			16-25%
Aluminium trioxide (Al2O3)			7%	12-16%

2.5.2. Glass manufacturing and usage

The glass industry is very diverse, with many different applications and branches. Glass is being used for many types of products nowadays. A typical classification is based on the six broad sectors of the glass manufacturing industry. These sectors are mentioned in Table 9 and visualised in Figure 18.

Table 9 Sectors of the glass manufacturing industry, applications, types of glass they are made of, and approximate production volumes in the EU-27 in 2007, data compiled from (BREF, 2009). Source: (Rodriguez Vieitez et al., 2011)

Glass manufacturing	Application or use	Type of glass
Container glass or packaging glass	75% beverage packaging 20% other food packaging 5% packaging cosmetics, pharmaceuticals and technical products	Soda-lime glass
Flat glass	95% float 75-85% buildings industry 15-25% automotive industry 5% rolled glass (wired or patterned)	Soda-lime glass
Continuous filament glass fibre	Roving, mat, chopped strand, textile, tissue, milled fibre (90% used for composite materials)	E-glass
Domestic glass	Tableware, cookware, vases, ornaments	Soda-lime glass Lead glass
Mineral wool	Insulation material	Borosilicate glass
Special glass (CRT not produced in EU anymore)	75% monitor glass 25% light bulbs/tubes, ceramic glass, high-temperature domestic glass	Soda-lime glass Borosilicate glass

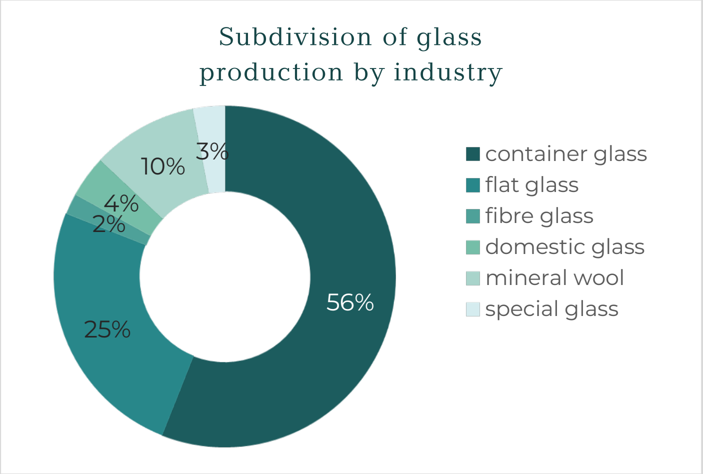


Figure 18 Sectors of the glass manufacturing industry, and their percentage contributions to the total production volume, self-illustrated with information from (BREF, 2009; Rodriguez Vieitez et al., 2011)

2.5.3. Typical manufacturing process of window glass

In order to create window glass from raw materials, several steps have to be taken. The following list describes the most common process to create glass windows:

i. Float line production
ii. Cutting and shaping
iii. Tempering
iv. Laminating
v. Coatings
vi. Fritting
vii. IGU assembly

Float line production

Raw materials are melted in a furnace at a temperature between 1300 and 1600°C, depending on the glass recipe and the manufacturer. While floating on a thin bath, controlled heating permits the glass to flow, allowing it to spread and create a flat smooth surface with a considerably uniform thickness. The thickness can be controlled by varying the rate at which the glass is drawn off the bath.

At the end of the tin bath, the glass will be slowly cooled on rollers in an annealing lehr. Annealing is a gradually cooling down process. When referring to annealed glass, it is generally used to describe float glass directly off the float line without further heat treatment.

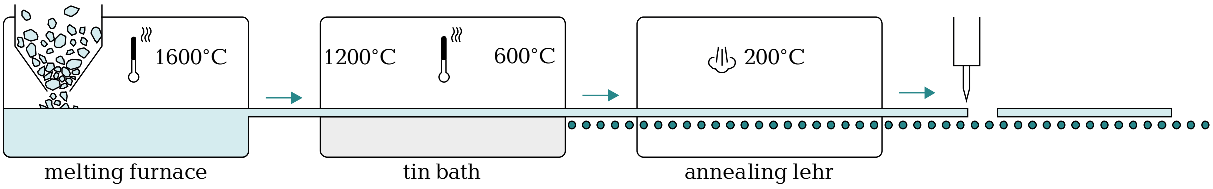


Figure 19 Float line process

Cutting and shaping

Float line production creates a continuous ribbon of glass, in which the process goes uninterrupted up to 15 years. When the glass comes out of the annealing lehr, it is cut to size. The glass edges are trimmed since they consist of imperfections as a result of the rollers that control the speed. Afterwards, the glass is cut to length.

Edge working can increase the strength of the final product, since fragile edges, prone to chip off, are sanded smoothly. This can be done in multiple shapes, preventing breakage, some not very suitable for structural purposed. The ground/polished edges are most common within laminates in the building industry, but other desired shapes can be produced. Drilling or shaping is typically undertaken before any heat treating for strength. (The Institution of Structural Engineers, 1999)

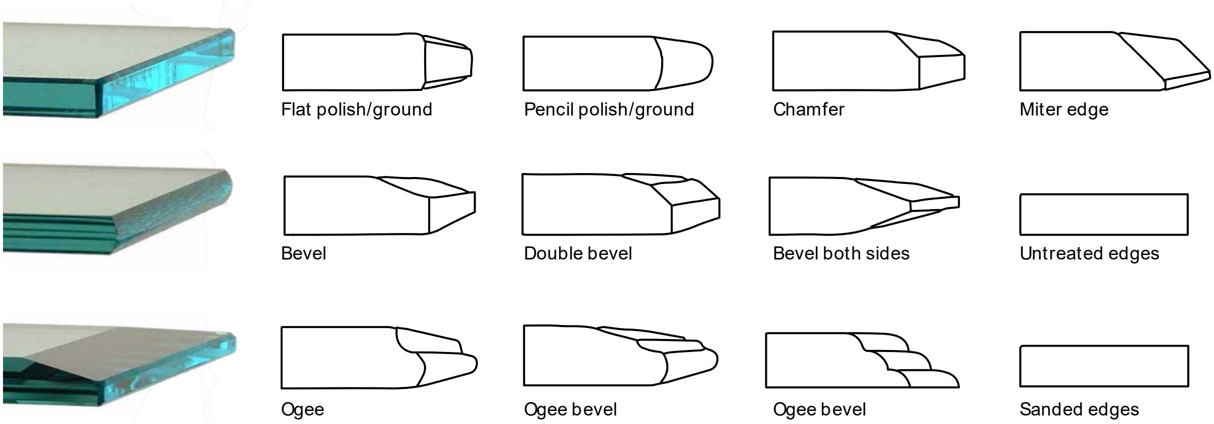


Figure 20 Edge post-production (*Glass Edge Finishes - A Cutting Edge Glass & Mirror*, n.d.; Louter, 2018a)

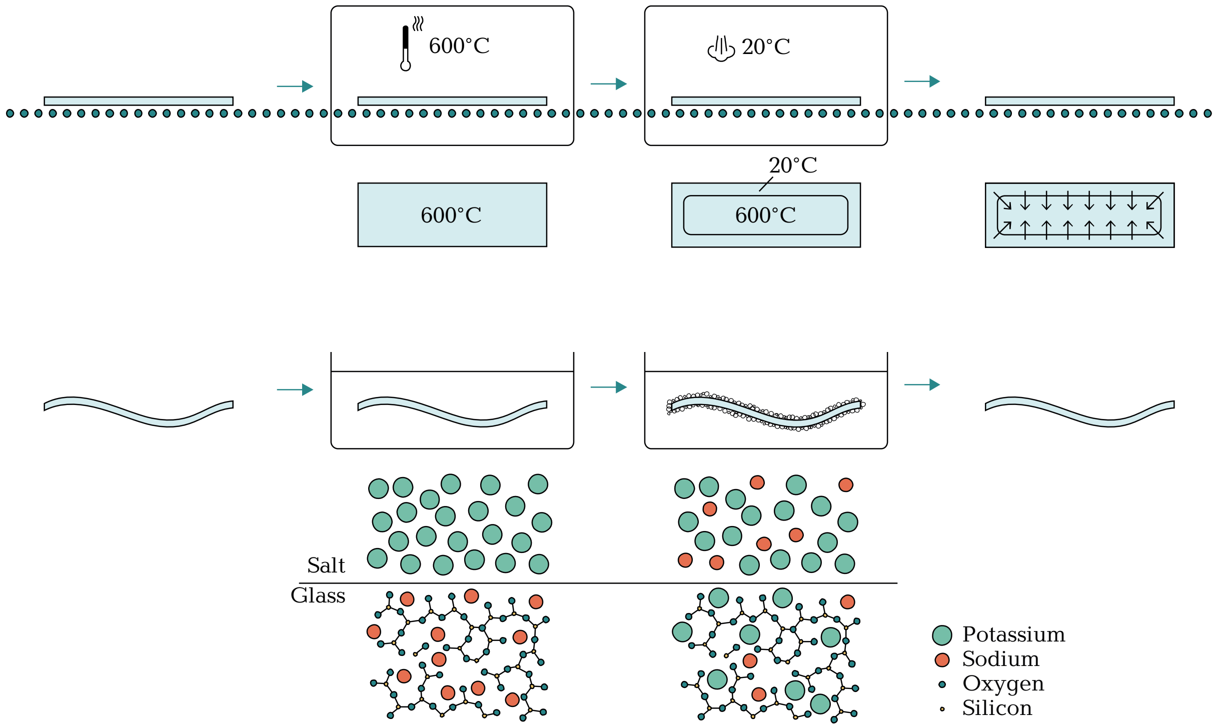


Figure 21 Tempering of glass

Tempering

Toughening or tempering is a strengthening process in which the surface characteristics of glass is changed to increase the tensile stress resistance. This can be done with either heat treatment or chemical treatment. Heat strengthening is a thermal treatment in which the glass is heated and then rapidly cooled. The outer edges are cooled down, while the inside is still hot. When the inside cools down over time, it tries to shrink and pulls on the already cold outer surface inwards. This puts the inner volume in tension and outer surface in compression. This surface compression closes the imperfections, with a higher overall tensile strength as a result. The tension inside the material influences the fracture pattern, resulting in small chunks of glass instead of larger sharp pieces. For this reason, tempered glass has a safer breaking pattern when it comes to reducing injuries. The disadvantage of this breaking pattern is the complete loss of shape.

There are two gradations of tempering: fully tempered and heat strengthened. Heat-strengthened glass is produced with the same process as fully tempered glass, but the cooling rate is lower. It has, therefore, a lower tensile strength than fully tempered glass. It has a fracture pattern more similar to annealed glass, which can be useful to maintain shape and stiffness after failure. Fully tempered glass has been mentioned above and has a higher tensile strength around 120 MPa compared to 40 MPa for heat-strengthened glass.

Strengthening can also be done with a chemical treatment. Glass can be treated in a potassium salt bath, which will result in a different residual stress profile. This bath is at 300°C and realizes ionic exchange. Large potassium ions in the molten salt replace the smaller sodium ions in the glass surface, which results in compressive stresses. These potassium ions are about 30% bigger. Chemical tempering is not common. It is mostly used for complicated geometry when thermal treatment is not suitable. Chemical treatment is not commonly used in the building industry, because the compression zone is very narrow and leaves little room for imperfections. Scratches penetrate the compression zone and result in a fracture. (Haldimann et al., 2008)

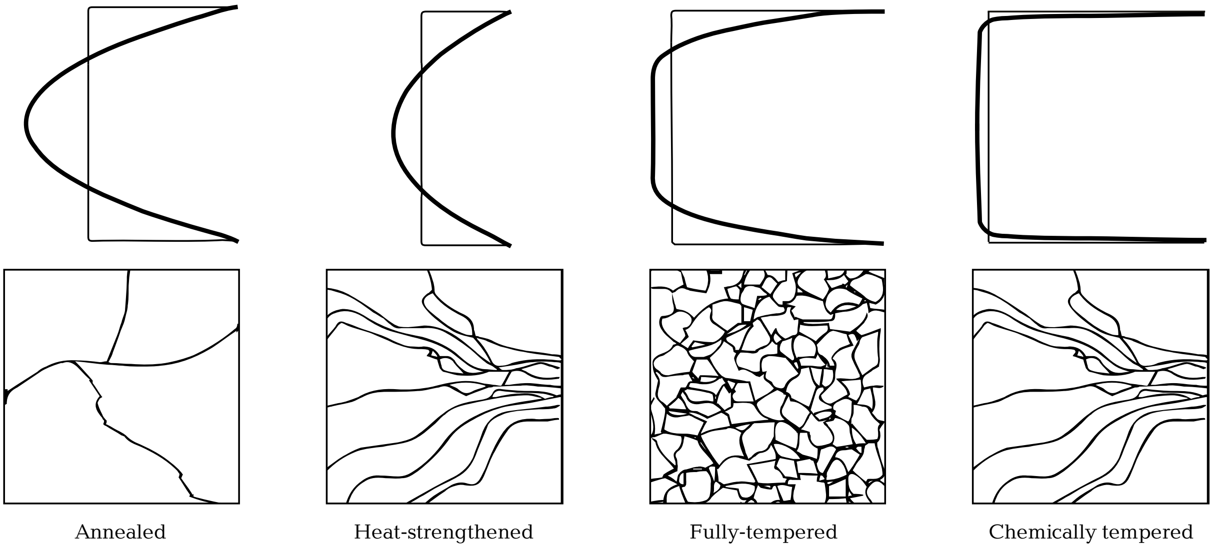


Figure 22 Impact of tempering on fracture patterns, originally from

Laminating

Laminating is a process in which two or more pieces of float glass are bonded using an interlayer. This interlayer can either be a type of plastic or resin. The main two reasons for lamination are increasing the safety performance and increasing the thickness (to a thickness not possible on float line production) to accommodate higher loads.

If a glass sheet breaks in a laminated panel, it will not directly fail. The other sheets that are still intact can compensate for the loss of a panel. Usually, three glass sheets are laminated, so two sheets protect the middle sheet. The broken sheets are still able to protect the underlying sheet, because of the bonding interlayer. It is also possible to add a sacrificial layer. This thin sheet of glass does not contribute to the structural performance and is glued onto the panel afterwards, which increases the replaceability. (Nijsse, 2003)

Glass coatings

Coatings to the glass are applied for several reasons, but particularly for the control of solar gains through the glass or improved thermal performance. Very fine layers of metal are sprayed onto the glass surface. *More in-depth information on coatings can be found in paragraph 3.2.1 'Coatings' on page 46.*

Fritting

For aesthetical, privacy or shading purposes, a frit can be printed onto the glass. Ceramic frits are painted onto the glass by screen-printing or digital printing and are then baked onto the surface during the tempering.

IGU assembly

Annealed glass from the float line can directly be used on site. However, nowadays insulated glass units are standard, to provide the thermal insulation to meet modern building regulations. IGUs are created by adding edge spacers between two glass panels, filling it with inert gas and sealing the edges. The edge seals utilise various polymer compounds to form an airtight seal around the perimeter of the unit.

2.5.4. Typical manufacturing process of hollow glass blocks

Glass blocks are made with similar raw materials as float glass; limestone, soda ash, sand and glass cullet. These ingredients are molten in a furnace at about 1500°C. A computerized system portions out enough material to make one half of a block, sliced off by automated shears.

The glob of glass is pushed down by a plunger into a mould, spreading the glass throughout the cavity, creating one-half block. If a surface finishing pattern is desired, the mould and/or the plunger can have a curved or waffled surface.

Ambient air blown onto the glass cools it down rapidly from 1000°C to 600°C in several seconds. At this temperature, glass is less prone to deform and handling of the product is eased. To ensure the glass temperature is kept constant, the block will then need to pass through several burners. A machine places two blocks facing each other while heating the edges to melting temperature. The two blocks are pushed together, forming an airtight seal.

The blocks are now transported through an annealing lehr, in which they are gradually cooled down to avoid cracking. The block is measured to make sure it meets all standards, in which digital alignment gauges are used to make sure both halves are flush. To increase the bonding capacity of the blocks to mortar, a liquid vinyl coating is sprayed onto the blocks. An inkjet printer labels all blocks with manufacturing date and code.

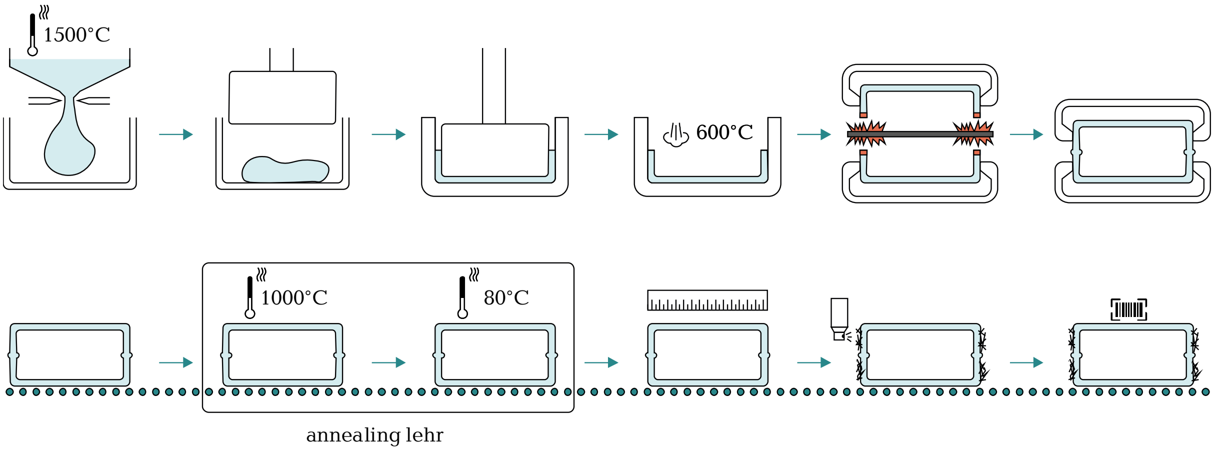


Figure 23 Production of hollow glass bricks

2.5.5. Typical manufacturing process of cast glass bricks

Typically, glass products are not manufactured with the casting method. However, within the technique lies the potential for an increase in the recycling of glass due to its tolerance for recycled cullet as input material. Float glass and hollow glass blocks only allow for a low cullet-to-raw materials ratio, whereas cast glass can achieve full cullet recycling.

Glass casting is a process in which molten glass is directed into a mould, where it cools down and solidifies. This can be done in several different ways, like kiln casting or hot pour/sand casting. First, the focus will lie on kiln casting. Kiln casting includes a mould that stays inside the oven during the whole melting process. This heat-resistant mould is often made of a mixture of plaster and refractory materials. “*A refractory material or refractory is a material that is resistant to decomposition by heat, pressure, or chemical attack, and retains strength and form at high temperatures.*” (‘Refractory’, 2020) To manufacture this mould, the ‘lost wax’ method is generally applied, in which a negative flexible mould of the model is created, oftentimes from silicone. This silicone mould can be used to produce wax copies of the original model. A heat-resistant stiff material is poured around this wax mould, creating a negative, from which the wax can be steamed out. The end result is a ‘disposable’ heat-resistant mould, that is demolished after usage, to release the final product. The mould either consists of a funnel-like top or a flowerpot on top, in which the glass granules, lumps or cullet are placed.

The firing of a glass element is a delicate process. Mistakes during this process will lead to inhomogeneous stress distribution or even failure due to cracking. The viscosity of glass influences the firing process tremendously. First, the glass should be heated to a viscosity where the glass can deform freely, to flow freely and take the shape inside the mould. During the heating process, the glass is dwelled two times, to homogenize the temperature within the mould and glass (and to dissipate stresses). At a temperature range of 827-1033°C, the glass is molten. Below this temperature, the Littleton softening point is encountered. Around this point, the glass starts to deform due to gravity. Temperatures inside the crystallization region should be avoided. For this reason, a rapid cooling down is necessary to avoid the formation of crystals, after which the annealing process takes place. During this process, a dwell time of multiple hours is necessary to dissipate the residual stresses in the glass. Below 480°C, the glass is stable and is cooled down more rapidly to room temperature.

When the prototype is taken out of the mould, it is not yet the final product. When the model comes out of the mould, it is not directly suitable for use. Possible overflow has to be sawn off, defects or imperfections have to be sanded and the surface has to be treated to create transparency. The treating of the surface can be done with two techniques. The best result will be achieved when the surface is polished. This removes the small irregularities that create the translucency. A polished model has a smooth, shiny and transparent appearance. A different approach is to cover the model with a resin or coating. This resin fills the small holes and creates a more transparent appearance. The result is not as smooth as a polished model, but it is less time-consuming and easier with difficult shapes that cannot be post-processed easily.

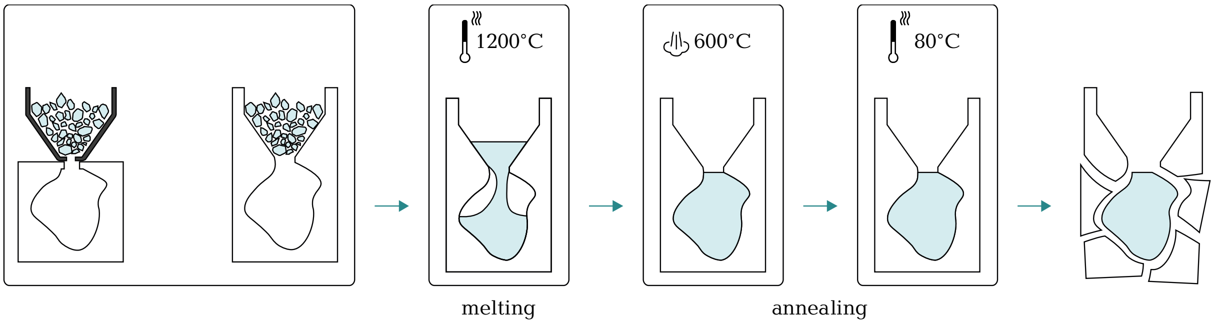
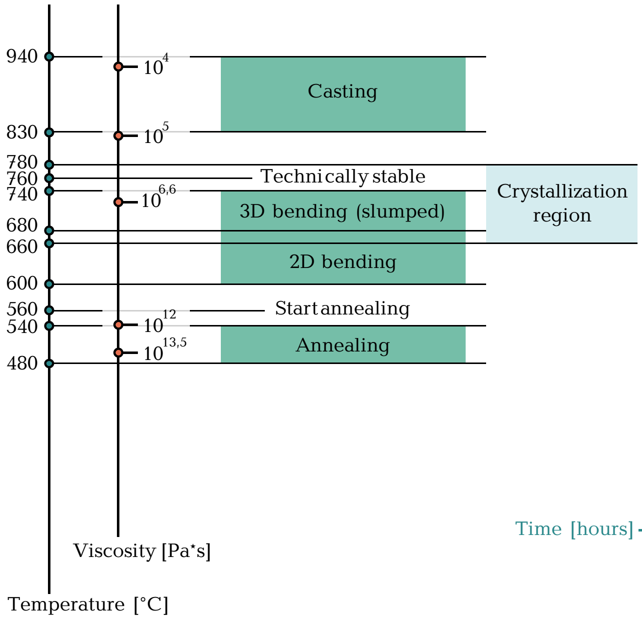


Figure 24 Casting steps



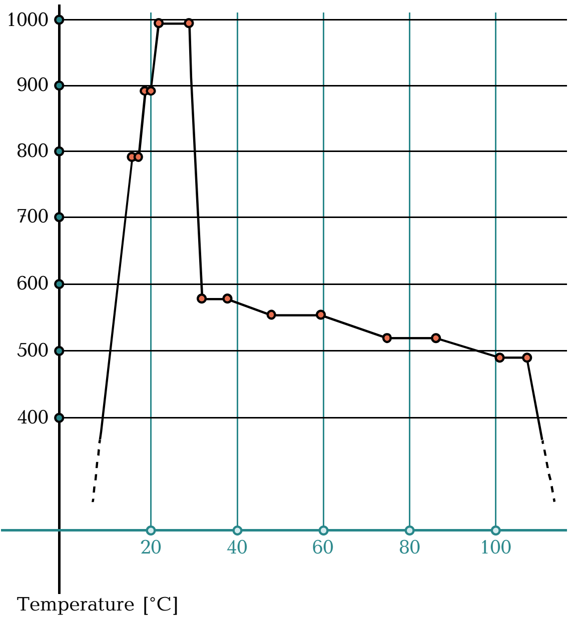


Figure 25 Temperature dependence of viscosity and corresponding workability of lens-glass (Bristogianni et al., n.d.)

Figure 26 Graphical representation of possible firing schedule, self-illustrated

The roughness of the mould determines the quality of the glass surface and thus the transparency. The former method is very suitable in a prototyping phase, due to the easy production of new shapes and moulds, but requires a lot of labour-intensive post-processing. For this reason, it is seldom used for mass production. Hot pour into steel moulds creates a more transparent product, which is more time-efficient. However, the production of steel moulds is less economically interesting for smaller batches.

2.6. The recyclability of glass

Glass in itself is a very recyclable material. However, post-processing of glass products can influence the recyclability. The recyclability is highly dependent on the final product and the investment of the industry in recycling infrastructure.

2.6.1. A circular economy

The influence of the scarcity of non-renewable resources on earth is increasing every year. Humanity is overusing the earth's natural resources and is currently living by a 'take, use, dispose' mentality. Every industry now has the challenge to change this and challenge themselves to aim for a better future. A perfect circular economy can exist in harmony with the earth without depleting its resources. Designers and engineers have to build more sustainable buildings and projects to tackle the problem and improve past behaviour. (DeBrincat & Babic, n.d.)

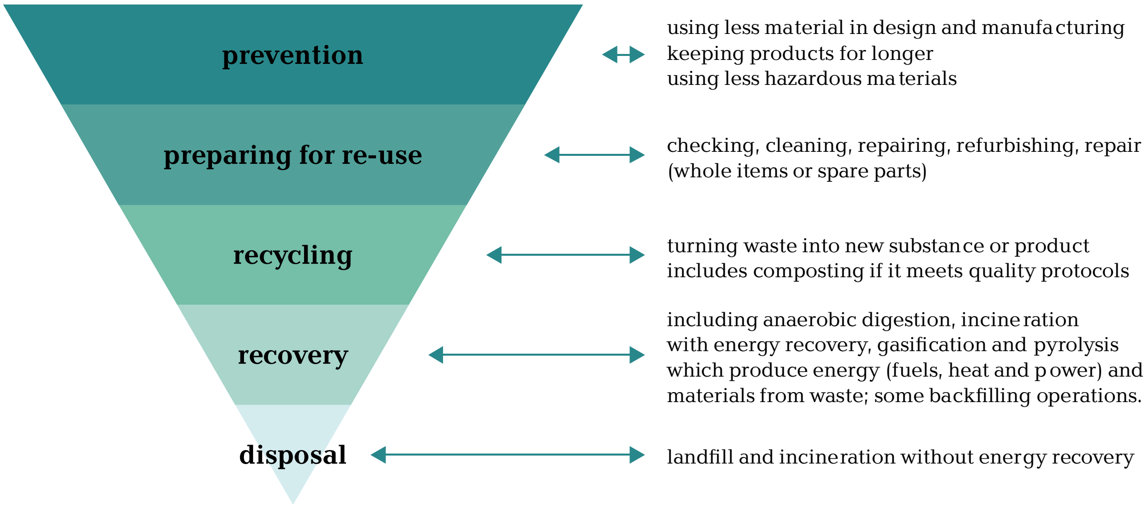


Figure 27 Waste hierarchy, originally from (DeBrincat & Babic, n.d.)

Closed-loop vs. open-loop

There are two types of recycling, open-loop and closed-loop recycling. Closed-loop recycling is a process focusing on the supply chain. All materials from the recycled product can be looped back into the manufacturing process. For closed-loop recycling, the manufacturing process is usually designed with recycling in mind. This is widely done in the beverage packaging, like glass bottles or aluminium cans. Aluminium can recycling is an example of a closed-loop recycling process because aluminium can be recycled to form new cans with little material degradation or waste creation. Regardless of what materials you have to recycle, sorting is important for a superior end result.

Open-loop recycling is a process in which the materials from the recycled product is not looped back into the same cycle but converted in new raw materials or waste products for other industries. Typically, materials are purposed differently than pre-recycling. The open-loop recycling industry is mainly focused on products which consist of various materials, from which each material is separated and has its own recycling loop. The recycling itself involves a process that can change the makeup of the material, through heat, chemical reactions or crushing. Open-loop recycling is often referred to as downcycling or reprocessing.

When comparing closed- and open-loop recycling, open-loop is more repeatedly criticised to be less valuable and sustainable. It is associated with a degraded value and loss of energy, whereas this does not have to be the case. When downcycling materials, lots of value and energy can be lost, but this is highly dependent on the product the materials are looped back into. Glass windows, for example, are seldom recycled and if recycled, heavily downgraded into aggregates. This unfavourable downcycling needs to be replaced by a more balanced open-loop process, in which the *value* of the recycled product is similar to the original product. Open-loop recycling can prove to be more environmentally efficient, depending on the criteria. For example, a closed-loop recycling option for a product may require more energy than the open-loop option, but this open-loop option requires more water for reprocessing, comparatively. ('Open-Loop vs Closed-Loop Recycling', 2018)

2.6.2. The lifecycle of bottled glass

The lifecycle of glass bottles is a perfect example of a closed-loop recycling process. At first, bottles are reused, which is the best scenario when it comes to material usage. Energy is needed to collect and clean the bottles, but the former is fully integrated into the infrastructure of supermarkets and industry and the latter is relatively little energy compared to the considerably higher energy-intensive process of remelting.

When the quality of the bottle is too poor for reuse, the glass is crushed into cullet and is remelted into new bottles. This recycling finishes the closed-loop of the bottling industry. However, unfortunately, not all bottles are collected. Some bottles end up in regular waste, due to incorrect handling of consumers. However, the collection percentage of glass bottles is considerably high.

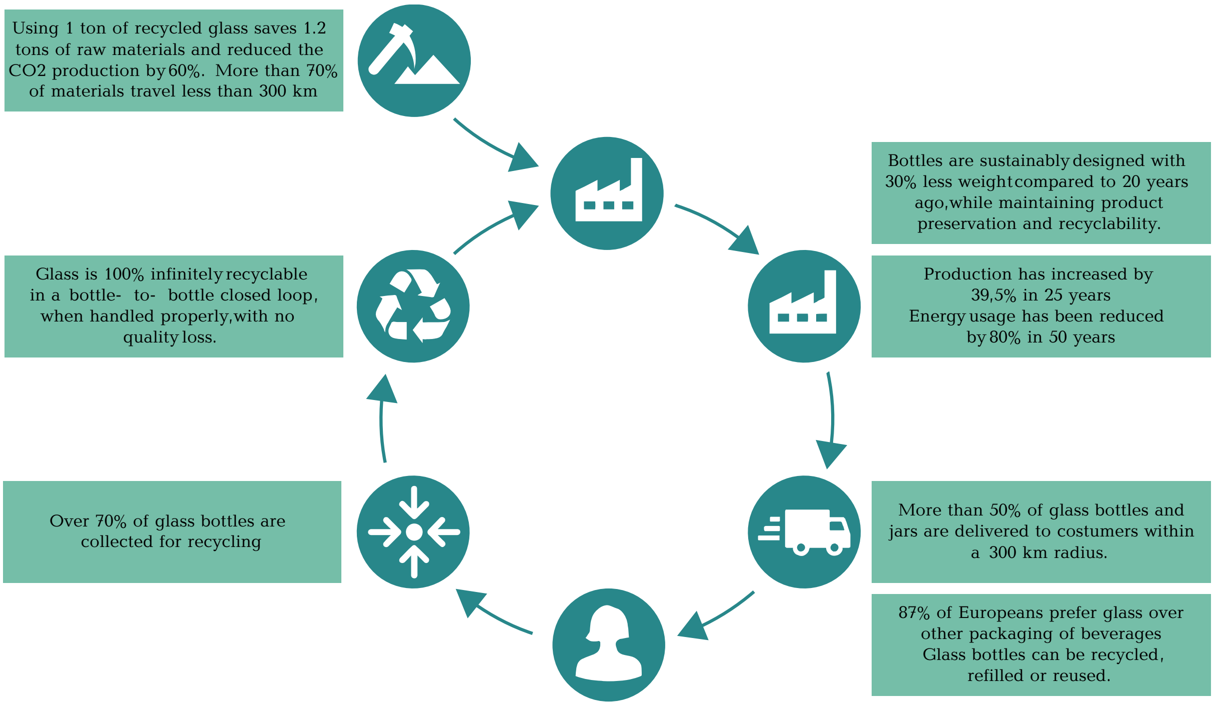


Figure 28 The closed-loop recycling of glass packaging (*Glass Packaging Closed Loop Recycling Up to 74% in the EU*, 2016)

2.6.3. The lifecycle of window glass

Influence of post-processing on the recyclability of window glass

As mentioned in paragraph 2.5.3 *'Typical manufacturing process of window glass',* steps included to produce glass windows are:

i. Float line production
ii. Cutting and shaping
iii. Tempering
iv. Laminating
v. Coatings
vi. Fritting
vii. IGU assembly

Each manufacturing step could introduce difficulties with recycling, which will be discussed here. Cutting and shaping of glass simply removes imperfections and thus not affect the recyclability. The influence of tempering is dependent on the type of recycling. When reaching very high temperatures, tempered glass does not have to affect the recycling. However, when looking at recycling at lower temperatures (remelting), tempered glass can significantly complicate this process. Combining tempered glass with float glass should be avoided.

Lamination has the biggest impact on the recyclability and is the main reason for the current lack of recycling industry. The interlayer can withstand high shear and thermal loads and does not easily dissolve in chemicals. This is particularly important for glass with a structural purpose, since this rigidity makes the glass durable. There is an uprising trend to develop machines that aim to separate glass cullet from the interlayer.

Laminated glass is crushed in the 'dry process' until all pieces reach granular state. Conventional glass crushers damage the interlayer, but some more innovative machines can remove 50 to 70% of glass cullet breaking the interlayer. The granular glass pieces are not contaminated with interlayer and can be recycled into new glass products. The crushed laminated glass plate undergoes separation or "wet process", which involves chemical stripping and tumbling to remove more glass fragments. This chemical solution separates the glass fragments from the interlayer, after which the fragments are washed off in a rotary drum. With this technique, neither glass nor interlayer gets damaged or changes its quality. After these two steps, 99.96% of the glass is removed and the interlayer can be recycled. (*Glass Recycling*, n.d.; *Shark Solutions - Glass Seperation*, n.d.)

Float glass manufacturers do not accept small granular glass cullet, since it is problematic in the production process, but container glass industry or cast glass production has more flexible tolerances. The separated PVB interlayer is also a valuable resource, which is utilized by the carpet tile industry. Methods not relying on pulverization are being developed, but do not have wide-scale usage yet. Delam, a company in Australia has patented a method in which flat and curved laminated panels are delaminated using heat, time and steam. This can be achieved with sized up to 1.8 metres by 3.5 metres.

Coatings have little to no influence on the recycling into float glass, since the temperatures are high enough to burn off the coatings. However, in cast glass, this is not the case. These coatings can affect the recycling process, depending on the type of coating and the ratio of coated glass cullet to clear glass. Some coatings can burn off in the remelting process at lower temperatures, while others are more problematic. Hard coatings might prove problematic due to nickel sulphide inclusions and heat-resistant coatings are not easily burnt off when the remelting temperature is not high enough. Frits use ceramic inclusions to create patterns. These ceramic inclusions make fritted glass unsuitable for recycling.

The assembly of glass panes into IGUs also has a high impact on the recyclability. The panes are separated with spacers and sealed at the edges. The edge seals utilise various polymer compounds to form an airtight seal around the perimeter of the unit. These seals are important to the performance and the service life of these insulating units. These spacers and seals make the recycling more labour intensive since these have to be removed before the glass is suitable for recycling.

Table 10 Glass processing effect on recyclability, adjusted, originally from (DeBrincat & Babic, n.d.)

Glass process	Recyclable to float line?	Recyclable in casting?	Notes
Annealed glass	Yes	Yes	Readily recyclable
Cutting and edge processing	Yes	Yes	No effect on recyclability
Laminating	Limited	Possible	Current methodology for delaminating reduces quality. Requires improved delamination processes to ensure stays in closed cycle level. Current methodology means laminated glass goes to container glass or mineral wool.
Heat strengthening	Yes	Yes	No effect on recyclability
Tempering	Yes	Limited	No effect on recyclability
Heat soak test	Yes	Yes	No effect on recyclability
Glass coating	Yes	Limited	No effect on recyclability
Ceramic printing and fritting	No	No	The current methodology does not allow for recycling of ceramic printed glass
Insulated glass units	Limited	Limited	Requires removal of the spacer bars and edge seals, limitations on the processing of individual panes as noted above
Low iron glass	Yes	Yes	Specifying low iron glass may require float manufacturers to reduce the recycled glass content to ensure a clear product is achieved. Further discussion with glass supplier on a project basis is required

Linear process of window glass

Due to current technologies and lack of infrastructure, window glass is not regularly recycled. It is mostly a linear flow, in which lots of energy and material go to waste. Very little product is now collected for downcycling, for example as aggregate fillings below asphalt highways. This way, the potential of the material is not used fully. The quality of the product diminishes tremendously.

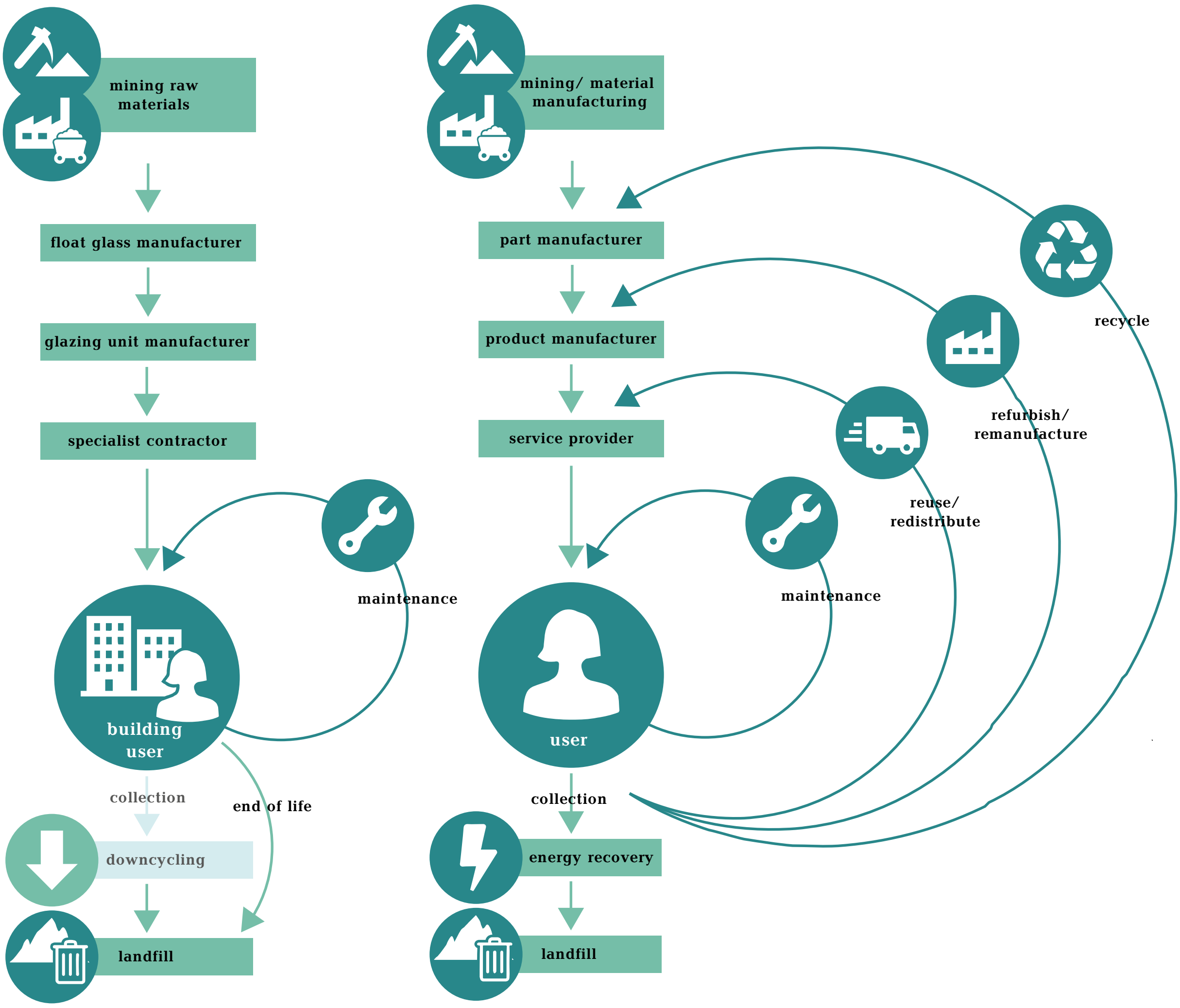


Figure 29 Circular economy and linear process of float glass, adjusted from ©Ellen MacArthur Foundation, originally from (DeBrincat & Babic, n.d.)

2.6.4. Optimizing the potential of waste window glass

The recycling industry where substantial opportunities lie ahead is the window glass industry. The material is not properly used to its full potential and lots of energy goes to waste. The problems arising with the closed-loop recyclability into new float-glass products are currently not easily solvable. Therefore, a different approach can be taken to extend the lifetime of the material.

Casting glass leaves room for wider tolerances, which is not possible within the float line production. When recycling window glass waste into bricks, the loop closes partially. Still, some material will be lost, due to the processing described before, but lots of material can be collected to be recycled back into a product that can be used in the building industry, rather than tremendous downcycling into the road infrastructure.

3. Strategy study for improving the thermal performance

In this chapter, some suggestions will be given for increasing the thermal performance of a cast glass brick wall, through reducing the thermal transmittance or solar gain. Most strategies will focus on the thermal transmittance, but some will deal with reducing the solar gain. Changing the thermal transmittance (U-value) can be done by either changing the properties, the design on element-level or by changing the typology of the entire wall (system-level). All design changes will be categorized within 'Cavities', 'Refracting light', 'Additional insulation ', 'Changing material properties' or 'Passive systems'.

3.1. Cavities

Still-standing air is a very good insulator, still standing air has a thermal conductivity as low as approximately 0.025 W/(mK) at room temperature and standard pressure. However, the thermal resistance of an air layer is reduced by the flow of air within the cavity: convection. The size and orientation of the cavity determine the thermal resistance. According to Eurocode NEN-EN-ISO6946, an unventilated air layer is one in which there is no express provision for airflow through it. Design values of thermal resistances are given in Table 11.

Table 11 Thermal resistance of unventilated air layers with high emissivity surfaces, originally from (Nederlands Normalisatie-instituut, 2008)

thickness of air layer $[mm]$	*thermal resistance* $[m^2K/W]$ **direction of heat flow**		
	Upwards	Horizontal	Downwards
0	0.00	0.00	0.00
5	0.11	0.11	0.11
7	0.13	0.13	0.13
10	0.15	0.15	0.15
15	0.16	0.17	0.17
25	0.16	0.18	0.19
50	0.16	0.18	0.21
100	0.16	0.18	0.22
300	0.16	0.18	0.23
NOTE Intermediate values may be obtained by linear interpolation.			

$$\lambda = \frac{d}{R_m}$$ Equation 2

$$U = \frac{1}{R_{tot}} = \frac{1}{R_{si} + R_{se} + \Delta T * \frac{A}{Q}}$$ Equation 3

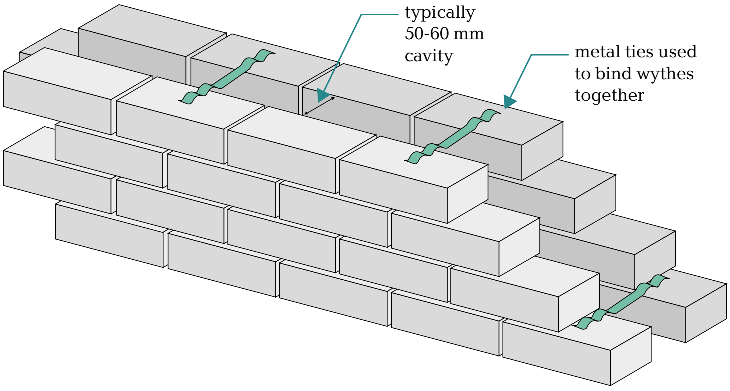
λ	*thermal conductivity*	W/mK
d	*depth*	m
A	*cross-sectional area*	m^2
Q	*heat flow*	W
U	*thermal transmittance*	W/m^2K
R_m	*thermal resistance*	m^2K/W
R_{si}	*internal surface resistance*	m^2K/W
R_{se}	*external surface resistance*	m^2K/W
ΔT	*temperature difference*	K

Table 12 Calculated thermal conductivity of unventilated air layers with high emissivity surfaces, originally from (Nederlands Normalisatie-instituut, 2008)

thickness of air layer d [mm]	**thermal resistance R_m [m^2K/W]**	**effective thermal conductivity λ [W/mK]**
0	0.00	0
5	0.11	0.0454
7	0.13	0.0538
10	0.15	0.0667
15	0.17	0.0882
20	0.18	0.1111
25	0.18	0.1388
30	0.18	0.1667
50	0.18	0.2777
150	0.18	0.8333

3.1.1. System-level insulation

The simplest solution for insulation is the system in which two elements are separated by air. This is common practice for mortar brick walls and insulated glass units (IGUs). In cavity brick systems, the inner and outer walls are called leaves (or wythes) and are interconnected using metal ties, as described in NEN-EN 845-1 (2016). These metal rods are essential for stability but have the disadvantage of introducing some cold bridges. (Skroumpelou et al., n.d.)



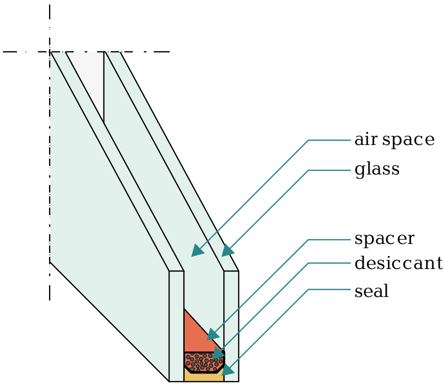


Figure 30 Typical cavity mortar brick
Figure 31 IGU section

3.1.2. Element-level insulation

Currently seen in hollow glass bricks, it is possible to insulate on an element level. The advantage of insulation on element level is the flexibility in application. Any configuration is possible and assembly is done fairly easy. However, each element can have cold bridges, which will occur more regularly than it can occur in system-level insulation. There, it is possible to minimize the number of cold bridges.

Similar to a cavity, bubbles or entrapped air can increase the insulation value. Each air pocket will have lower thermal conductivity and thus contribute to the overall decrease of conductivity. However, the big downside of a high number of small air pockets compared to a low number of big air pockets is the increasing number of cold bridges, originating from continuing pieces of glass. The heat transfer will simply go around the pockets. Nevertheless, the impact could be high enough to be influential.

Table 13 Comparison of U-values (1) **(van der Linden et al., 2017)**

build-up	**U-value U_T $[W/m^2K]$**
concrete cavity wall (1)	0.5-1.8
glass brick	3.33-6.67
IGU 4-12-4 (1)	3.0
IGU HR++	1.2

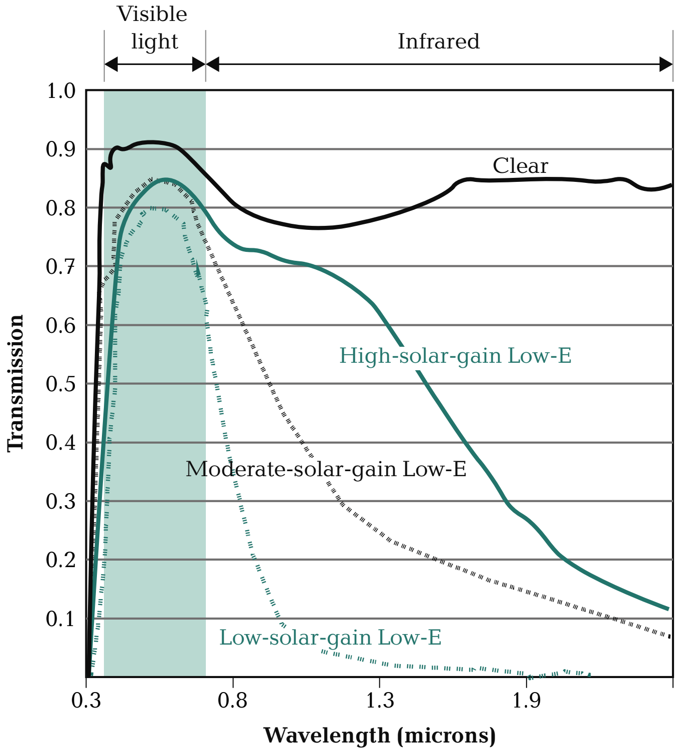
3.2. Refracting light

3.2.1. Coatings

Radiation hitting the glass is either transmitted, absorbed or reflected, as shown in the top half of Figure 33. Energy absorbed by the glass is dissipated by convection of moving air or it is re-radiated by the glass surface (as explained in paragraph 2.1.1 "Transfer of energy" and visible in the bottom half of Figure 33). The ability of a material to radiate energy is called its emissivity. All materials radiate heat as long-wave, infrared energy and radiant energy is one of the main heat transfer mechanisms occurring in windows. Reducing this emissivity with coatings is profitable for the insulating performance of windows. Clear glass has an emissivity of 0.84 for long-wave radiation.

There are four important values for evaluating the performance of coatings: thermal transmittance (U-value), solar heat gain coefficient (SHGC or g-value), visible transmittance (VT) and light-to-solar gain (LSG).

- **Thermal transmittance** is the rate of (non-solar) heat flow. The lower the U-value, the greater the insulating capacity.
- **Solar heat gain coefficient** is the fraction of radiation transmitted through a material to the total incoming radiation. The lower the SHGC, the less solar heat it transmitted and the greater its shading ability.
- **Visible transmittance** is the fraction of visible light (380-720 nm) that is transmitted through the material.
- **Light-to-solar gain** is the ratio between SHGC and VT, the relative efficiency of glazing in transmitting daylight while minimalizing heat gain.



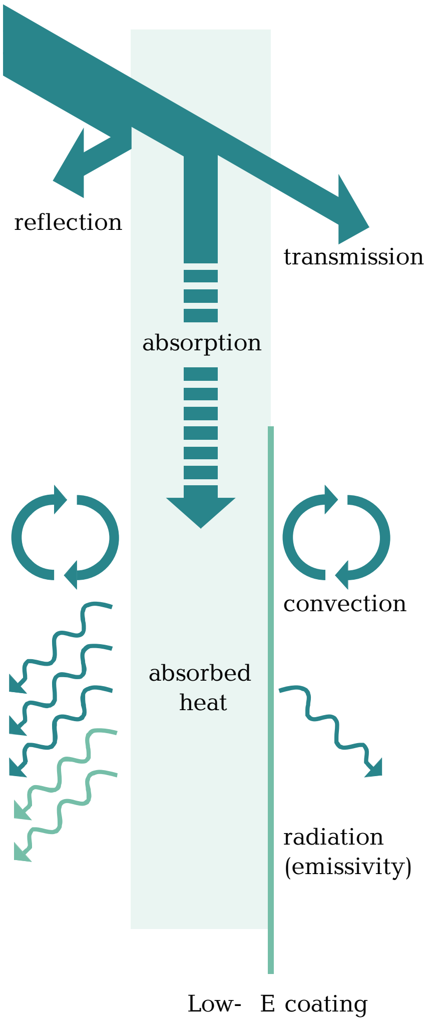


Figure 32 Transmission in coatings, original from (*Low-E Coatings | Efficient Windows Collaborative*, n.d.)

Figure 33 The behaviour of heat transfer in Low-E coated windows, self-illustrated

There are two types of coatings; hard coatings and soft coatings. Soft coatings are based on a physical process, called vacuum deposition or magnetron sputtering. Very thin layers of target material are sprayed onto the glass surface within a vacuum chamber. It is applied in multiple layers of optically transparent silver, sandwiched between layers of metal oxide. This process provides the highest level of performance and a nearly invisible coating. All soft coatings that contain silver metal must be edge deleted to avoid corrosion due to moisture contact. Edge deletion is the removal of a narrow strip of coating around the perimeter of a sheet of glass, which will be used to make an insulating glass unit or a laminated glass sandwich.

Hard coatings are based on a chemical process, called pyrolysis process. Metal oxides are deposited onto the glass surface during its production process along the float line. At this stage, the glass temperature is still considerably high and the metal oxides are therefore baked onto the glass surface. This is usually a solar control coating. This type of coating is not applicable for cast glass since it is baked in the float line process.

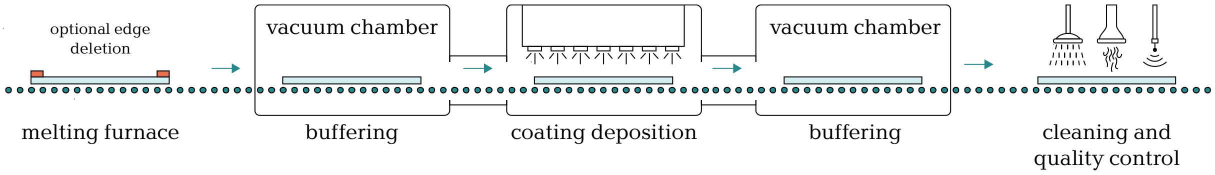


Figure 34 Magnetron Sputtering Coatings (Soft and Semi-Hard Coatings)

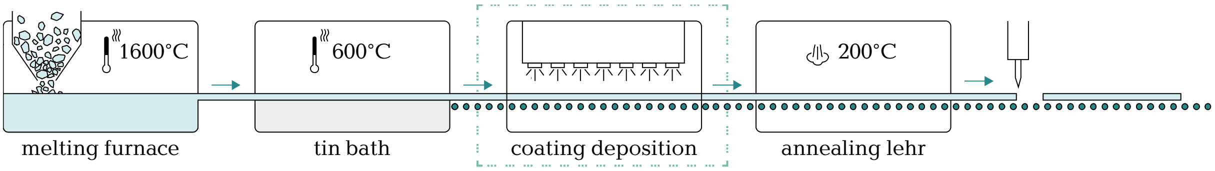


Figure 35 Pyrolytic Coatings (Hard Coatings)

Soft coatings

- \+ high visible light transmission
- \+ low emissivity
- \+ optical clarity
- \- soft coat low-E must be used in a double-glazed unit; the soft coating is sensitive to handling
- \- most soft coat low-E products require tempering the glass prior to the coating application
- \- edge deletion of the coating is required to ensure a proper seal in an insulated unit
- \- there could be a slight colour variation within the coating on the panel

Hard coatings

- \+ the advantage is that the coating is relatively durable, which allows for ease of handling and tempering
- \+ can be toughened after the coating application
- \+ can be used in single glazing applications
- \+ improved scratch resistance of the coating
- \+ will not oxidize, so no edge deletion required
- \- typically, does not improve U-value
- \- g-value is directly proportional to light transmission, so better (lower) g-value means a lower light transmission
- \- usually quite reflective

3.2.2. Surface refraction

It is possible to redirect light by using prisms, which can be used to manipulate the incoming light. Frank Lloyd Wright designed a brick to redirect the sunlight to the ceiling of a room, to increase the brightness in a room. These so-called 'Luxfer tiles', produced by the Luxfer Prism Company, were ingeniously designed to brighten the interior by bending the sunlight to fall upon the walls and ceiling instead of the floor; a useful innovation due to the underdevelopment of electric lighting during the very early 1900s. Frank Lloyd Wright designed this tile in 1895 when he was 28 years old. ('Rare Antique Frank Lloyd Wright Glass "Prism" Tiles Discovered in Windows of Historic Springfield Building in the Square.', n.d.)

Depending on the needs, light can be directed upward, downward or even outward. When redirecting some light outward again, the solar gain can be reduced. This does not contribute to the improvement of the U-value, but it can help with the g-value.

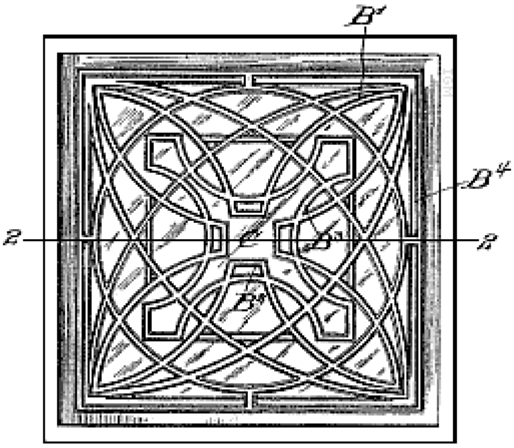


Figure 36 Frank Lloyd Wright's Luxfer Prism tiles (***Frank Lloyd Wright's Prism Tile Designs | Glassian*, n.d.)**

3.3. Additional insulation material

3.3.1. Inert gasses

Not only air chambers or cavities lead to improved thermal performance. If these voids are filled with inert gasses, the resistance can be even further increased. While air itself is a good insulator, filling the voids between the glass with a lower-conductivity gas (for example argon or krypton) can improve performance by reducing conductive and convective heat transfers. The thermal conductivity of these gasses is lower because it is much denser than air.

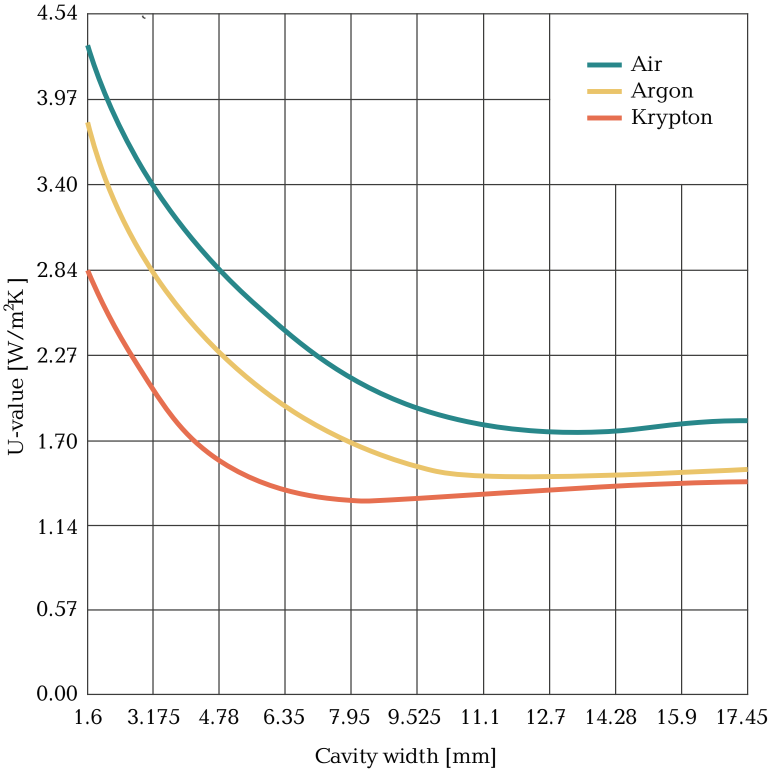


Figure 37 Influence of the type of gas for U-value of IGUs, originally from (Crandell, n.d.), units converted

3.3.2. Aerogel

Like other building materials, most of them are combined to benefit from the strength of each material. A typical wall is not built with only a single material. Glass is in this way exceptional, due to the transparency. Normally, a wall build-up consists of a structural member and some added layers of insulation and moisture barriers. This is obviously also possible with cast glass bricks. However, transparency and light transmittance are important values of glass and will disappear when combined with regular insulation materials. A modern approach to increase the insulation value of IGUs is the inserting of granular and monolithic aerogel panels. *"Two types of aerogel exist, the monolithic and the granular aerogels. Monolithic silica aerogels have higher solar transmittance than granular ones; for example, 10 mm monolith translucent silica aerogel windows have shown a solar transmittance up to 0.8, whereas the maximum solar transmittance of granular silica aerogel windows is around 0.5. However, cracks often occur when manufacturing large pieces of monolithic aerogels, so glazing systems with monolithic aerogel have not yet been used beyond research prototypes."* (Berardi, 2015)

The production and handling of aerogels are very sensitive process since this material is incredibly fragile. This makes the application a costly process. Within a very controlled environment, it is possible to sandwich these panels within two float glass panels. One requirement for the aerogel is the absence of moisture. For this reason, the panels must be sealed off completely.

The influence of aerogel, however, can be quite compelling. Aerogels can have a thermal conductivity as low as 0.018 W/mK (*Lumira Translucent Aerogel*, 2013), which is roughly 5% of the thermal conductivity of glass, similar to an air cavity of 5 mm and roughly 36% of the thermal conductivity of a 20 mm air cavity.

3.3.3. Fibre-based composites

Translucent (glass) fibre insulation material enhances the insulation of glass façade systems. It scatters incoming light and is thus not transparent, but translucent. These fibres operate similarly to 'regular' insulation materials, like rock wool. Air is trapped between the fibres, increasing the thermal resistance.

New research is also diving into mechanically strong composite materials of high optical quality. Many different approaches exist to create these transparent composites, including bacterial nanofibres, plant nanofibres, chitin particles, nylon fibres, polymer nanofibres, and fibres made from polymer ribbons. The thermal conductivity of these composites is not yet known, but if these values are significantly lower than the glass thermal conductivity, this could be an interesting insulator, since it does not degrade the transparency much.
(*High-Strength and Optically Transparent Fiber-Reinforced Composites | SBIR.Gov*, n.d., p.)

3.3.4. Non-transparent materials

If the transparency of glass would not be of importance, 'regular' insulation materials could be used. Since light transmittance is considered to be of great importance, this strategy lies outside the scope of this thesis.

3.4. Changing material properties

The thermal conductivity of a silicate glass is very low near the absolute zero (0 K) and it increases with temperature. The thermal conductivity of glasses is not influenced a lot by composition. In Table 14, several examples are given at a temperature of 30°C, showing the range of thermal conductivities. Many more compositions are given by (Bansal et al., 1986), but all within the same range. From this can be concluded that glass has a thermal conductivity between 0.6 and 1.0 around 30°C.

Table 14 Thermal conductivity of several glass compositions at 30°C **(Bansal et al., 1986)**

glass family	composition	thermal conductivity λ
lithium silicate glass	29.97 mole % Li_2O	0.95
	46.29 mole % Li_2O	0.65
cesium silicate glass	16.67 mole % Cs_2O	0.637
	$3Na_2O-1Cs_2O-20SiO_2$	0.928
Several other glass types	$10Na_2O-9Cs_2O-50SiO_2$	0.645
	$39.26Na_2O-7.57SrO-53.16SiO_2$	0.542
	$39.24Na_2O-10.15BaO-50.60SiO_2$	0.466

The thermal conductivity has a direct influence on the thermal transmittance (U-value) of a solid glass brick. The glass recipe influences the thermal conductivity of the material. In the literature review, some values are given from literature. The thermal conductivity λ ranges from approximately 0.45 to 1.0. Thus, when properly selecting the recipe, the thermal transmittance could be halved. However, this is a very costly process and does not align with the prospect of using recycled glass in the bricks. Therefore, it will not be further investigated within this thesis.

3.5. Passive systems

The biggest motivation for increasing thermal performance is the decrease in energy usage for cooling and/or heating. Another way to tackle this is by gaining energy through the system. By doing this, the system can balance its energy usage with its own production of energy. However, this system is less desirable since the production of PV cells also requires energy and materials and these cells need to be maintained and after a certain time period, replaced. It is not actually tackling the main problem; it only balances out the negative effects. Since it is not solving the problem, but trying to complement the negative results, this strategy will not be tackled further.

4. Concept generation

The strategies from the previous chapter will be translated into design concepts. The focus of this thesis lies primarily on the introduction of air cavities or chambers since it is an effective yet simple solution in its principle. The designs generated here will be later scored in the multi-criteria analysis in chapter eight.

4.1. Cavity wall (system-level)

4.1.1. Simple cavity wall

Similar to clay bricks, two walls can be constructed with an air cavity in between. This will not result in a change of design for the bricks themselves. If a secondary wall is created, the depth of each layer can be minimized, if the two walls can collaborate structurally. For this, ties are needed to provide stability for out-of-plane loads on the slender wall. These ties are common practice in clay brick walls and are dealt with in the Eurocode. In order to use ties for glass walls, modifications to the ties are necessary. Transparent acrylic ties could generate more transparency, but its structural integrity has to be analysed and tested.

Another way to approach this connection is by designing a glass connector piece, that functions as a tie. This could be an interesting design, in which no additional materials will be introduced.

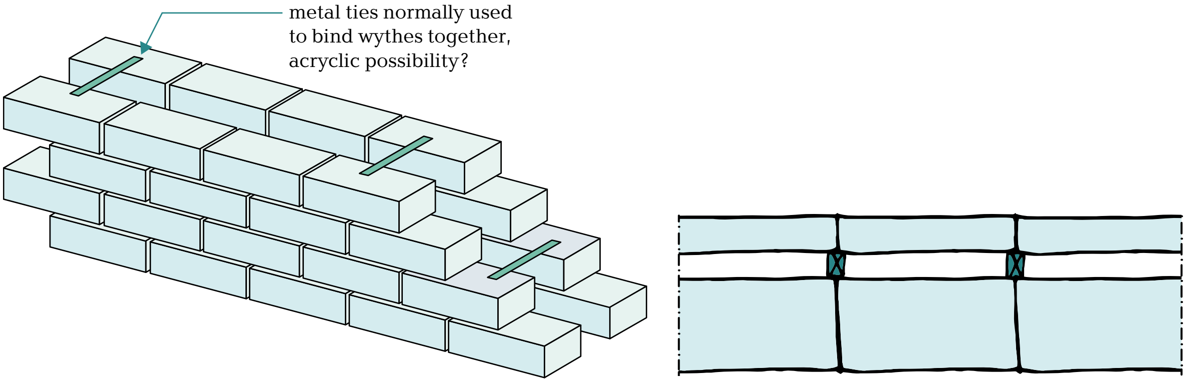


Figure 38 Secondary brick wall design

4.1.2. Creating a float glass secondary wall

Current insulating facades mostly consist of float glass panels, forming an IGU. Creating an insulation air layer with a float glass layer is feasible. However, this does not fully align with the goal of this thesis. To lengthen the life cycle of float glass waste, the possibility is researched to recycle it into bricks. Introducing a new layer of float glass does not follow this ambition. Additionally, the bricks are modular, each element can be used to create several systems, and thus façade sizes. Float glass panels have a fixed size and are thus not generally applicable and reusable.

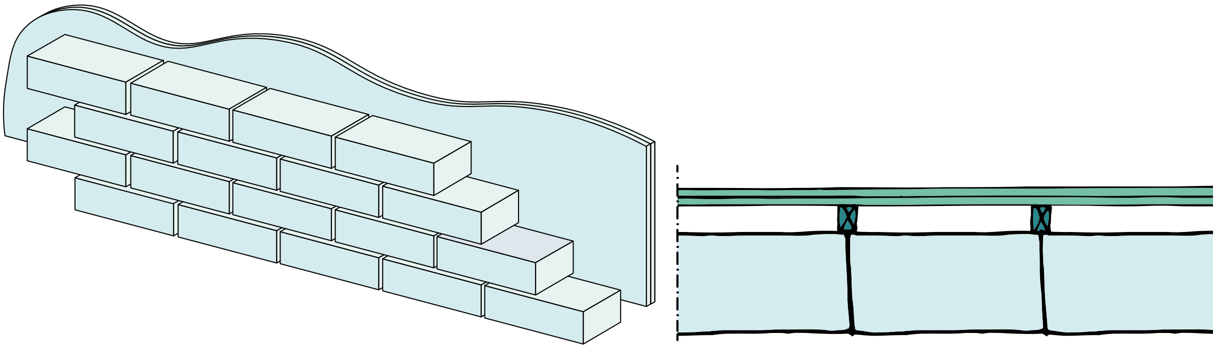


Figure 39 Float glass + brick wall combination

4.2. Air pockets (element-level)

4.2.1. Hollow glass bricks

The first concept derives from hollow blocks; half a hollow block will be fused or glued to a structural brick. Each block will have at least one air chamber, which will act as the thermal barrier. Fusing has the advantage over glueing that there is no need for additional materials, and it is easier to recycle. On top for that, it is an airtight seal. However, this will result in some residual stresses within the brick due to the uneven cooling down.

The second concept is based on the idea that the thermal resistance of cavities is not linearly increasing with the depth. Convection will reduce thermal resistance. If an air chamber is split in two, the thermal resistance will be more than the equivalent thickness of a single chamber with the same total thickness.

Because two chambers on one side can be more difficult to produce, the third design places two chambers on opposite sides of the brick. This can be beneficial for the production complexity, while still profiting from a double cavity.

The fourth design tries to reduce the thermal bridging occurring in the former designs. Optional in this design, is trying to make the plastic interlock with the glass. With this innovative system, a dry connection can be made which can easily be taken apart again to recycle each part separately. This is possible because of the form-freedom of cast glass.

Design number five and six are derived from the same principle of trying to reduce the thermal bridge by using another material as a spacer, i.e. plastic. When doing this, the additional glass piece has a simple rectangular geometry. This can also easily be executed with float glass or even something very thin like gorilla glass. This layer does not contribute to the vertical load-bearing capacity and if placed on the inside, will not take any wind loads. This does, however, introduce a different glass production type, which is not preferable in terms of recycled waste glass usage.

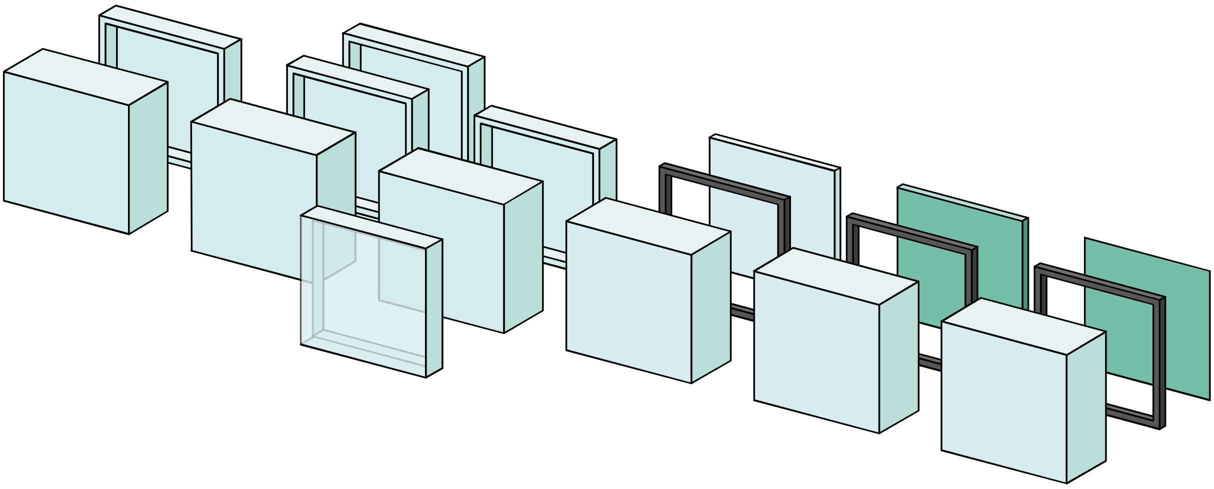
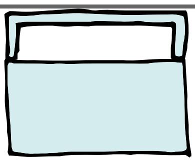
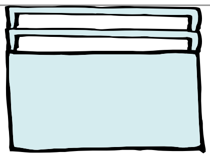
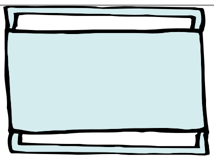
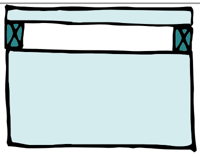
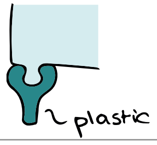
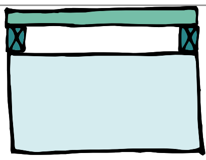
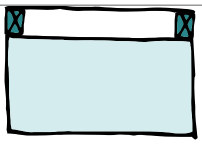


Figure 40 Overview of hollow glass brick design suggestion build-ups

Table 15 Overview of hollow glass brick concepts

	materials	production	transparency
	cast glass	fusing or glueing	++
	cast glass	fusing or glueing	+
	cast glass	fusing or glueing	+
 optional 	cast glass polymer	glueing or interlocking	++
	cast glass polymer float glass	glueing	+++
	cast glass polymer gorilla glass	glueing	+++

4.2.2. Bubbles

There are three main means of deliberately creating bubbles in the glass. These methods will be referenced according traditional Venetian Murano names. The first method (bullicante) relies on physically creating bubbles with either a spike mould (also called a pineapple or nail mould) or by rolling on a flatbed of spikes. Another layer of glass is added and bubbles remain where the glass was penetrated. The second method (pulegoso) creates bubbles by a chemical reaction within the glass. With the third method (reticello), bubbles are created by trapping air between glass canes.
(*Murano Glass Making Techniques: Bullicante | Everything About Venice and Murano Glass*, n.d.; *Pulegoso*, n.d.; ‘What Is Reticello in Glass?’, 2013)

Figure 41 [left] A casting with fibreglass powder, the more the bubbles the less transparent and it is quite fragile and [right] "Deconstructed Being III" is a glass work by Joanne Mitchell. (O'Driscoll, n.d.)

4.2.3. Encapsulated air pockets

In glass art, encapsulated and pre-engineered air pockets can be found. These could prove interesting since it allows for forcing the air pockets in a certain smart configuration. This can be an optimization of thermal vs. structural performance.

Two design alternatives arose, trying to improve the irregular surface area in the bubbled brick design. A smooth outer surface is structurally beneficial and in both designs, a ‘box’ is created, which is filled with glass and air pockets. The first design is based on glass strips, laid in a chess-like pattern and the second design focuses on glass shards, randomly organised.

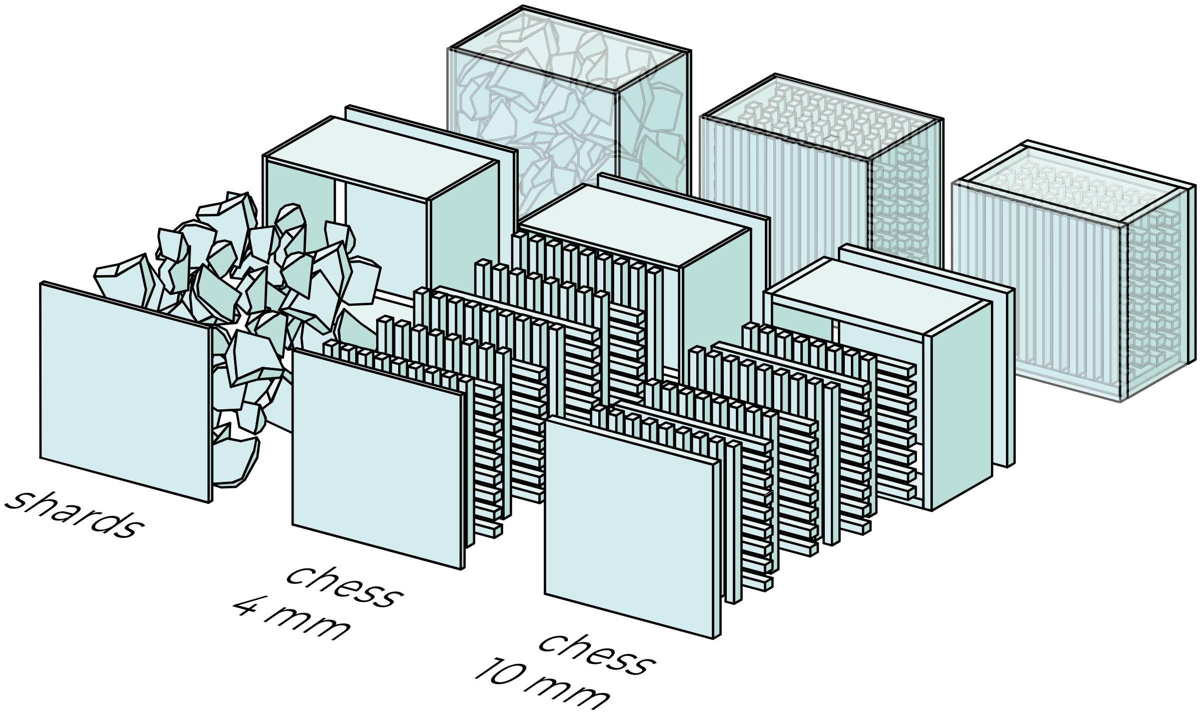
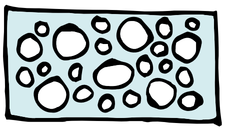
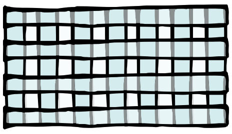
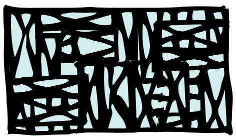


Figure 42 Overview of encapsulated air brick design suggestion build-ups

Table 16 Designs with encapsulated air pockets

	materials	**production**	**transparency**
	cast glass	casting with bubbling agents or powdered casting	Dependent on technique and porosity
	float glass strips	Fusing	+-
	waste shards	fusing	--

4.3. Influence studies

During the development of these concepts, air cavity depth influence studies were performed in TRISCO. The 3D steady-state program TRISCO will be later explained in chapter 6: 'Steady-state 3D thermal evaluation'. These analyses were done in the earlier design phase, to see what the influence of air cavities is.

Air cavities are attached to a brick with dimensions of 100x150x250 mm^3. The thickness of the brick and the outer glass pane is kept constant, respectively 150 mm and 10 mm. The spacer is 10 mm wide, goes along all vertical edges and is increased in depth. The thickness of the gorilla glass is considered at 2 mm.

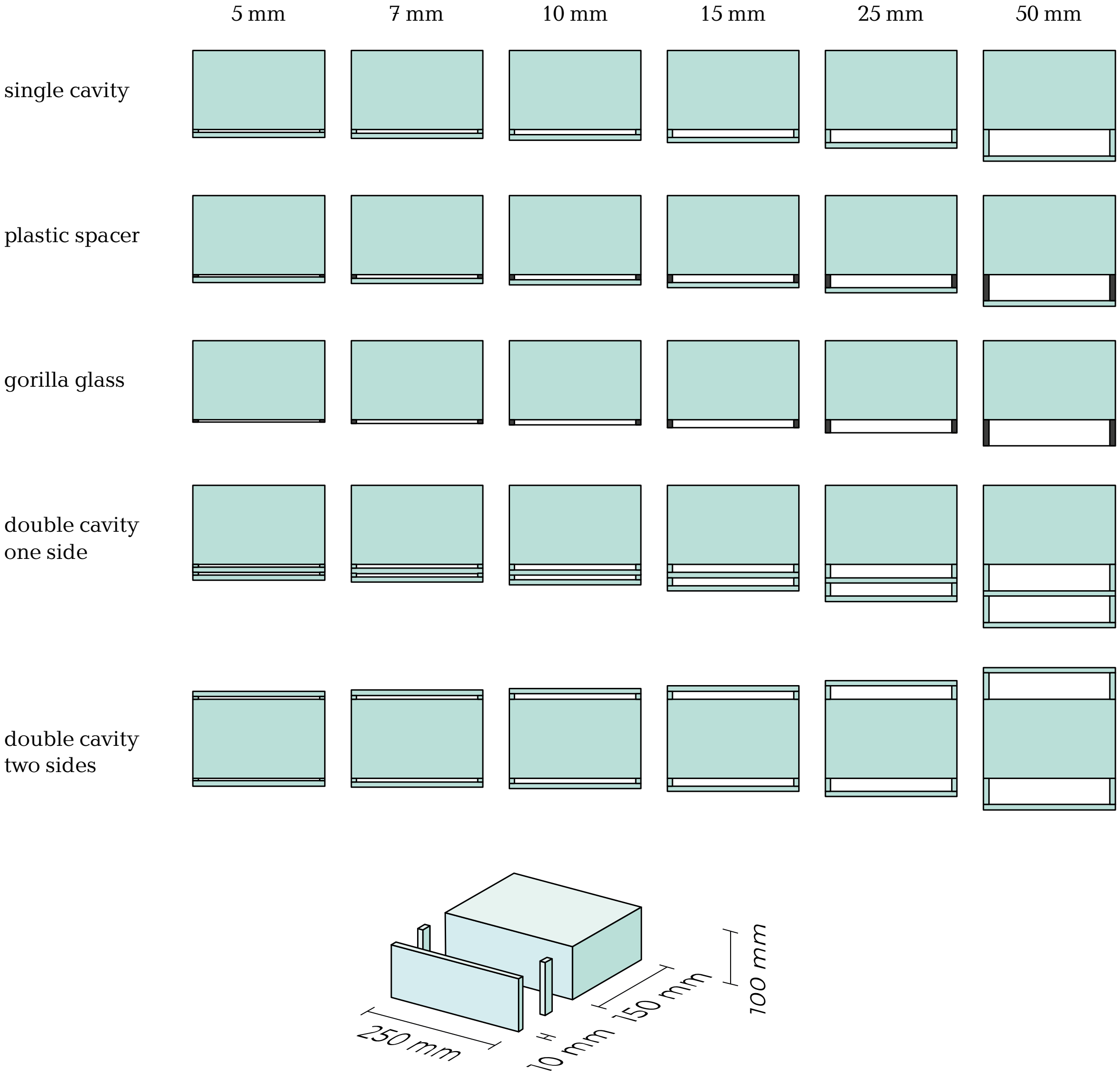


Figure 43 Geometries with increasing cavity depth influence study

The corresponding thermal transmittance per cavity depth is visualised in the graph in Figure 44. The cavity depth of bricks with multiple cavities are combined (2x10 mm cavity is visualised as 20 mm). From the graph, it can be concluded that with the increment of the first millimetres, the the thermal performance increases significantly (steep-slope), whereas the slope flattens with the increasing cavity depth. This is also clearly visible when comparing 'single cavity' with 'double cavity', the cavity is simply split in two, with a glass plane in between, and the performance difference is significant. This is all due to the reduction of the thermal resistance of air layers due to convection, explained in paragraph 3.1 'Cavities'.

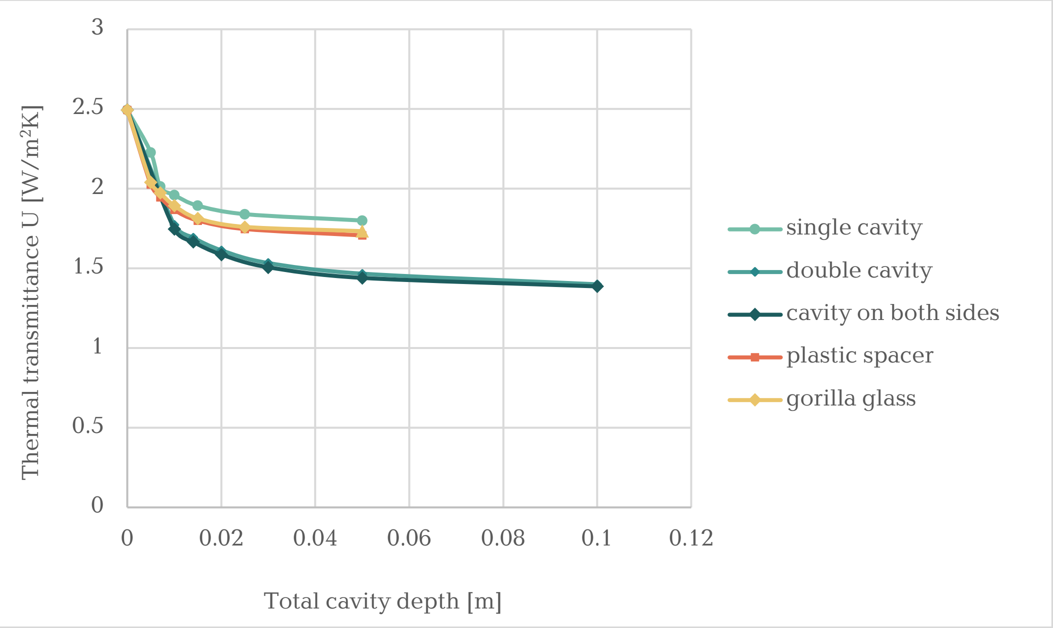


Figure 44 Influence of cavity depth for U-value

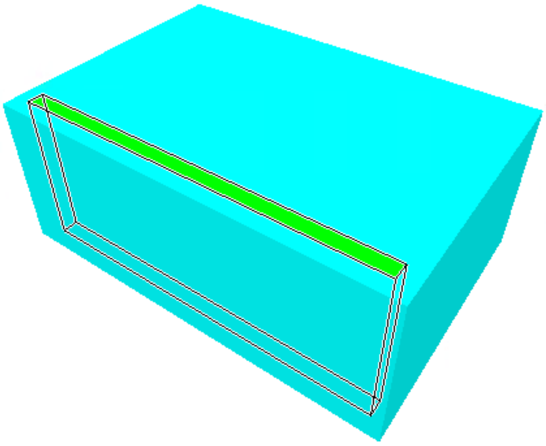


Figure 45 Screenshot from TRISCO, showing the air cavity (green) and the glass (blue)

The second correlation that is researched is the ratio of the porosity to the thermal transmittance. For this, small 5 mm air pockets are designed, going from a 50% porosity to 0%. This is visualised in the figure below, where the grey squares represent the air pockets. The porosity is linearly related to the overall thermal performance. This is modelled in a 150 mm, 10x10 mm^2 strip, considering symmetry in the boundary conditions.

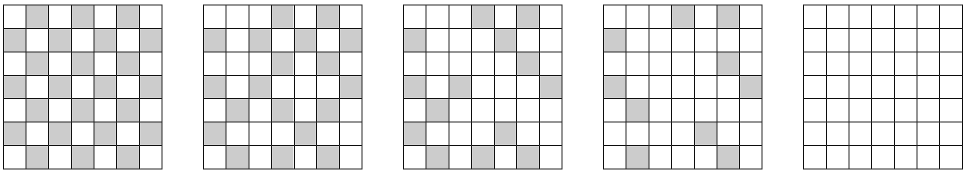


Figure 46 Porosity visualisation

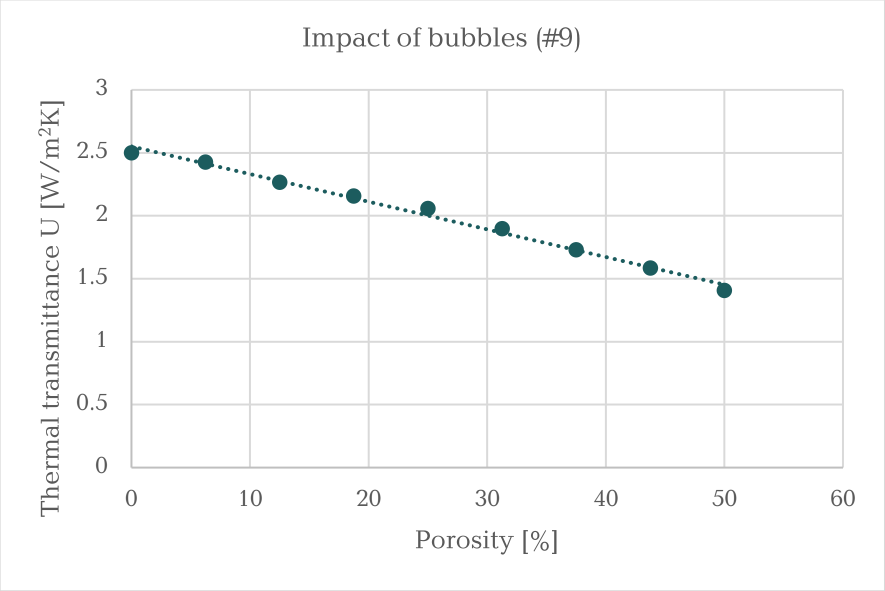


Figure 47 Porosity to U-value correlation

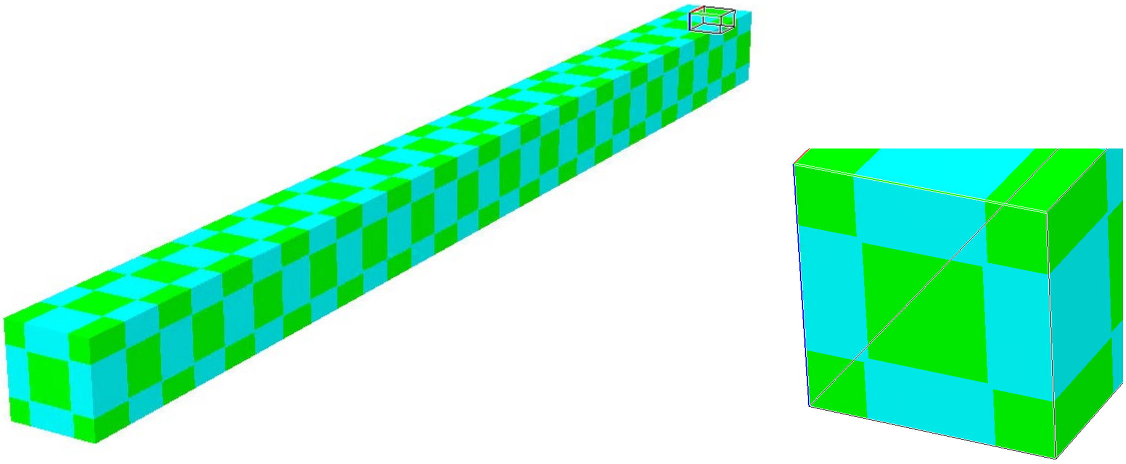
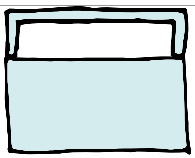
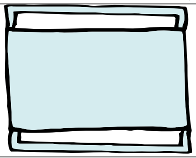
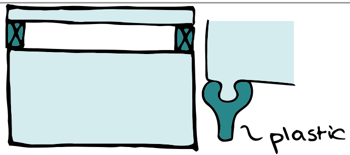
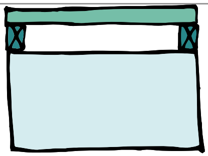
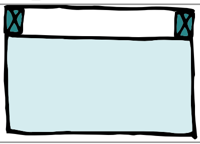
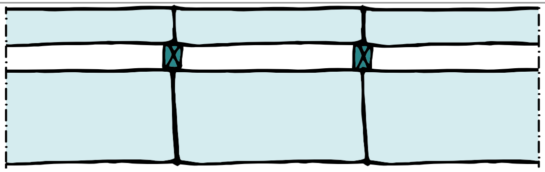
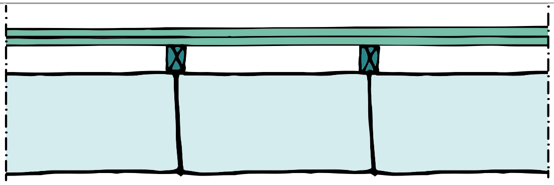
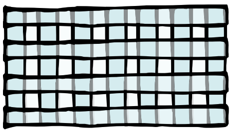
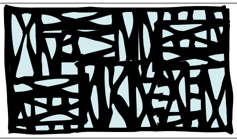


Figure 48 Screenshots from TRISCO, narrow modelled strip to investigate the influence of bubbles, showing the air pockets (green) and the glass (blue)

4.4. Summary

Due to time constraints, not all designs are further investigated. The double cavity on one side of the brick is left out, since it is very similar to the double cavity brick on either side, but has some feasibility problems for production. The bubbling agent is not taken into account, since the resources were not available to test and produce this.

Table 17 Overview of all chosen designs for MCA

#	Name	Cavity depth	Sketch
0	Solid		
1	Single cavity	10 20 30	
2	Double cavity	2*5 2*10 2*15	
3	Single cavity with spacers	10	
4	Float glass with spacers	10	
5	Thin glass		
6	Double-wall		
7	Secondary float glass wall		
8	Chess Chess wide Chess 4 mm Chess 4 mm wide		
9	Shards		

5. The plausibility of tack fused glass connections

During the development of the prototypes, an interesting concept arose. Incorporating air bubbles can be a challenging process, especially with bubbling agents. It leaves the outer surface irregular with many imperfections. What if it would be possible to create bubbles only in desired places, with a predetermined shape? In art, the answer can be found, for example in the art of Joan Mitchell (Mitchell, n.d.). In her art, the glass is heated until a viscosity where the glass fully fuses with itself.

However, at lower temperatures, tack fusing might prove sufficient. The lowered temperature will increase sustainability by the less amount of energy required. An investigation has to be made, at which temperature the material can stick to itself, without sagging much.

The focus in this chapter will be on determining how to develop such heat-bonded surface connections and their shear strength. The required temperature and dwell time must be known in order to create samples. A simple shear test will be executed, in which a short and longer dwell time will be compared and additionally, where the samples will be compared to DELO 4468 connections.

5.1. Evaluation of required fusing temperature

5.1.1. Fusing temperature

"A review of material science research into the properties of glass when heated found that the molecular structure of glass changes continuously with temperature, rather than passing through a sudden phase transition." (Mitchell, n.d.) The temperature to viscosity correlation is highly dependent on the composition of glass. Figure 49 shows some examples of common compositions and their temperature to viscosity curves.

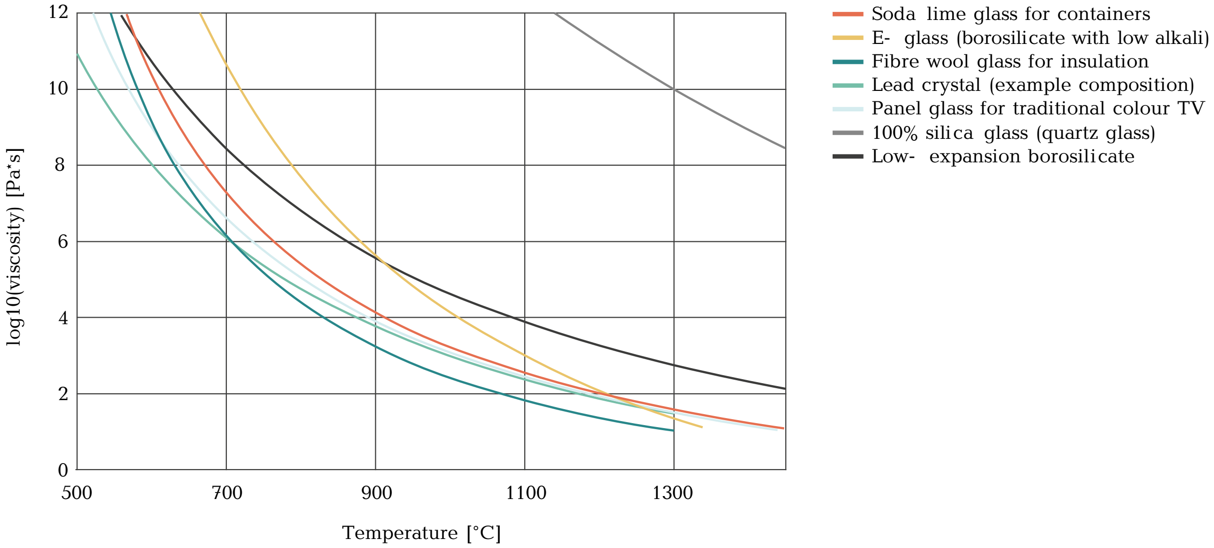


Figure 49 Temperature dependence of viscosity (Juejun, n.d.)

A wide range of temperatures is found in literature when looking at fusing temperatures. Mostly, the fusing temperatures are specified above the drape and slump temperature, which means the glass will flow due to gravity. However, from experience, it is found glass does have the ability to 'tack fuse' at much lower temperatures, proved in the research from J. Mitchell and A. Eskes.

When investigating the points defined by A. Fluegel, combined with the experience of T. Bristogianni, it was found that fusing occurs around the so-called dilatometric softening point. Successful tests were executed at 650°C. It is important that the chosen temperature results in bonding, without relaxation. Otherwise, the unsupported areas will sag.

Table 18 Viscosity calculation from spreadsheets bases on "Glass viscosity calculation based on a global statistical modelling approach'' for glass composition used in samples ('Ceramic Engineering 122', 2004; Fluegel, 2007)

10log (viscosity/Pa*s)	10log (viscosity/Poise)	Temperature	name	description
1	2	1484.2	Melting point	Glass melt homogenization and fining
3	4	1053.6	Working point	temperatures in which glass is formed into ware in a specific process (pressing, blowing, gob forming)
4	5	933.0	Flow point	At this point, glass begins to flow freely if unrestrained
6.6	7.6	739.3	Littleton softening point	Glass deforms under its own weight
9	10	636.2	Dilatometric softening point	the temperature at which a pushrod is able to deform the sample because the viscosity is too low to withstand the applied force.
12	13	554.3	Glass transition temperature	The temperature where the polymer substrate changes from a rigid glassy material to a soft (not melted) material
12.3	13.3	547.9	Annealing point	Stress is relieved within the glass within minutes
13.5	14.5	524.6	Strain point	Stress is relieved within the glass in hours

5.1.2. Firing schedule of prototypes

When talking about firing schedules, one has to keep in mind that the experience of T. Bristogianni plays an important role in the development of determining and finetuning the firing schedules. Her PhD is among other things focused on the impact of changes in the firing schedule and this process is based on trial and error. Important to notice within these schedules is the maximum temperature and its dwell time, the annealing time (at 560) and the cooling down rate.

Two firing schedules were used in the production of the prototypes. Some tests were done with either a one hour dwell at the maximum temperature (650 °C) or a 3 hours dwell. The annealing time was dependent on the size of the specimen. When only small samples were inserted into the oven, 5 hours of annealing would suffice, whereas if the object became larger (like the complete brick), 10 hours seemed more appropriate.

Table 19 Firing schedule of the first batch, with a dwell of 1 hour at 650 °C

Stage	Ramp [°C/h]	Temperature [°C]	Dwell [h]
1	50	650	1
2	-160	560	10
3	-5	500	0
4	-35	25	END

Table 20 Firing schedule of the second batch, with a dwell of 3 hours at 650 °C

Stage	Ramp [°C/h]	Temperature [°C]	Dwell [h]
1	50	650	3
2	-160	560	5
3	-10	500	0
4	-35	25	END

5.1.3. Prototypes results and findings

Even though the 650 degrees is below the Littleton softening point of float glass (Fluegel, 2007), some sagging occurred. This was most visible in the longer dwell time. It would be interesting to research if lowering the temperature slightly will improve this, but this is outside the scope of this thesis. Important to understand is that, when changing the geometry and the size of the prototype, a new firing schedule must be determined.

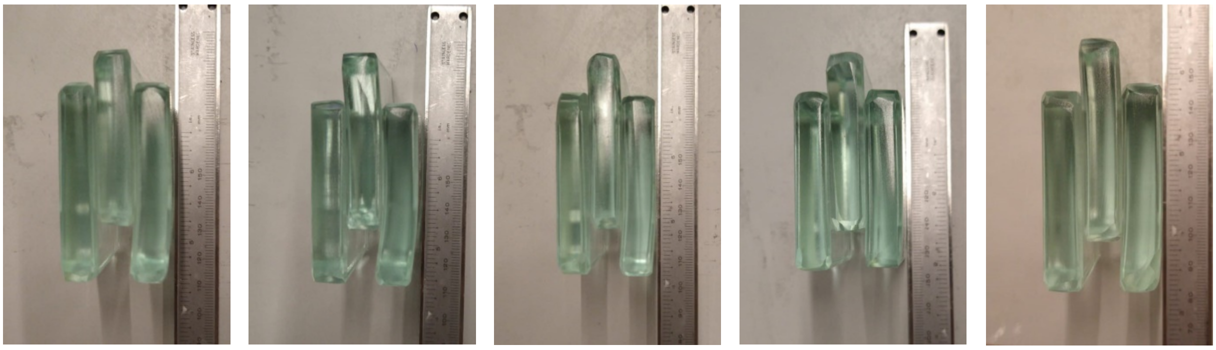


Figure 50 Five 3hr dwell prototypes, numbered 1 to 5 from left to right and their deformations due to the fusing

5.2. Experimental evaluation of shear strength

5.2.1. Test set-up

The test set-up used to evaluate the shear strength of the fused contact surface is shown in Figure 51. With this kind of test, theoretically, pure shear stresses will occur in the contact surfaces. The force applied, divided by the sum of the contact surfaces, results in the occurring surface shear stress. However, one must note that these tests will never be 100% accurate, due to eccentricities and occurring undesired bending stresses.

Special attention needs to be drawn to choosing an intermediate. Depending on the maximum force, different types of intermediates are suitable. Preferably, the intermediate yields during the test, providing a smoother contact surface and preventing peak stresses in the glass. If the material is too soft, it will deform too much for the tests to be executed. On the other hand, if the material is too stiff, the glass will break due to occurring peak stresses at the supports due to sample imperfections. With the first test, 'soft' plywood was used, which proved insufficient. Both samples did not fail, even though the wood did. Secondly, soft aluminium was introduced as an intermediate. This proved too stiff, resulting in failure at lower stresses. Finally, a balance was found with hardwood plywood, which has a yield strength in between.

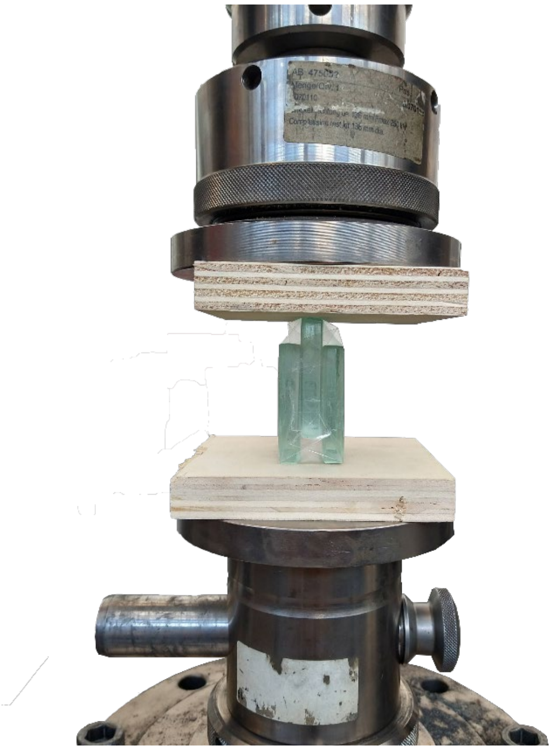


Figure 51 Photograph of test set-up for test run 2 and 3.

Figure 52 Intermediates during tests (soft wood, soft aluminium, hard wood)

5.2.2. Trial tests

The first trial tests were needed to evaluate the intermediate material, as explained in the previous paragraph. Some failures were due to the stiffness of the aluminium. These resulted in a chaotic failure pattern, with no clean cuts. A complete overview of pictures from these failed samples can be found in Appendix C: Failed shear tests, initial run.

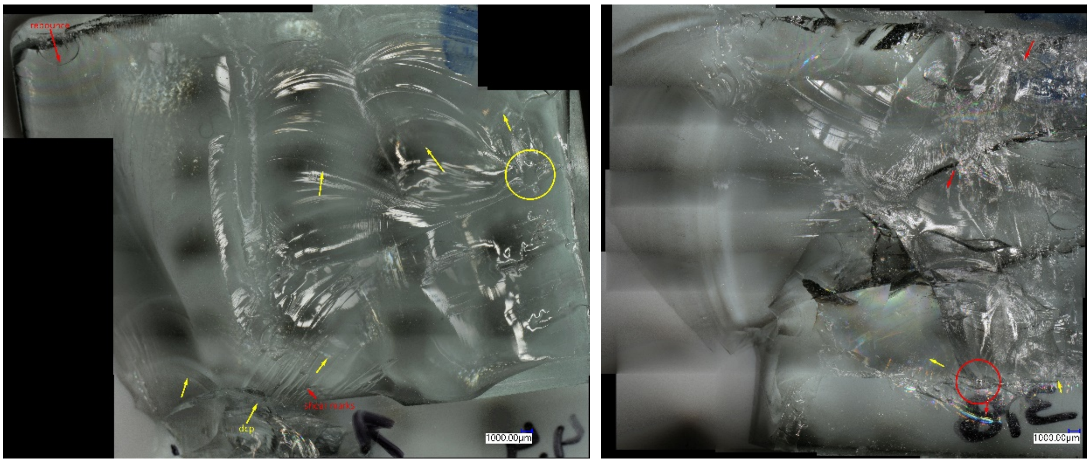


Figure 53 Microscopic pictures of test sample 4 and 5

Interesting also, was the visibility of the unbonded areas. Bubble-like areas with colour gradients are visible under the microscope. These bubbles entrap dirt and might also have something to do with the tin-side of glass. With these samples, it was not known if the contact surfaces where air-to-airside, tin-to-airside or tin-to-tinside.

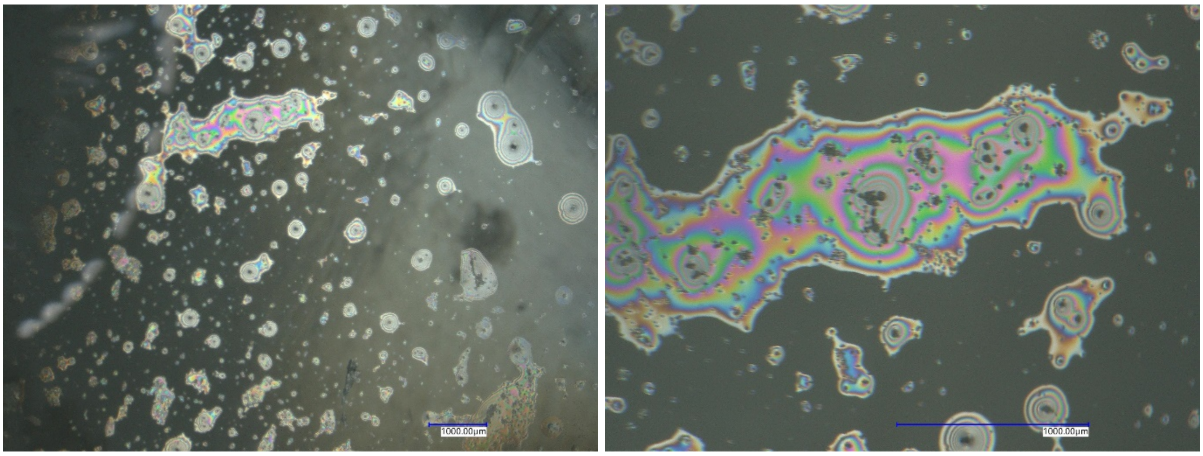


Figure 54 Microscopic pictures of unbonded areas with entrapped dirt in test samples

Table 21 Trial shear test results

test run	intermediate	failure?	maximum force [n]	single surface area [mm^2]	stress [N/mm^2]	type of failure
1	-	-	-	-	-	-
2	softwood	no	11713.96	2000	2.92	-
3	softwood	no	20066.88	2050	4.89	-
4	aluminium	yes	18190.58	2080	4.37	complete failure
5	aluminium	yes	14377.27	1911	3.76	complete failure
6	aluminium	yes	15739.88	1960	4.02	clean split
7	aluminium	yes	13883.90	2050	3.39	clean split
8	aluminium	yes	13559.77	2000	3.39	semi-clean split

5.2.3. Final test results

All tests were performed until the first failure mechanism of the sample. If the sample is split into two from the contact surface, the maximum shear strength is achieved. However, the sample is still able to take loads. This is visible in the Force-displacement curve of test run 3 (Appendix D) since the test was not stopped after the first split, but after chaotic failure at a much higher strength. This sample is not suitable anymore for clear investigation.

The final test results show consistent failure mechanisms. At both the 1-hour and 3-hour dwell, the failure starts at the edge of the fused area and then spreading through the material. This means the contact area is the weakest point, but strong enough to withstand a clean sliding plane. In the glass, the force is concentrated and thus the crack goes to the centre.

Contrary to the fused samples, the DELO samples show crack origins along the interface. As visible in Figure 55, the origin of the crack is moved upwards, while the path after the origin is similar. There is no proven failure preference for the right or left surface since the tests had too many varying parameters for this to be concluded. What could have played a role was:

- Tinside and airside of the float glass
- Placement in test set-up (slight off-centring)
- The thickness of the glue
- Upper or lower placement in the oven (and thus temperature during fusing)

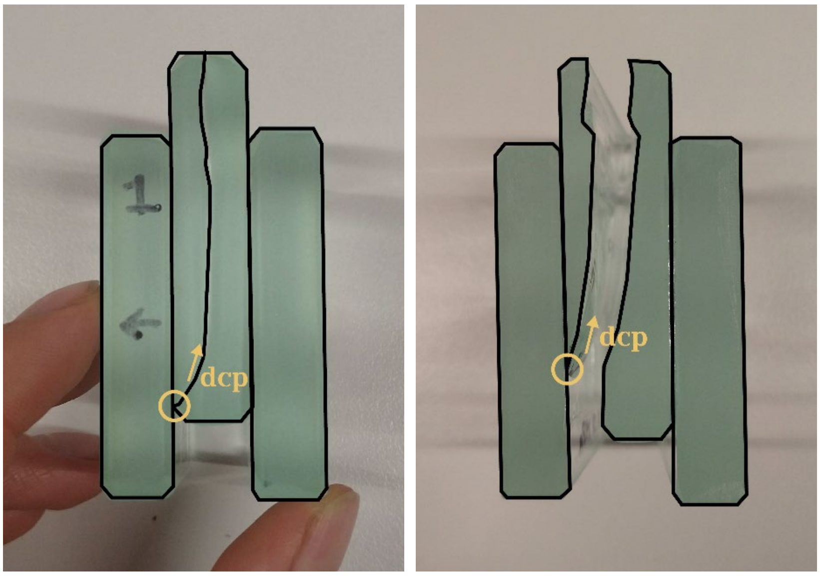


Figure 55 Origin and direction of crack propagation in tack fused sample (1-hour dwell #1) [left] and DELO 4468 glued sample (#5) [right]

Table 22 Final shear test results

specimen	sample #	failure?	maximum force [N]	force at failure [N]	surface area [mm^2]	Stress at failure [N/mm^2]	type of failure
1	1hr dwell 1	yes	20626.10	18686.41	3220	5.803233	clean split
2	1hr dwell 2	yes	26268.84	22427.64	3675	6.102759	semi-clean split
3	1hr dwell 3	yes	32494.70	17552.99	3107	5.649498	clean split
4	1hr dwell 4	yes	28884.38	22695.78	3301	6.875426	clean split
5	1hr dwell 5	yes	21068.19	20164.23	3765	5.355705	clean split
6	3hr dwell 1	yes	17885.42	16577.66	3116	5.320173	clean split
7	3hr dwell 2	yes	20809.22	19221.46	3105	6.190486	clean split
8	3hr dwell 3	yes	26507.30	25084.51	3336	7.519338	clean split
9	3hr dwell 4	yes	19905.98	19031.02	3071	6.197011	clean split
10	3hr dwell 5	yes	22398.00	21954.55	2956	7.427114	clean split
11	DELO 1	yes	34420.30	31664.98	3915	8.088117	clean split
12	DELO 2	no	46683.10	-	3516	13.27733	-
13	DELO 3	yes	52287.39	49396.86	3339	14.79391	semi-clean split
14	DELO 4	yes	35134.98	35117.86	3139	11.18759	clean split
15	DELO 5	yes	38865.16	37169.70	3382	10.99045	clean split

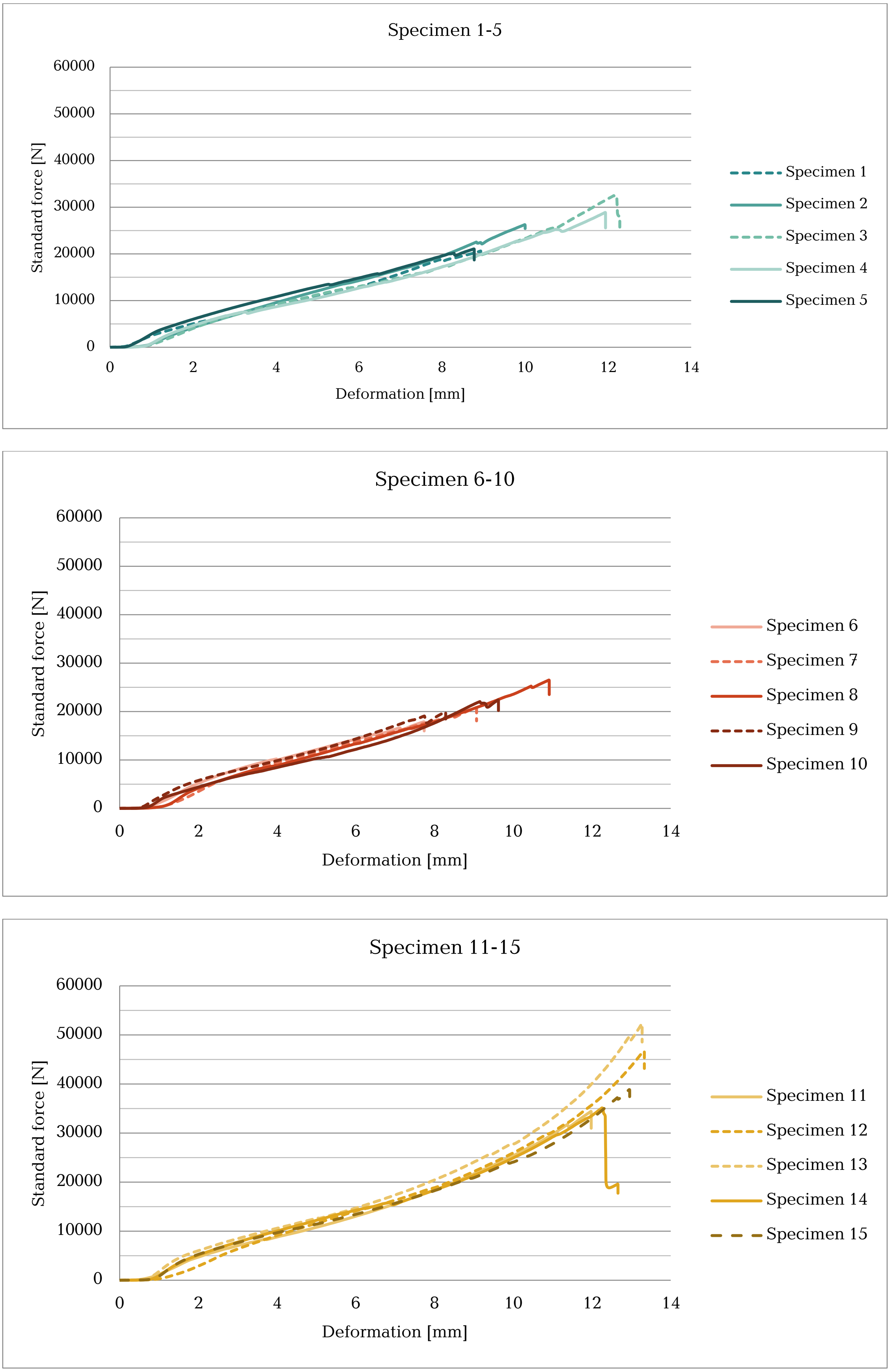


Figure 56 Three graphs, showing the force-deformation curves of (1) the 1 hour dwell samples, (2) the 3 hour dwell samples and (3) the DELO samples

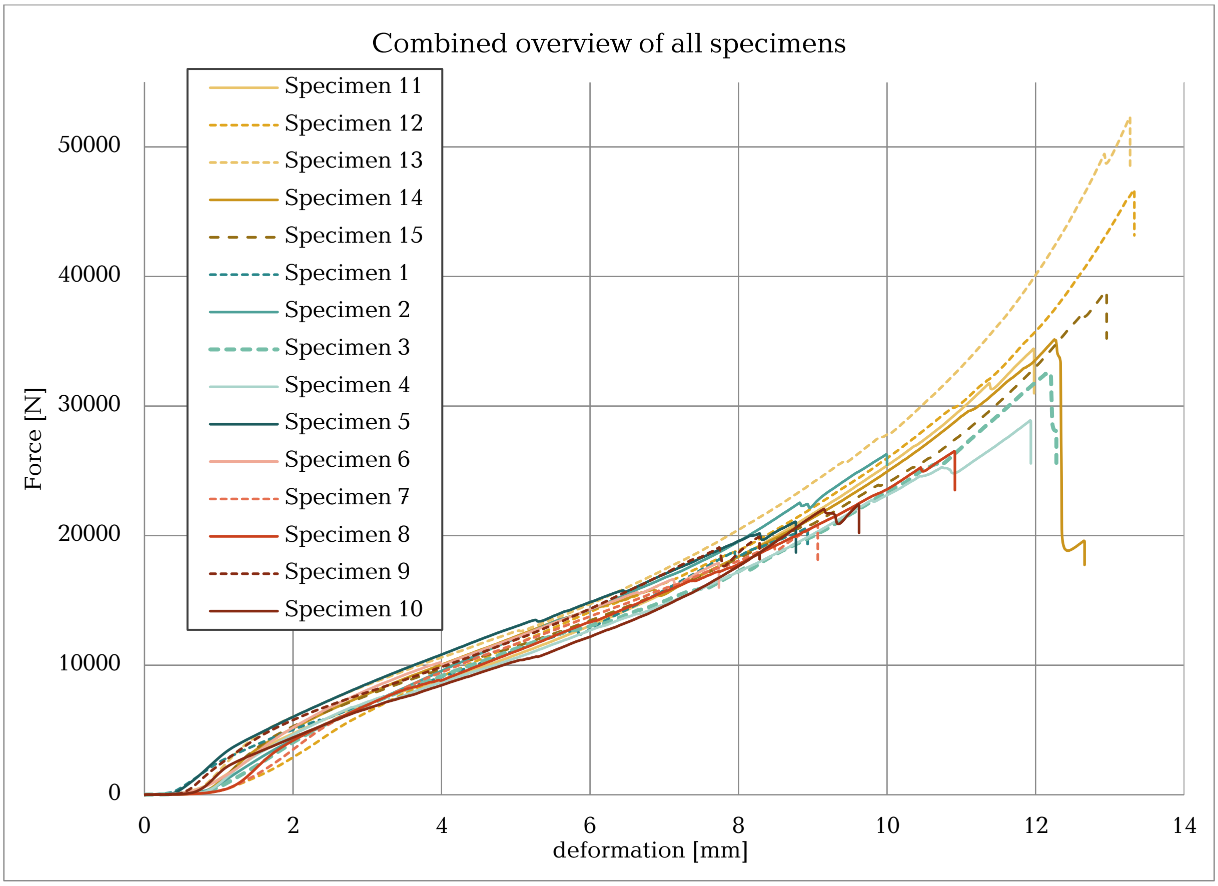


Figure 57 Combined overview of Force-deformation curve during tests of all specimens

As visible in Figure 57, all samples show similar overall Young's modulus. This is mostly due to the hardwood intermediate, which deformed significantly. The deformations of the glass can not accurately be measured from this test. The DELO has overall higher performance. Research from T. Bristogianni concludes that DELO glued samples have a significant reduction in Young's modulus and the strength reduces in correlation with the glue thickness. (Bristogianni et al., 2020)

This thickness-strength correlation can be identified in the spread of the test results, visible in Figure 58. The DELO samples show more variation in stress than the fused samples. These samples do not have the inaccuracy of the thickness of the interlayer material. However, the 3-hour samples do show a wider spread than the 1-hour samples, probably due to the more deformed samples and wider spread in sample geometry (sagging visibly in Figure 50).

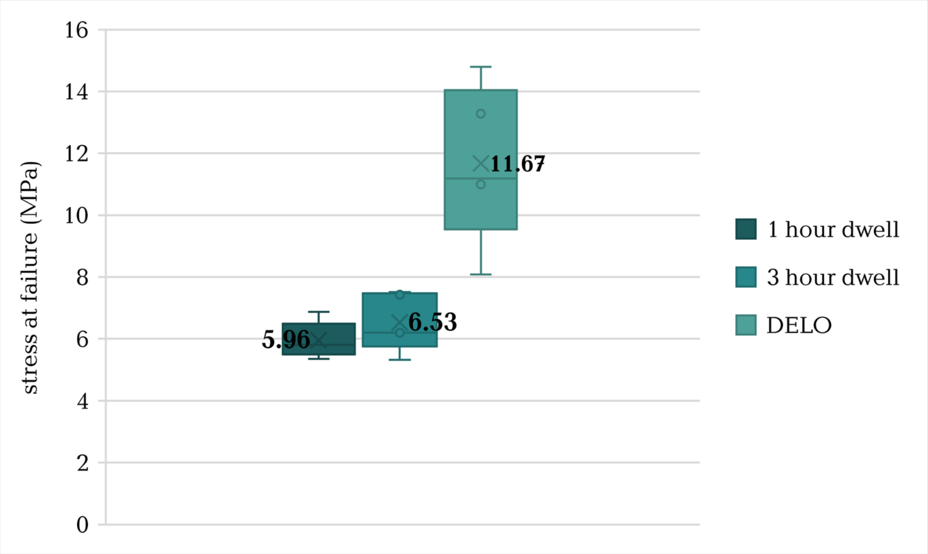


Figure 58 Average stress and spread of test results

5.2.4. Bending tests from the literature

In research conducted by T. Bristogianni, “Investigating the flexural strength of recycled cast glass”, fused glass beams were also tested in bending. Both 1 hour dwelled and 2.5 hours dwelled beams were tested. The test concluded that with 2.5 hours fusion the plies would bond properly and the beam would break as a homogeneous beam. With 1 hour fusion, the beams would fail at the interface under shear strength at a much lower applied force. In both cases, the E-modulus was similar to the original float glass, which is not the case with for example glued beams. (Bristogianni et al., 2020)

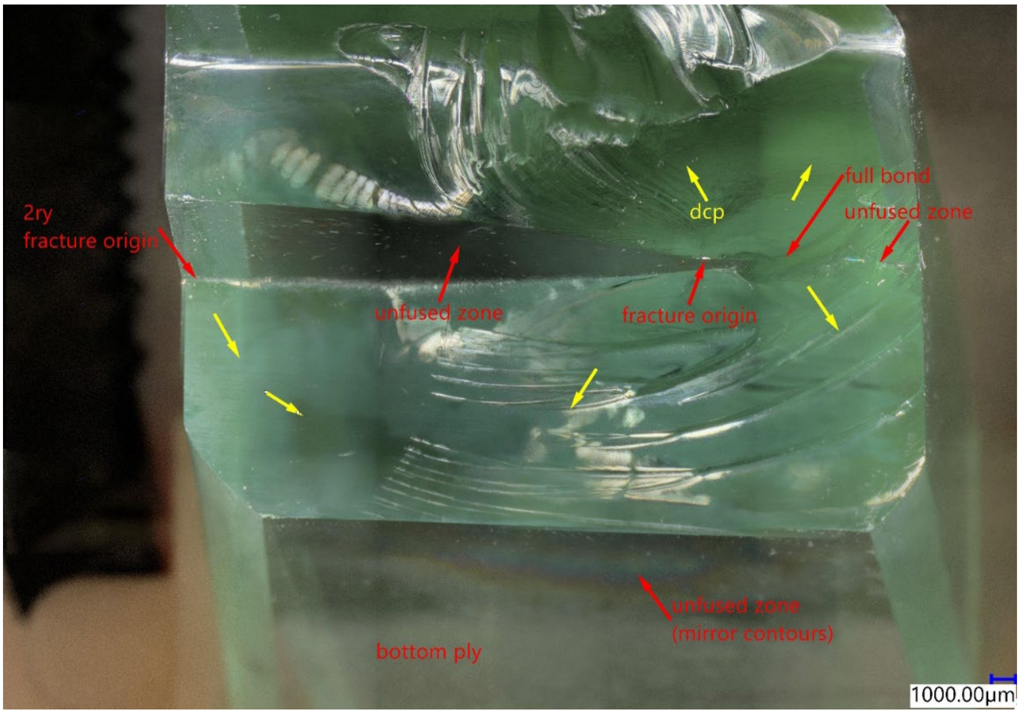


Figure 59 Failure in surface due to shear stress in 1 hour beam (Bristogianni et al., 2020)

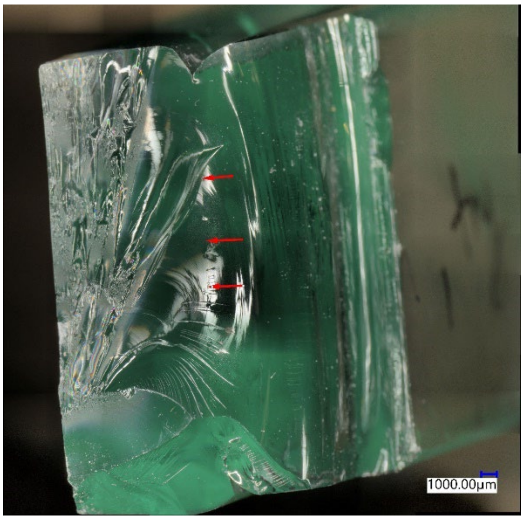


Figure 60 Monolithic failure in 3 hour beam, highlighting the visible fusing surface line (Bristogianni et al., 2020)

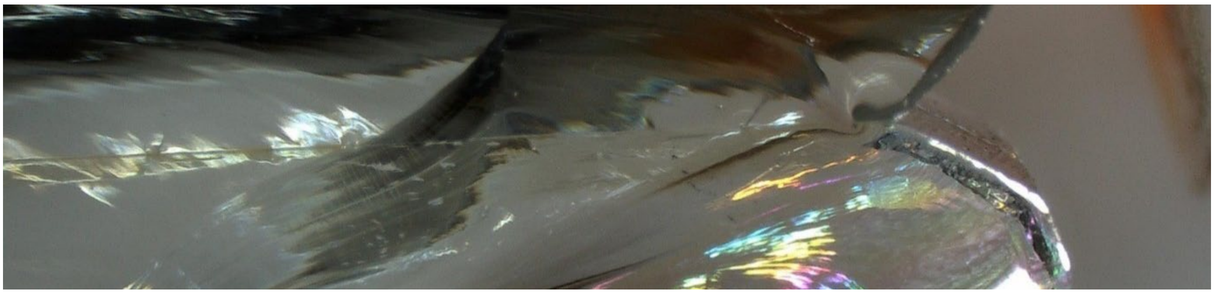


Figure 61 Close-up of fusing surface line in 3 hour beam (Bristogianni et al., 2020)

5.2.5. No-bond zones

During the production of these samples, it was found that the samples have zones with insufficient bonding. There is a clear distinction visible in the bonding between the two dwell times. This can be explained by the increased relaxation within the glass. The glass can form around dirt/dust. The influence of the air- and tin side of the float glass is not investigated here but might play a role in the ultimate strength of the surface.

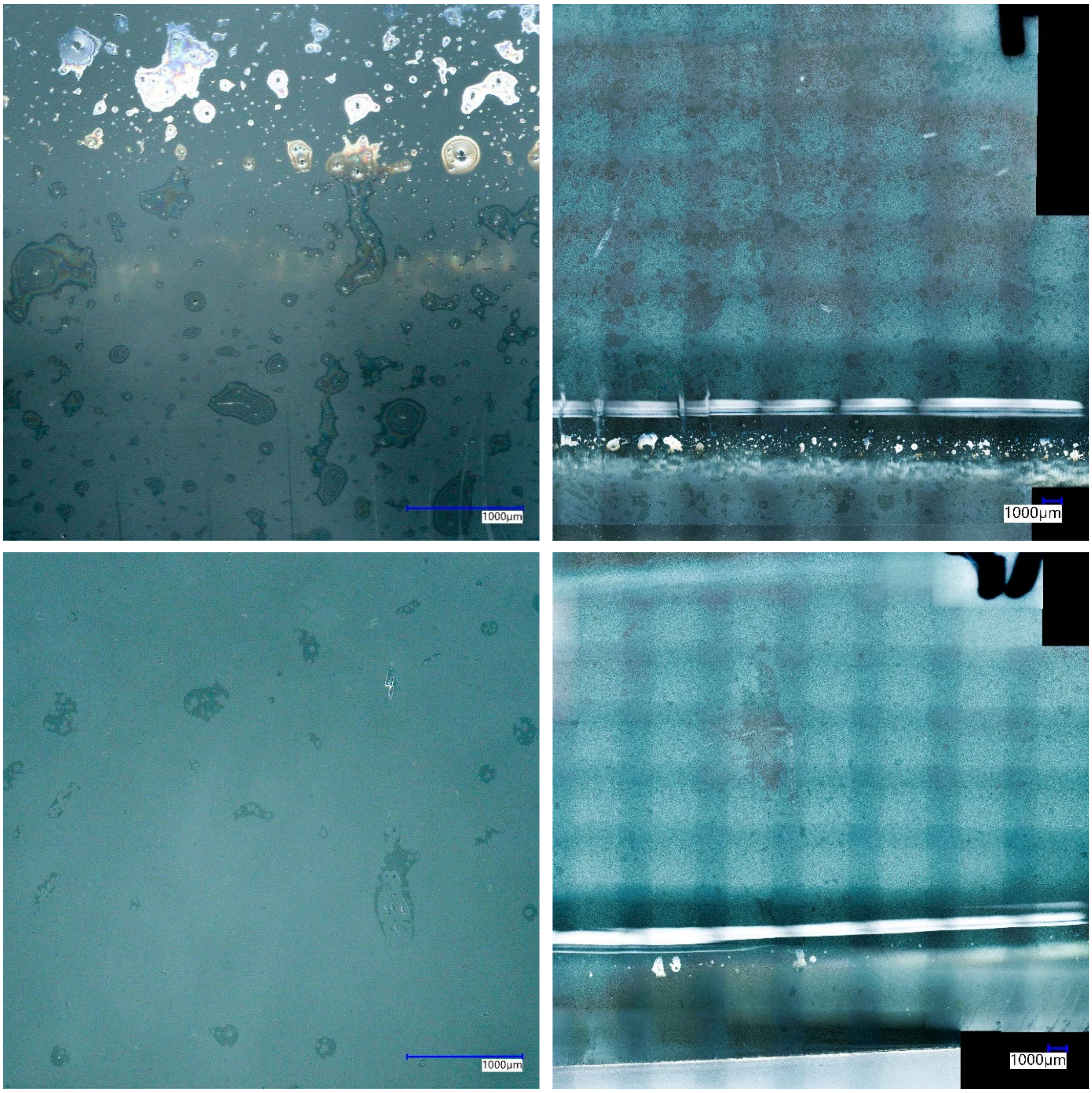


Figure 62 Insufficient bonding zone difference in 1 hour [top] and 3 hour [bottom] samples

5.2.6. Findings summarized

The most important finding will be summed here. A more elaborate explanation can be found in the corresponding sections previously in this chapter:

1. The 3-hour dwell samples show a different 'no-bond-zone' pattern. There are less small dots and some more combined non-circular zones.
2. The fracture origin is located next to a no-bond-zone, where stress concentrations/peak stresses occur.
3. The stiffness of the samples is not readable from these tests, due to the flexible wood support conditions. Deformation is mostly due to the wood, the glass is only a slight percentage of that.
4. The fracture origin of the glued samples differs from the fused ones, since it is moved up along the interface surface.
5. The DELO has a wider spread in results, due to the inaccurate application of glue. The thickness highly influences the strength.

5.3. Possible applications

The original purpose of this bonding method was to replace glueing by a more recyclable and thus sustainable alternative, to create brick with engineered air pockets. However, this is not the only potential this method has. Within the scope of bricks, colourful applications could be a very interesting architectural approach. This could be any kind of glass (marbles, coloured shards etc.).

An interesting potential application arose, in which the aluminium spacers in glass IGUs are replaced by fused glass strips. The IGUs are nowadays made with the introduction of many different materials, which makes recycling a complicated process. If this could be replaced by a more transparent and more recyclable solution, it could prove very appealing. The entire IGU could be recycled without the need of removing the spacers and sealants.

Figure 63 Engineered air pocket bricks

Figure 64 IGU [left] and marbles [right] (Franz, n.d.; Yujiannet, n.d.)

Figure 65 Mock-ups of coloured shard/marble brick suggestions

5.4. Conclusion and recommendations for further research

The tests were performed to evaluate the feasibility of tack fused glass surfaces. It can be concluded that this type of fusing is indeed promising.

The strength of these specific samples is roughly half of that of similar DELO 4468 bonded samples. This glue is used for high performance and high strength applications. However, high shear strength is not always needed by the design brief. Additionally, these samples were not made in a controlled environment, which might influence the strength (due to the increased amount of dirt and imperfections in the contact surface.

It shows sufficient potential to be further researched. Some interesting research questions are:

- What is the biggest surface area possible without breaking the glass?
- What residual stresses occur and how is the size and/or shape influencing this?
- What is the correlation between the fusing temperature and the sagging/strength? And thus what is the ideal temperature?
- Which dwell time is most suitable?
- What is the influence of the air- or tinside of the float glass on the bonding capacity?
- What is the weather tightness of this fused area? What depth is needed to ensure water-tightness?’

6. Steady-state 3D thermal evaluation

One of the scoring criteria of the MCA is the thermal transmittance, which is mostly referred to as the U-value. This U-value is related to the heat flow through a specified surface, between a temperature differential. Scoring these alternatives will be done based on a steady-state 3D computation, executed with the software TRISCO. TRISCO is based on the finite-difference method, in which orthogonal geometries can be analysed. TRISCO will then calculate the heat flow, which can be translated to a U-value.

6.1. Principles of Trisco

Trisco is a **steady-state** thermal **FDM** simulation of 2D & 3D **orthogonal building components.**

Thermal analyses can be **steady-state** or transient. Transient means that the loading conditions vary, whereas steady-state implies that an equilibrium has been found and continue with no time dependency. All thermal loads and boundary conditions are constant in time.

Trisco is based on an **FDM** or finite-difference method, which is related to the more well-known FEA. FEA (finite element analyses) method is a numerical method that uses discretisation to transform a continuous domain into a discrete domain. FDM is also a method based on the principle of discretisation, but the equations are solved differently. The finite-difference method relies on discretizing ordinary differential equations (ODE) or partial differential equations, which may be non-linear. The new system of linear equations can be solved by matrix algebra techniques. The FDM uses a topologically square network of lines, so complex irregular geometries are not very suitable with this method. For this reason, TRISCO works with **orthogonal building components.**

6.2. Model input properties

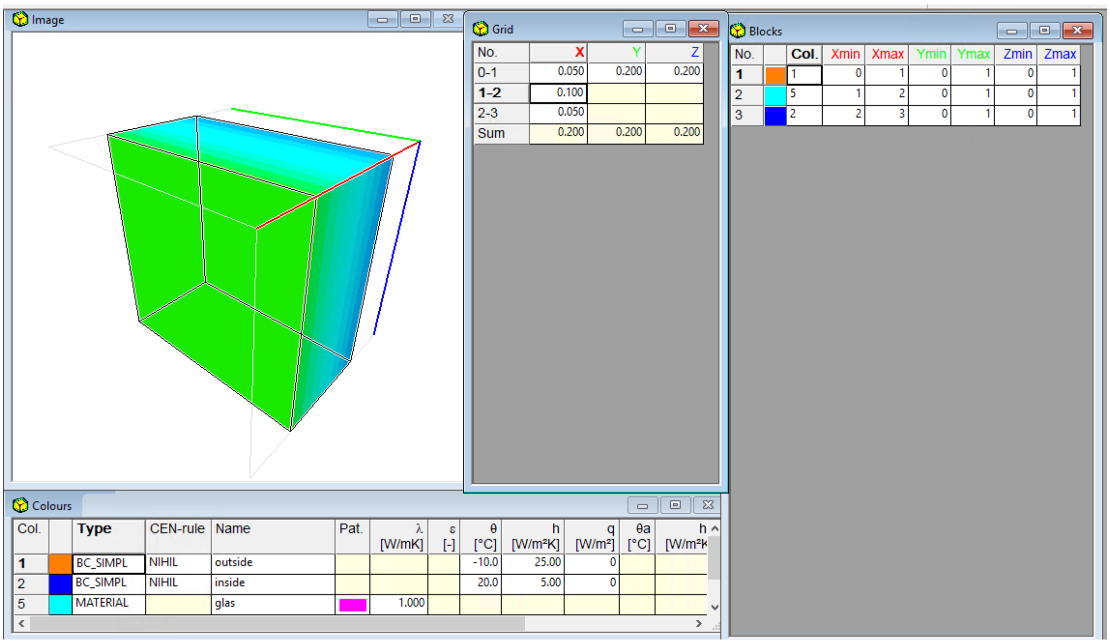
The following tables show all variables that are entered within the TRISCO model. The thermal resistance varies with the thickness of the air layer. For this reason, the *effective thermal conductivity* is calculated by dividing the thickness with the thermal resistance. According to the thickness in the model, the representing conductivity is entered.

Table 24 Different variables within the TRISCO model

variable		value	unit
thermal conductivity	glass	1.0	[W/mK]
	air	varying (Table 24)	[W/mK]
	rubber	0.015	[W/mK]
heat transfer coefficient	outside	25	[W/m^{2}K]
	inside	5	[W/m^{2}K]
temperature	outside	-10	[°C]
	inside	20	[°C]

Table 24 Effective thermal conductivity of glass, depending on cavity size

thickness of cavity d [*mm*]	*thermal resistance* *R* [m^{2}K/W]	*effective thermal conductivity* λ [W/mK]
0	0.00	
5	0.11	0.04545
7	0.13	
10	0.15	0.0667
15	0.17	
20	0.175	0.1111
25	0.18	
30	0.18	0.1667
50	0.18	0.2777
100	0.18	



No.	X	Y	Z
0-1	0.050	0.200	0.200
1-2	0.100		
2-3	0.050		
Sum	0.200	0.200	0.200

No.		Col.	Xmin	Xmax	Ymin	Ymax	Zmin	Zmax
1	🟧	1	0	1	0	1	0	1
2	🟦	5	1	2	0	1	0	1
3	🟦	2	2	3	0	1	0	1

Col.		Type	CEN-rule	Name	Pat.	λ [W/mK]	ε [-]	θ [°C]	h [W/m²K]	q [W/m²]	θa [°C]	h [W/m²k
1	🟧	BC_SIMPL	NIHIL	outside				-10.0	25.00	0		
2	🟦	BC_SIMPL	NIHIL	inside				20.0	5.00	0		
5	🟦	MATERIAL		glas	🟪	1.000						

Figure 66 Screenshot of solid brick TRISCO model

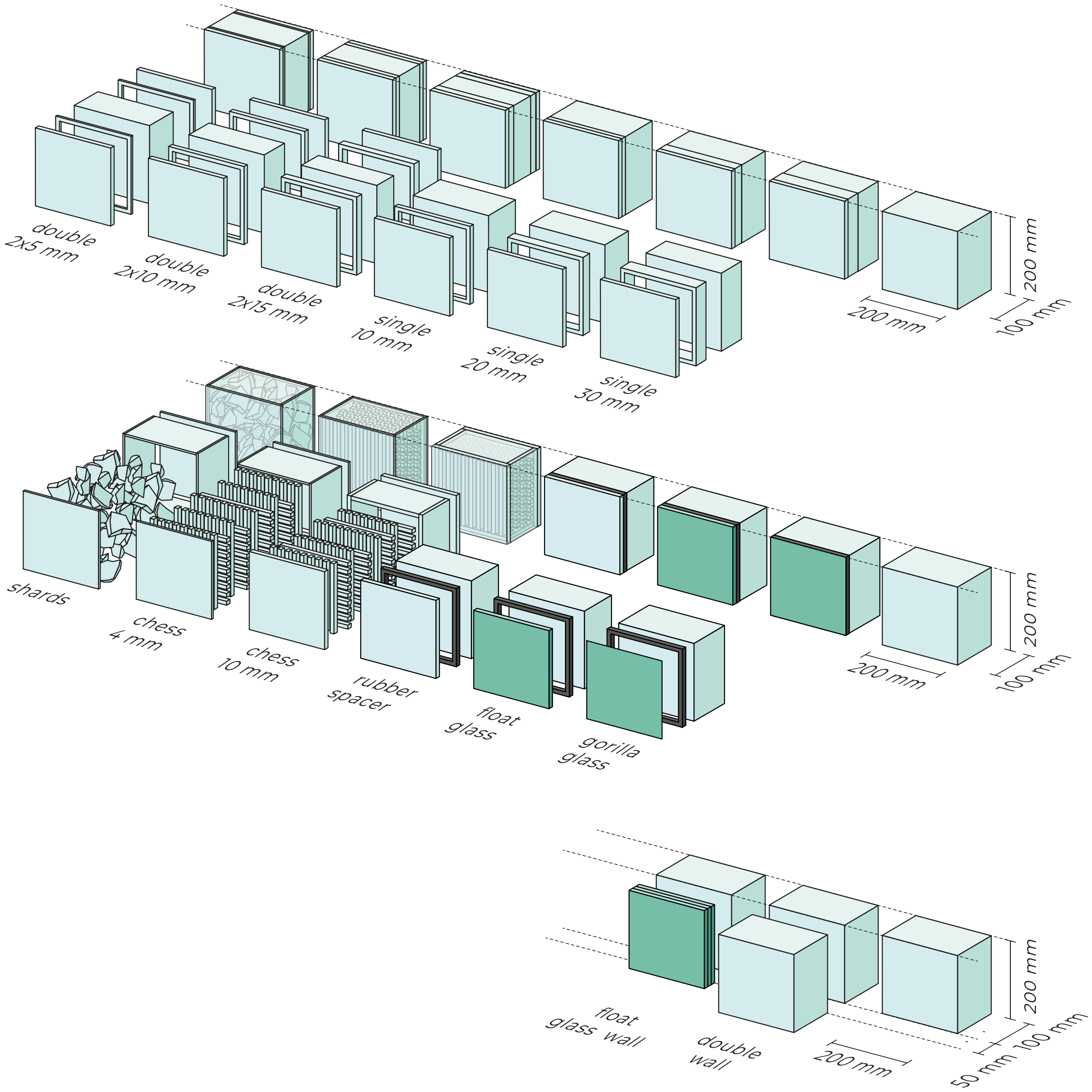


Figure 67 Overview of all geometries

Table 25 Geometry input

#	Prototype	Cavity size [mm]	Outer pane thickness [mm]	Spacer width [mm]	Strip size [mm]	Box thickness [mm]	l [mm]	b [mm]	d [mm]
0	Solid						200	200	100
1	Single cavity	10	10	10			200	200	100
		20	10	10			200	200	100
		30	10	10			200	200	100
2	Double cavity	2*5	10	10			200	200	100
		2*10	10	10			200	200	100
		2*15	10	10			200	200	100
3 + 4	Rubber spacer	10	10	10			200	200	100
5	Gorilla glass	10	2	10			200	200	100
6	Double-wall	50					200	200	250
7	Float glass wall	50					200	200	200
8	Chess				10 x 10	10	190	190	100
	Chess wide				10 x 10	10	200	200	100
	Chess 4 mm				10 x 10	4	198	198	98
	Chess 4 mm wide				10 x 10	4	188	188	98

6.3. Validity of the model

A hand calculation check for the solid brick can verify the validity of the simulation in the program. The thermal transmittance U followed from TRISCO for the solid brick is 2.94. With basic building physics, this value can also be determined.

$$\boldsymbol{R_{model} = R_{si} + R_{glass} + R_{se}} \quad \text{Equation 4}$$

$$\boldsymbol{R_{si}\ or\ R_{se} = {}^{1}/_{\alpha_{si}}\ or\ {}^{1}/_{\alpha_{se}}} \quad \text{Equation 5}$$

$$\boldsymbol{R_{glass} = d/\ \lambda} \quad \text{Equation 6}$$

R_{model}	*total resistance of model*	$[m^2K/W]$
R_{si}	*heat transfer resistance inside*	$[m^2K/W]$
R_{glass}	*resistance of glass mass*	$[m^2K/W]$
R_{se}	*heat transfer resistance outside*	$[m^2K/W]$
α	*heat transfer coefficient*	$[W/mK]$
d	*thickness*	$[m]$
λ	*thermal conductivity*	$[W/mK]$

$$R_{si} = \frac{1}{25}; R_{se} = \frac{1}{5};$$

$$R_{model} = \frac{1}{25} + \frac{0.100}{1.0} + \frac{1}{5} = 0.04 + 0.1 + 0.2 = 0.34$$

$$U_{solid\ brick} = \frac{1}{R_{model}} = \frac{1}{0.34} = 2.94118\ \ W/m^2K$$

The TRISCO value deviated 0.02% from the calculated value.

6.4. Results

Nine designs will be examined in this thesis, all numbered in the first column in Table 26. The last design, brick number nine, is not in this table, since it is not being evaluated in TRISCO. Design three and four are thermally similar, only the production technique is different. Therefore in this table, they are considered the same.

The output from TRISCO is heat flow Q in Watts, which is converted to thermal transmittance, the U-value. All thermal transmittances will be compared to the 'original' solid brick performance, to investigate what the increment in resistance is.

$$\boldsymbol{U_{Trisco} = 1/R_{TRISCO}} \quad \text{Equation 7}$$

$$\boldsymbol{R_{Trisco} = Q/(A * \Delta T)} \quad \text{Equation 8}$$

Q	*heat flow output TRISCO*	$[W]$
A	*cross-sectional area*	$[m^2]$
ΔT	*temperature difference*	$[K]$
R_{Trisco}	*thermal resistance from analyses*	$[m^2K/W]$
U_{Trisco}	*thermal transmittance from analyses*	$[W/m^2K]$

An increased cavity will automatically lead to reduced thermal transmittance, which is also investigated in paragraph 4.3 'Influence studies'. The introduction of a less conductive material for the spacers does have a big impact on the performance (number 3 +4). The 'wide' chess brick eliminates half of the strips, which results in bigger cavities. The double-wall has twice the amount of glass, and therefore a significant reduction in thermal transmittance. The last column describes the air to glass ratio, which is the total volume of air divided by the total volume of glass.

Table 26 Overview matrix of TRISCO calculations for several designs

#	**Prototype**	**Cavity size**	**l [mm]**	**b [mm]**	**d [mm]**	**A [m²]**	**eff. therm. cond. air λ [W /mK]**	**Trisco value [W]**	**Corresp. U-value [W/m²K]**	**Relative to solid brick [%]**	**Air-glass ratio**
0	Solid		200	200	100	0.04		3.53	2.9417	1.0000	1
1	Single cavity	10	200	200	100	0.04	0.0667	3.2	2.6667	0.9065	0.919
		20	200	200	100	0.04	0.1111	3.05	2.5417	0.8640	0.838
		30	200	200	100	0.04	0.1667	2.97	2.4750	0.8413	0.757
2	Double cavity	2*5	200	200	100	0.04	0.0667	3.14	2.6167	0.8895	0.919
		2*10	200	200	100	0.04	0.1111	2.93	2.4417	0.8300	0.838
		2*15	200	200	100	0.04	0.1667	2.81	2.3417	0.7960	0.757
3 + 4	Rubber spacer	10	200	200	100	0.04	0.0667	2.37	1.9750	0.6713	0.900
5	Thin glass	10	200	200	100	0.04	0.0667	3.19	2.6583	0.9036	0.919
6	Double-wall	50	200	200	250	0.04	0.2777	1.94	1.6100	0.5495	0.800
7	Float glass wall	50	200	200	200	0.04	0.2777	2.11	1.7583	0.5977	0.750
8	Chess		190	190	100	0.0361	0.0667	2.78	2.5669	0.8726	0.7030
	Chess wide		200	200	100	0.04	0.1111	2.44	2.0333	0.6912	0.4725
	Chess 4 mm		198	198	98	0.0392	0.0667	2.88	2.4487	0.8324	0.5747
	Chess 4 mm wide		188	188	98	0.0353	0.1111	1.85	1.7448	0.5931	0.3452

7. Experimental evaluation of the thermal resistance of a prototype

One of the design alternatives is a shard-filled brick, from which the thermal performance is yet unknown. Modelling this would prove difficult since the geometry is not straightforward and randomly organised. For this reason, the thermal performance will be investigated by means of an experiment. This experiment recreates a temperature differential between two surfaces of the prototypes. Sensors will measure the temperatures and the heat flow, which then can be translated into a U-value.

7.1. Test set-up

Figure 68 shows a visual representation of the test set-up used. A sample with a 100*100mm square surface is placed in a hole in the Styrofoam box. On both sides, a temperature sensor and a heat flow sensor are attached with double-sided tape. The inner and outer ambient air temperature is also measured. The system measures thus six variables; two heat fluxes and four temperatures. These variables are measured over time until an equilibrium is found. Theoretically, the inner and the outer surface will have the same heat flux, if the sample is heated up with solely conductive heat and the flow is only 2D.

The box is heated up with a shielded light bulb, which results with this specific Styrofoam box with an inner volume of 1 m^3 in a final temperature between 45 and 50 °C. To speed up the heating process, a second lamp is used, which is turned off when the inside temperature is approx. 50 °C.

Table 27 Variables in the test set-up

Number	Variable [units]	Location
1	Temperature [°C]	Inside box
2	Temperature [°C]	Inner surface test sample
3	Temperature [°C]	Outer surface test sample
4	Temperature [°C]	Outside box
A	Heat flux	Inner surface test sample
B	Heat flux	Outer surface test sample

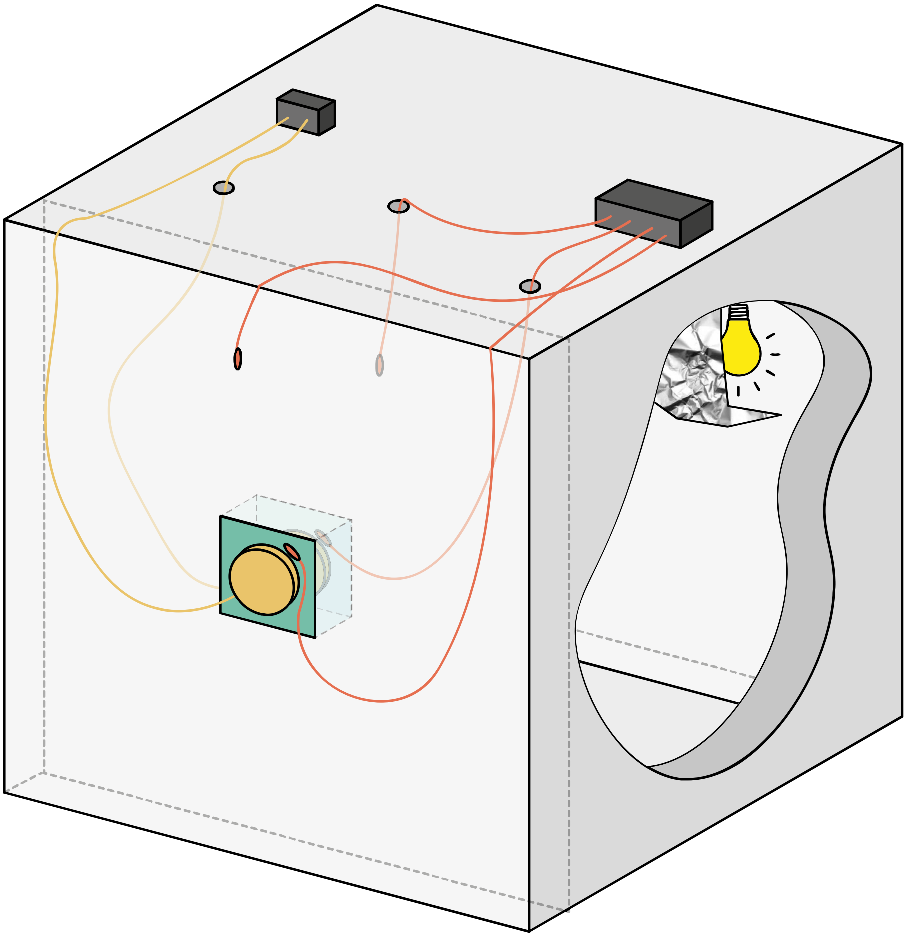


Figure 68 Schematization of the styrofoam box with sensors

Hardware:
Heat flux sensor Hukseflux HFP01
Thermocouples type T
Eltek transmitter GS44H
Eltek transmitter GS24
Eltek squirrel logger

7.2. Trial test runs and findings

During the execution of these tests, some trial runs were initiated to investigate the accuracy of the tests. Some issues and/or inaccuracies were found.

Firstly, ideally only conductive heat would be transferred through the brick. However, due to the heat source being a light bulb, this was impossible. The light bulb was shielded from direct light with a piece of aluminium foil. However, this still leaves reflection from the inside white surface in the box. An upgrade from this would be a box (with ventilation holes) around the bulb, preferably from white material or aluminium foil (low emissivity), providing a heat source with less to no radiation. To minimise the effect of the radiation going through the glass, the glass samples were taped to prevent light penetration.

Another aspect to be considered is the 2D or 3D heat flow behaviour. With an inhomogeneous sample, like the chess brick and the shard brick, the heat flow will not be 2D. An edge effect will occur, which might result in a non-converging test.

The location and size of the sensor are also of importance. If the measuring area of the sensor is too big, it might not have a single material property behind it. This problem cannot be solved by changing the size of the sample. However, it would be best to redo the test several times with the replacement of the sensors and taking the average of all test runs.

Sensors always have certain accuracies and thus inaccuracies. The given uncertainty of calibration for the HFP01 is ± 3% (k = 2). (*HFP01 Heat Flux Plate | Hukseflux*, n.d.) The Thermocouples T have a standard accuracy of +/- 1.0C or +/- .75% (whichever is greater). (*Type T Thermocouple*, n.d.)

Lastly, the imperfections in the prototypes have a significant impact on the heat flow. If two pieces of glass are supposed to touch, but they do not in the actual prototype, it will change the resistance due to the introduction of an air cavity. Also, if the outer surface is not completely flat, it is impossible to tape the sensor firmly to the sample. It will always leave air cavities and thus inaccuracies.

7.3. Test results for evaluation thermal resistance of prototypes

Because of the inaccuracies described above, it is concluded that these types of tests are in the current set-up not suitable for accurate determination of the thermal resistance. However, the tool will still be used to estimate the behaviour of the shard brick, compared to the thermal resistance of known samples (solid brick and/or chess brick). If the heat fluxes of the inner and the outer surface do not converge, both upper and lower limit will be evaluated. These values will be compared to the Trisco values from chapter 6.

7.3.1. Solid brick

As a reference, a solid brick with dimensions of 100x100x65 mm^3 was tested. During the first test run, the measurements turned chaotic halfway in. This problem later disappeared and the inner and outer surface heat flow converged. However, the computer software did not save the last set of data points and thus the final values are lost.

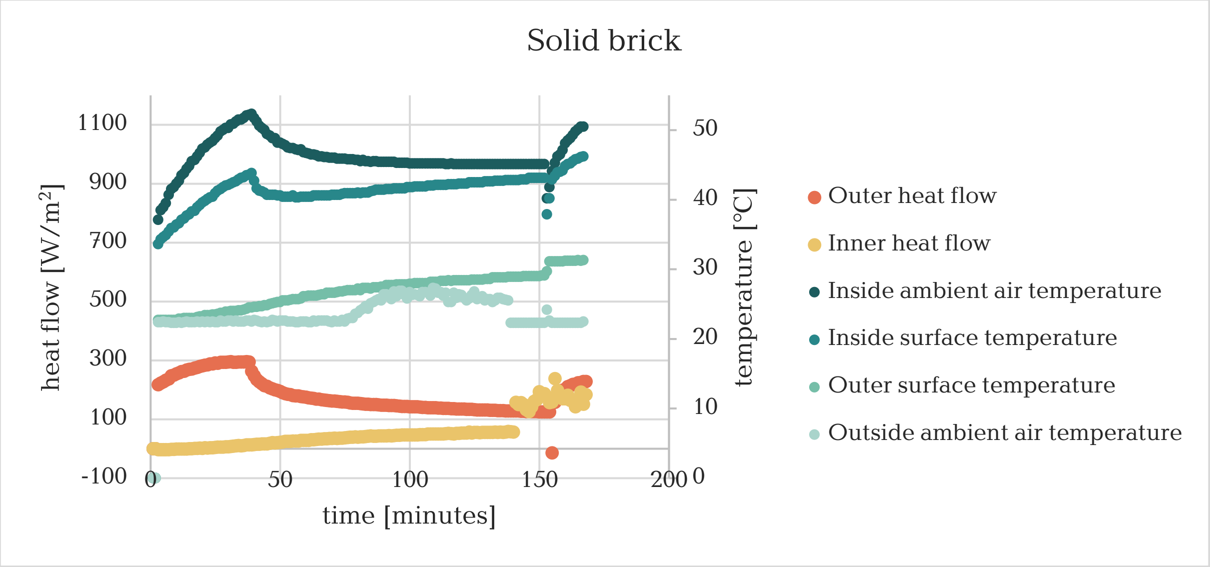


Figure 69 Solid brick heat flow test data

This test was performed again, however, this time the outer surface sensor measures values that do not seem to correspond with reality. The temperature difference from both sides of the sensor is approximately 0.8 °C, which cannot correspond with a negative heat flow of -6.88 mV. This value has to be a value close to zero.

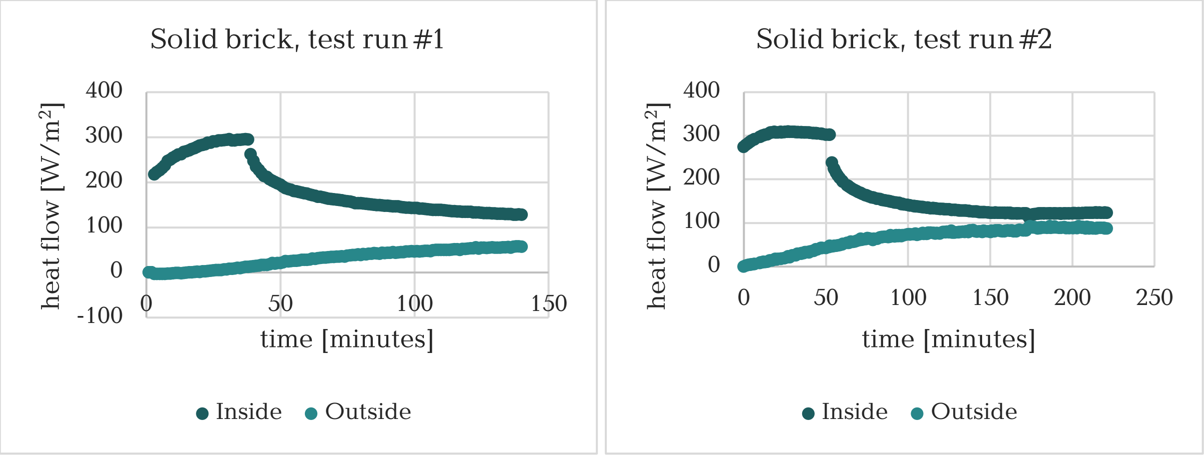


Figure 70 Comparison of both solid brick test results

For the purpose of illustration, a vertical shift is applied where the new outside heat flow value at the start is 0. This provides a graph with predicted behaviour and a close to convergence outcome. The measurements deviate a little constantly, so for the final value, an average of the last 5 are taken. This value needs to be converted to W/m^2. Each sensor has its corresponding sensitivity, 62.23 μV/(W/m^2) for the inside sensor and 61.22 μV/(W/m^2) for the outside sensor.

Inside heat flow: 123.41 W/m^2
Outside heat flow: 88.14 W/m^2
Temperature difference ΔT*: 42.8 - 28.9 = 13.9 °C*

7.3.2. 10 mm chess brick

A sample is made in which 10 mm thick float glass is used to make a chess-like pattern. This prototype is far from precise, which results in many undesired air gaps. For this reason, it is expected the value will not correspond perfectly with the TRISCO calculation. Also, one surface is concave, due to some sagging in the fusing process. The flow is also three dimensional and the precise placement of the sensors will influence the measurements.

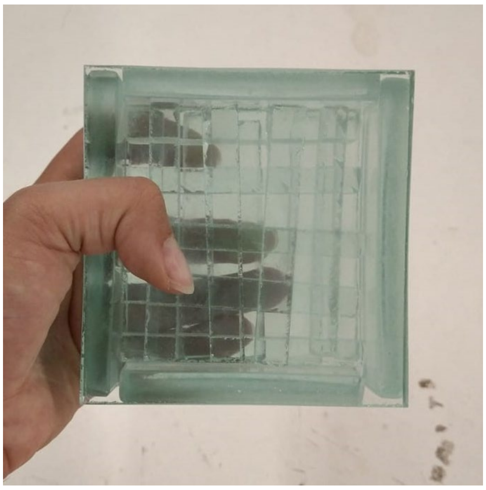


Figure 71 10 mm float glass chess brick prototype

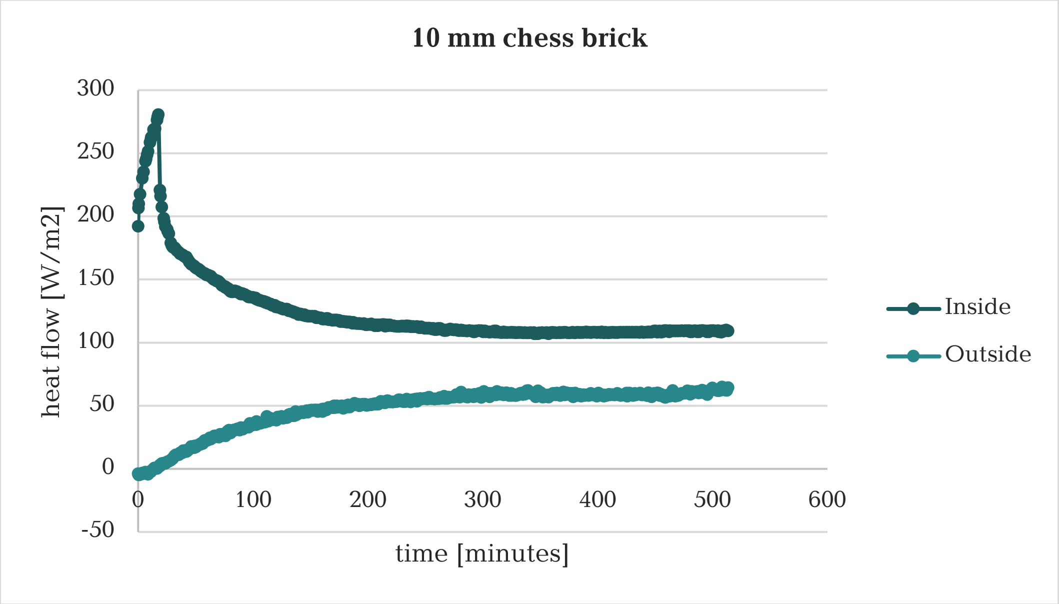


Figure 72 10 mm chess brick thermal test

Inside heat flow: 109.26 W/m²

Outside heat flow: 60.61 W/m²

Temperature difference ΔT: 49.6 – 36.5 = 13.1 °C

7.3.3. 4 mm chess brick

The 4 mm chess brick is very similar to the previous one, but the side 'walls' are made of 4 mm thick float glass, instead of 10 mm.

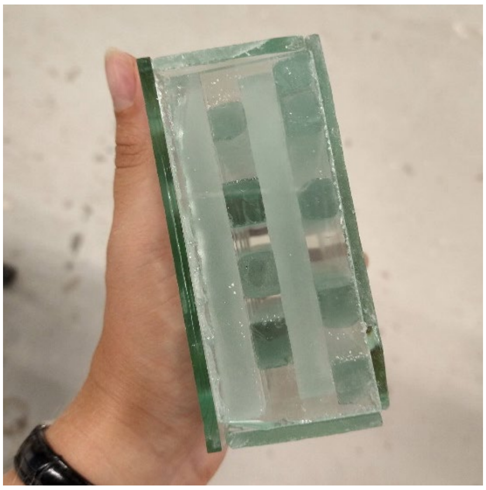


Figure 73 4 mm float glass chess brick **prototype**

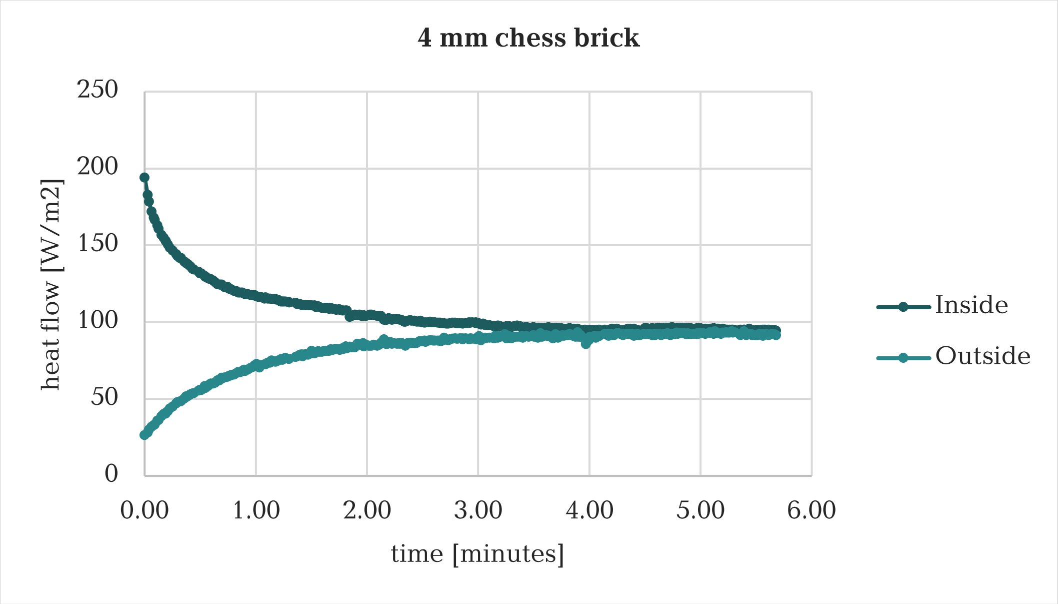


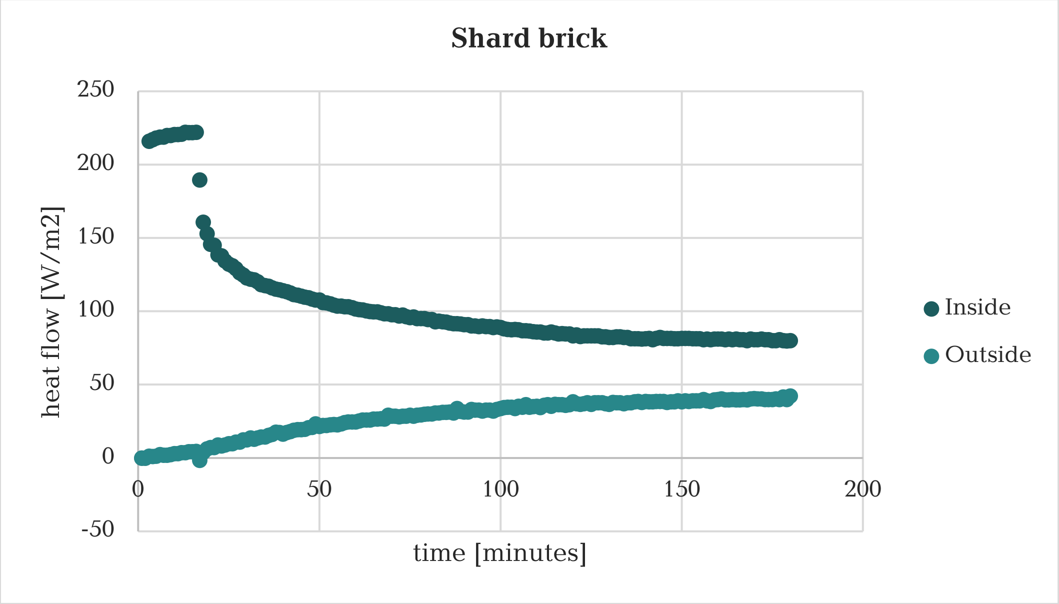
Figure 74 4 mm chess brick test results

Inside heat flow: 94.76 W/m^2
Outside heat flow: 91.96 W/m^2
Temperature difference ΔT*: 45.3 – 30.8 = 14.5 °C*

7.3.4. Shard brick

The shard brick is produced with 4 mm thick sidewalls and filled with chunky glass pieces and smaller shards. The tests are performed twice, aiming to achieve a better insight into the performance. However, during the second test, some sensor problems occurred and this test is considered null.

Figure 75 Shard brick prototype



Inside heat flow: 80.34 W/m²

Outside heat flow: 40.34 W/m²

Temperature difference ΔT: 44.2 – 27.9 = 16.3 °C

7.4. Comparison

In an ideal situation, the inner and outer heat flux converges into one value $[q]$. With the temperature difference, the 'measured thermal resistance of brick only' can be calculated (Equation 9). This value represents only the thermal resistance of the brick and does not include the heat transfer resistance. Similar resistances are used as within the TRISCO model. The inverted sum of these values gives the computed thermal transmittance (U-value) for comparison (Equation 10 and Equation 12).

$$\boldsymbol{R_c = \Delta T/q} \qquad \text{Equation 9}$$

$$R_{total} = R_c + R_{si,Trisco} + R_{se,Trisco} \qquad \text{Equation 10}$$

$$R_{si,Trisco} + R_{se,Trisco} = \frac{1}{25} + \frac{1}{5} = 0.24 \quad m^2K/W \qquad \text{Equation 11}$$

$$U_{total} = 1/R_{comparison} \qquad \text{Equation 12}$$

R_c	*measured thermal resistance of brick only*	$[m^2K/W]$
ΔT	*measured temperature difference*	$[K]$
q	*measured heat flow*	$[W/m^2]$
$R_{s,Trisco}$	*heat transfer resistance similar to Trisco*	$[m^2K/W]$
R_{total}	*total computed thermal resistance*	$[m^2K/W]$
U_{total}	*computed U-value for comparison*	$[W/m^2K]$

These tests were also run in TRISCO (except for the shard brick). The same geometries are used as an input, however, this does not incorporate the production inaccuracies or misalignments. With the steps described by Equation 9 to Equation 12, the corresponding thermal transmittance is calculated for both boundaries.

Table 28 Comparable TRISCO U-values

	depth t [mm]	**ΔT [K]**	**Cross-sectional area A [m²]**	**Q-value [W]**	**U-value [W/m²K]**
Solid	65	30	0.0100	0.98	3.2667
	50	30	0.0100	1.03	3.4333
10 mm chess	50	30	0.0100	0.99	3.3000
4 mm chess	50	30	0.0096	0.91	3.1597
Shards	50	30	0.0100	-	

Unfortunately, as the previous paragraph shows, the values do not converge in all cases. Interestingly, with the first test run of the solid brick, the values converged, but in the second they did not. This leaves for speculation on how to interpret the performance. The main goal of these tests was to estimate the thermal performance of the shard brick. The other samples are used as references, in order to compare the values of several prototypes.

Table 29 includes both the inner heat flow q and the outer heat flow q. The inner heat flow is the upper boundary and the outer surface is the lower boundary. The actual performance should be between these values.

Table 29 Experimental U-values

	depth t [mm]	**ΔT [K]**	**Lower boundary**		**Upper boundary**	
			q-value [W/m²]	U-value [W/m²K]	q-value [W/m²]	U-value [W/m²K]
Solid	65	13.9	88.14	2.514435	123.41	2.835812
10 mm chess	50	13.1	60.61	2.192329	109.26	2.778569
4 mm chess	50	14.5	91.96	2.514602	94.76	2.544412
Shards	50	16.3	40.34	1.552637	80.34	2.257909

The TRISCO values and the experimental values will never be exactly the same. Due to the limitations of this paper, assumptions had to be made, which can lead to inconsistencies. The thermal conductivity of the glass, for example, is not known. This will deviate from the value used in TRISCO. The upper boundary values are closest to the (more reliable) TRISCO value. Therefore, these will be considered determinative.

Table 30 Ratio between the experimental U-value and the TRISCO analysis

	$\xi = \frac{\textbf{U}-\textbf{value experiment}}{\textbf{U}-\textbf{value TRISCO}}$	
	Lower boundary	Upper boundary
Solid	0.7697	0.8681
10 mm chess	0.6643	0.8420
4 mm chess	0.7958	0.8053

The thermal performance for the MCA is done with models that have a geometry of 200x200x100 mm^3. These tests were done (for practical reasons) at a 1:2 scale. Therefore, the value must be converted to an upscaled version. This must be done **without** the heat transfer resistances. Thus, the 'measured thermal resistance of brick only' must be multiplied by two (since the brick will have twice as much depth), then the heat transfer resistances need to be added and finally multiplied by the 'conversion factor', which incorporates the measuring inaccuracies.

$$q_{shard} = 80.34\ [W/m^2]$$

$$\Delta\mathrm{T} = 16.3\ [\mathrm{K}]$$

$$R_c = \frac{\Delta T}{q_{shard}} = 0.202888\ [m^2K/W]$$

$$R_{MCA} = \left(2 * R_c + R_{si,TRISCO} + R_{se,TRISCO}\right) = (2 * 0.202888 + 0.24) = 0.645775\ [m^2K/W]$$

$$U_{MCA} = \frac{\frac{1}{R_{MCA}}}{\xi} = \frac{\frac{1}{0.645775}}{\xi} = \frac{1.54853}{\xi} = \begin{matrix} U_{MCA,min} = 1.78381 \\ U_{MCA,max} = 1.92292 \\ U_{MCA,avg} = 1.84685 \end{matrix}\ [W/m^2K]$$

The thermal performance of this specific shard brick, on a full scale, is considered approx. 1.85 $[W/m^2K]$, which is approx. 63% compared to a solid glass brick of the same dimensions. Important to note is that the thermal performance of this brick is highly dependant on the configuration and size of the shards.

7.5. Conclusion and recommendations for further research

In paragraph 7.2 'Trial test runs and findings' some uncertainties and inaccuracies are discussed. All these 'errors' combined lead to an almost unusable data set. For the sake of this thesis, an estimated guess was sufficient, but this might not be for other applications.

When accurately evaluating the thermal performance through this experimental test, one must rule out the uncertainties. Studies into the impact of each uncertainty on the actual behaviour need to be conducted.

The first recommendation will be to study the impact of the shield for the heat source. Which light bulb cover shields the most radiation? Is the behaviour better analysed with for example a thin aluminium film around the glass prototype? Does this lead to irregularities? Important to note is that this foil needs to be stuck firmly onto the glass, to prevent air cavities.

The size of the prototype influences the 3D heat flow. Which prototype size is sufficient to present 2D behaviour in the centre? What happens when multiple sensors are placed, from which some in the corners? Will this accurately show non-2D behaviour?

When using inhomogeneous prototypes (perpendicular to the outer surface), the location of the sensor will influence the measurements. If the sensor is located on an air cavity, it will have a direct impact on the heat flow present at that certain location. Several tests need to be conducted, from which an average value will give the most accurate result.

Lastly, when interested in prototyping complex geometries, the accuracy of the actual prototype will play an important role. The accuracy of these prototypes was fairly low. One must pay attention to better alignment, fusing surfaces and the sealing of the cavities. It would be best if several prototypes of the same design will be tested, to minimise the impact of the inaccuracies.

8. Multi-criteria analysis

The final chapter of this thesis will focus on multi-criteria analyses. All design alternatives will be scored against several criteria. First, the criteria will be determined and weighed, since the weight of each criterion varies according to its importance. Most scoring can be concluded from previous chapters and the criteria that remain will be scored within this chapter. This is either done by some simple calculations or a small expert survey.

The highest scoring alternative is not the sole outcome of an MCA. It could also prove interesting to combine designs or to generate interesting future fields of study from the results.

8.1. Definition of criteria

All designs should be scored against multiple criteria. These criteria will be defined to fully assess the potential of each design.

First of all, thermal performance, which is the most straightforward criterion. The scores correspond to the results found in Chapter 6 'Steady-state 3D thermal evaluation'. This is one of the most, if not the most important criteria. Better thermal performance of the final product will directly lead to less energy usage during the lifetime of the façade. Each alternative will be scored with the same sample size, compared to a solid glass brick of the same size.

Secondly, a sustainable production method is chosen as a criterion. The amount of energy required to make a sample, the origin and amount of raw materials and/or the recyclability of the final product are evaluated. A checklist will give each alternative a score.

Harder to subjectively assess, but not negligible is the aesthetic potential of an alternative. These bricks are ultimately designed for architectural purposed and thus the aesthetics are of importance. Due to the highly subjective nature of these criteria, a small survey will be done with a small pool of experts within this area of expertise.

Another subjective criterion that will be scored with the survey will be the producibility. It is nearly impossible to fully estimate the amount of effort and money it will take to produce each alternative. However, experts can give a ranking, based on their personal experience. All these opinions combined result in a more substantiated score.

The transparency of the glass is an important incentive for using the material. For this reason, transparency will also be evaluated. This is done by calculating the ratio of the cross-sectional area of non-transparent materials to the glass plus the amount of refracting surfaces in the design. Each transition from glass to air results in a loss of transparency.

8.2. Weighing of criteria

As mentioned before, not all criteria contribute to the same extent to the design goal. The designer must choose which criteria influence the outcome the most and which the least. The thermal performance is the main reason for this research, for its contribution to the sustainability in means of energy usage. Therefore, the highest score is the thermal performance with a weight of 4. The sustainability in terms of production comes next, since it is, combined with the thermal performance, the overall sustainability. In order words, this thesis aims to improve this specific aspect of the current brick design. Both criteria are numeric scaled values, which is substantiated by measurable variables.

Producibility and aesthetical potential are weighted with 2, since they are considered of importance, but are not easily justifiable. These criteria are based on an expert survey, which is inter-subjective and not precise. Transparency of cast glass walls is of importance, but even with the 'original' brick glass wall, image formation is almost not possible. Light will be transmitted, but one cannot as clearly view through the wall as one could with window panes. The bricks could still have a high potential, even if the transparency is less. Therefore it is considered the lowest weight of 1.

The weighing of these criteria is no strict science and is influenced by the designer. A design problem can be tackled in many ways and there is not one design that solves all. The role of a designer is aiming to solve the problem in the way that they seem fit. For the evaluation of the criteria themselves, subjectivity is ruled out as much as possible. However, this is not desirable for the weighing of the criteria (or even the definition of the criteria) within this thesis since this would be out of proportion and therefore this does not lie within the scope.

Table 31 Criteria weights

Rank#	Criteria	Weight
1	Thermal performance	4
2	Sustainability	3
3	Producibility	2
4	Aesthetical potential	2
5	Transparency	1

8.3. Scoring of alternatives

8.3.1. Thermal performance

For the thermal performance, the relative U-value to the solid brick is shown. Since the preferred final score is from 0 to 1, where 1 is the 'best' score, all values are inverted (1 minus value). The highest score goes to the design where less-conductive spacers are used.

Table 32 Scoring thermal performance

	Prototype		**Relative to solid brick [%]**	**Score [0⟶1]**
	Solid		1	
1	Single cavity	10	0.9065	0.0935
		20	0.8640	0.1360
		30	0.8413	0.1586
2	Double cavity	2*5	0.8895	0.1105
		2*10	0.8300	0.1700
		2*15	0.7960	0.2040
3	Single cavity with spacers		0.6713	0.3286
4	Float glass with spacers		0.6713	0.3286
5	Thin glass		0.9036	0.0963
6	Double-wall		0.5495	0.4505
7	Secondary float glass wall		0.5977	0.4023
8	Chess		0.8726	0.1274
	Chess 4 mm		0.8324	0.1675
9	Shard brick		0.6300	0.3700

8.3.2. Sustainability

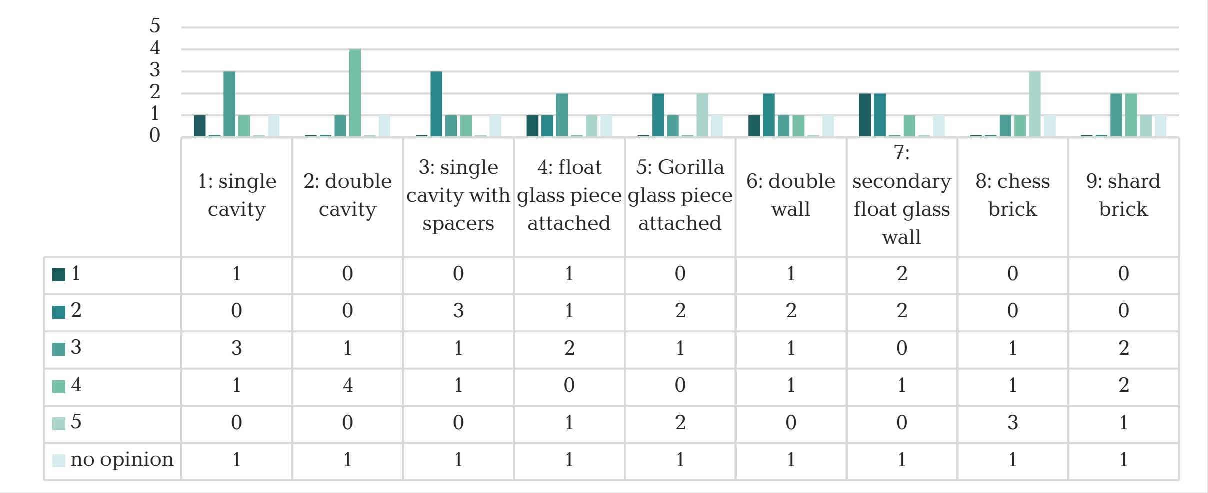
The sustainability of the production process is scored with an MCA within this MCA. Five criteria are scored: the amount of weight saved, compared to the solid brick (the first column is the air-glass ratio shown in Table 26), if the brick can fully be made out of either recycled cullet or recycled float glass panels, what the required temperature is for the production of the brick and if the final result is fully recyclable in itself (this does not consider the installation). The material usage is rescaled to fit between 0 and 1 and is considered the biggest impact, with a weight of 2.

Table 33 Scoring sustainability

	Prototype		**Weight saving**		**Can be made from recycled cullet?**		**Can be made from recycled float glass?**		**Temperature?**		**Fully recyclable?**		**Total score**	**Score [0⟶1]**
0	Solid		1	0	Yes	1	Yes	1	>750	0	Yes	1	3	0.50
1	Single cavity	10	0.919	0.5405	Yes	1	Yes	1	>750	0	Yes	1	4.08	0.68
		20	0.838	0.7746	Yes	1	Yes	1	>750	0	Yes	1	4.54	0.75
		30	0.757	0.8286	Yes	1	Yes	1	>750	0	Yes	1	4.65	0.77
2	Double cavity	2*5	0.919	0.7206	Yes	1	Yes	1	>750	0	Yes	1	4.44	0.74
		2*10	0.838	0.7746	Yes	1	Yes	1	>750	0	Yes	1	4.54	0.75
		2*15	0.757	0.8286	Yes	1	Yes	1	>750	0	Yes	1	4.65	0.77
3	Single cavity with spacers		0.9	0.7333	yes	1	yes	1	>750	0	No	0	3.47	0.57
4	Float glass with spacers		0.9	0.7333	No	0	Yes	1	>750	0	No	0	2.47	0.41
5	Thin glass		0.919	0.7206	No	0	No	1	>750	0	No	0	2.44	0.40
6	Double-wall		2	0.0000	Yes	1	Yes	1	>750	0	Yes	1	3.00	0.50
7	Secondary float glass wall		1.5	0.3333	No	0	No	1	>750	0	No	0	1.67	0.27
8	Chess		0.703	0.8646	No	0	Yes	1	<750	1	Yes	1	4.73	0.78
	Chess 4 mm		0.574	0.9506	No	0	Yes	1	<750	1	Yes	1	4.90	0.81
9	Shards		0.500	1	Yes	1	Yes	1	<750	1	Yes	1	6.00	1.00

8.3.3. Producibility

For the producibility, a small expert survey has been conducted. Five experts were asked to score given design on a scale from 1 to 5, on both aesthetical/architectural potential and producibility. They were given Appendix E, in which all designs are explained. The results of this survey are shown in Figure 76 and Figure 77. The first graph shows the number of times a certain score was chosen (1=easy, 5=labour intensive/hard). When showing the spread and averages in the second graph, the 'no opinion' results are not taken into account. Table 34 shows the averages of the survey results. These scores have been rescaled to fit between 0 (originally 1) and 1 (originally 5). Then the values are inverted since the most preferred score should be the highest, which is the easiest to produce.



	1: single cavity	2: double cavity	3: single cavity with spacers	4: float glass piece attached	5: Gorilla glass piece attached	6: double wall	7: secondary float glass wall	8: chess brick	9: shard brick
■ 1	1	0	0	1	0	1	2	0	0
■ 2	0	0	3	1	2	2	2	0	0
■ 3	3	1	1	2	1	1	0	1	2
■ 4	1	4	1	0	0	1	1	1	2
■ 5	0	0	0	1	2	0	0	3	1
■ no opinion	1	1	1	1	1	1	1	1	1

Figure 76 Survey test results for producibility, total overview

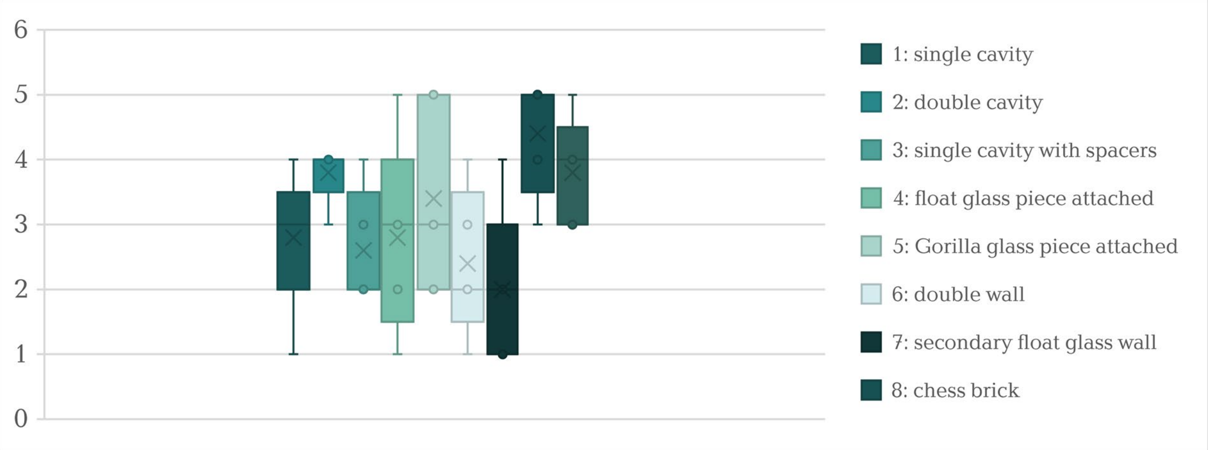


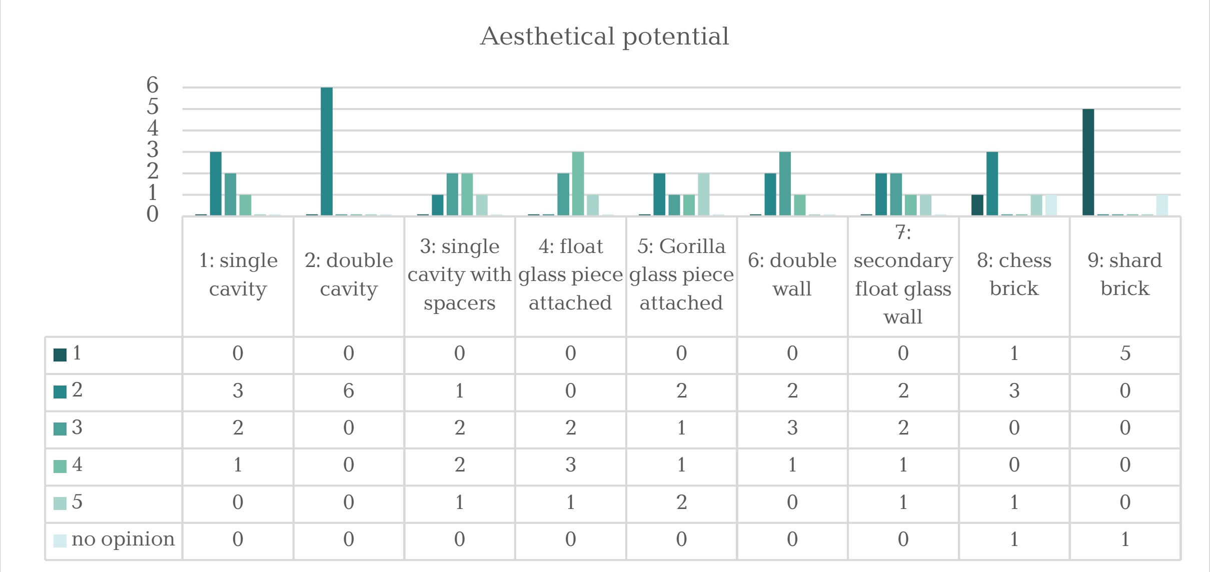
Figure 77 Survey test results for producibility, spread and averages

Table 34 Scoring producibility

	Prototype		Average from survey	Score [0⟶1]
	Solid			
1	Single cavity	10	2.8	0.55
		20	2.8	0.55
		30	2.8	0.55
2	Double cavity	2*5	3.8	0.30
		2*10	3.8	0.30
		2*15	3.8	0.30
3	Single cavity with spacers		2.6	0.60
4	Float glass with spacers		2.8	0.55
5	Thin glass		3.4	0.40
6	Double-wall		2.4	0.65
7	Secondary float glass wall		2.0	0.75
8	Chess		4.4	0.15
	Chess 4 mm		4.4	0.15
9	Shard brick		3.8	0.30

8.3.4. Aesthetical potential

Similar to the previous criterion ‘producibility’, the aesthetical potential was scored according to an expert survey. The results are rescaled and flipped again, to range from 0 (least preferred) to 1 (most preferred). Since the shard brick got the highest achievable score, it was awarded a final score of 1.



	1: single cavity	2: double cavity	3: single cavity with spacers	4: float glass piece attached	5: Gorilla glass piece attached	6: double wall	7: secondary float glass wall	8: chess brick	9: shard brick
■ 1	0	0	0	0	0	0	0	1	5
■ 2	3	6	1	0	2	2	2	3	0
■ 3	2	0	2	2	1	3	2	0	0
■ 4	1	0	2	3	1	1	1	0	0
■ 5	0	0	1	1	2	0	1	1	0
■ no opinion	0	0	0	0	0	0	0	1	1

Figure 78 Survey test results for aesthetical potential, total overview

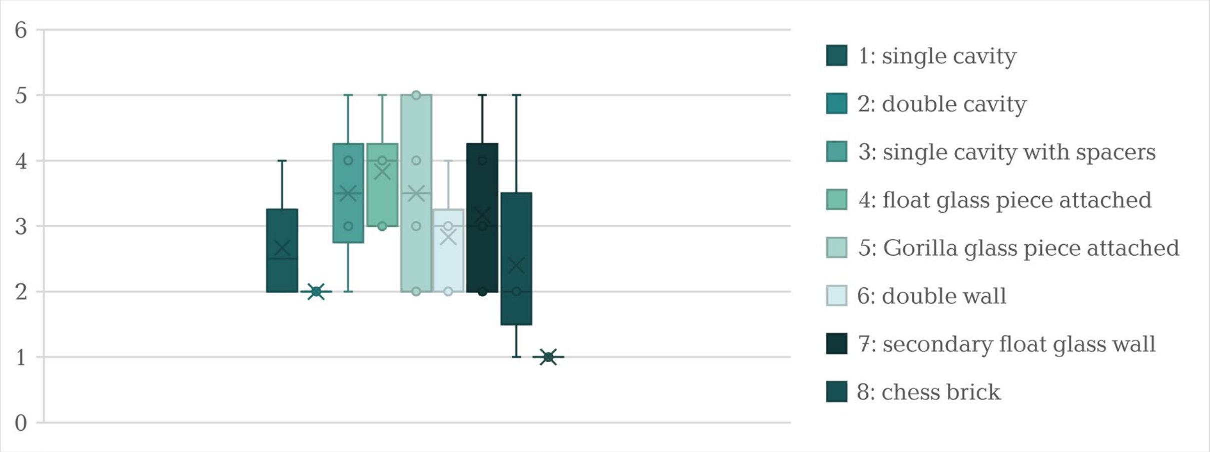


Figure 79 Survey test results for aesthetical potential, spread and averages

Table 35 Scoring aesthetical potential

	Prototype		**Average from survey**	**Score [0⟶1]**
	Solid			
1	Single cavity	10	2.3	0.67
		20	2.3	0.67
		30	2.3	0.67
2	Double cavity	2*5	3.0	0.50
		2*10	3.0	0.50
		2*15	3.0	0.50
3	Single cavity with spacers		3.5	0.37
4	Float glass with spacers		3.5	0.37
5	Thin glass		2.8	0.55
6	Double-wall		2.5	0.63
7	Secondary float glass wall		2.8	0.55
8	Chess		1.6	0.85
	Chess 4 mm		1.6	0.85
9	Shard brick		1.0	1.00

8.3.5. Transparency

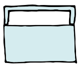
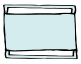
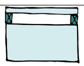
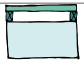
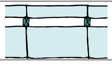
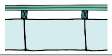
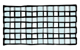
The transparency of the prototypes is influenced by the presence of non-transparent materials and the refraction surfaces. When there is a transition from glass-to-air, some reflectivity will occur. This will reduce the clear view and thus reduce the sense of transparency. For this criterion, the cross-sectional area is analysed and the percentage of non-transparent material is calculated. Also, the amount of glass-to-air transitions is counted. The scoring is calculated by taking two times the non-transparent surface area and adding the number of refractive surfaces divided by four. The best achievable score is considered as the solid brick (at 0.5) and the poorest at 5 (the non-transparent, yet translucent shard brick). The number of refractive surfaces of the shard brick is not measurable but is set at 20 as a rough estimate. The scores are rescaled to fit between 0 and 1 and then flipped (for ascending order).

Table 36 Scoring aesthetical potential

	Prototype		**Surface area of non-transparent materials**	**Number of refractive surfaces**	**2*NTSA+RSA/4**	**Score [0⟶1]**
0	Solid		0%	2	0.5	
1	Single cavity	10	0%	4	1	0.889
		20	0%	4	1	0.889
		30	0%	4	1	0.889
2	Double cavity	2*5	0%	6	1.5	0.778
		2*10	0%	6	1.5	0.778
		2*15	0%	6	1.5	0.778
3	Single cavity with spacers		19%	4	1.38	0.804
4	Float glass with spacers		19%	4	1.38	0.804
5	Thin glass		19%	4	1.38	0.804
6	Double-wall		0%	4	1	0.889
7	Secondary float glass wall		0%	4	1	0.889
8	Chess 10 mm		0%	6	1.5	0.778
	Chess 4 mm		0%	7	1.75	0.722
9	Shards		0%	20	5	0.000

8.4. Performance matrix

The performance matrix is the combined scoring of all criteria. All criteria are scored between 0 and 1, where 1 is the highest achievable score. The total score considers the weight of each criterion.

			Aesthetical potential (2)	**Producibility (2)**	**Sustainability (3)**	**Thermal performance (4)**	**Transparency (1)**	**Total**
0		Solid						
1		Single cavity	0.68	0.55	0.68	0.0935	0.889	5.76
			0.68	0.55	0.75	0.1360	0.889	6.14
			0.68	0.55	0.77	0.1586	0.889	6.29
2		Double cavity	0.50	0.30	0.74	0.1105	0.778	5.04
			0.50	0.30	0.75	0.1700	0.778	5.31
			0.50	0.30	0.77	0.2040	0.778	5.50
3		Single cavity with spacers	0.38	0.60	0.57	0.3286	0.804	5.79
4		Float glass with spacers	0.38	0.55	0.41	0.3286	0.804	5.21
5		Thin glass	0.55	0.40	0.40	0.0963	0.804	4.29
6		Double-wall	0.63	0.65	0.55	0.4505	0.889	6.90
7		Secondary float glass wall	0.55	0.75	0.27	0.4023	0.889	5.91
8		Chess	0.85	0.15	0.78	0.1274	0.778	5.63
		Chess 4 mm	0.85	0.15	0.81	0.1675	0.722	5.82
9		Shards	1.00	0.30	1.00	0.3700	0.000	7.08

8.5. Conclusion

Three typologies are scoring the best: the single cavity, the double-wall and the shard brick. The double-wall has the best thermal performance since it is literally twice a wall. The downside of this is the material usage (and thus sustainability). The shard brick scores well to high in every criterion except transparency. This brick has no image formation due to the shards inside. The single cavity is one of the simplest designs and scores average in almost every category. The biggest cavity has (as expected) the best score (mostly due to the thermal performance).

Conclusion

The objective of this research was to **explore possibilities** to **increase** the **sustainability** of a structural cast **glass brick wall**, in both **thermal performance** and **production** process.

Currently, three main glass building skin applications for environmental control in the built environment exist; float glass, hollow glass blocks and cast glass bricks. Each application with its pros and cons. The most common application is **float glass.** This is widely used throughout the whole world. For using float glass as a load-bearing material, the common practice is to laminate it into thicker components. Float glass combined in an IGU offers good insulation, however, the main concern with float glass and laminated glass structures is the **absence of a sustainable life cycle of the material**. Very little recycled cullet is used and the final product is merely downcycled into other usages. Similar reuse/recycling issues occur with hollow glass blocks. Although such blocks are quite insulating due to their cavity, they have a minimum structural capacity. The more sustainable and robust **cast glass**, which allows for complete use of **recycled raw materials**, has some **thermal performance issues**, due to its solid nature and thus the absence of voids (in comparison to IGUs or hollow glass blocks). A new path is searched, which allows for a more overall sustainable solution with glass as the main building material.

There are many ways in which you can tackle the thermal performance, like adding additional insulating material, inert gasses, coatings, but the most simple, cheap and yet elegant solution is by the introduction of **air cavities**. Air is the one matter on earth that we cannot deplete. It is effective, yet easily applicable. Creating cavities also introduces opportunities to create new shapes, products or optimisations, with much architectural potential. This air pocket creation can be dealt with on a **system or unit level**, either changing the typology of the entire wall, or the geometry of a single brick. When adapting on an element level, more design freedom is possible and the final product is adaptable for multiple configurations, whereas a wall is more project-specific. Additionally, when introducing for example a secondary wall, much extra material is required, which is not the most sustainable approach.

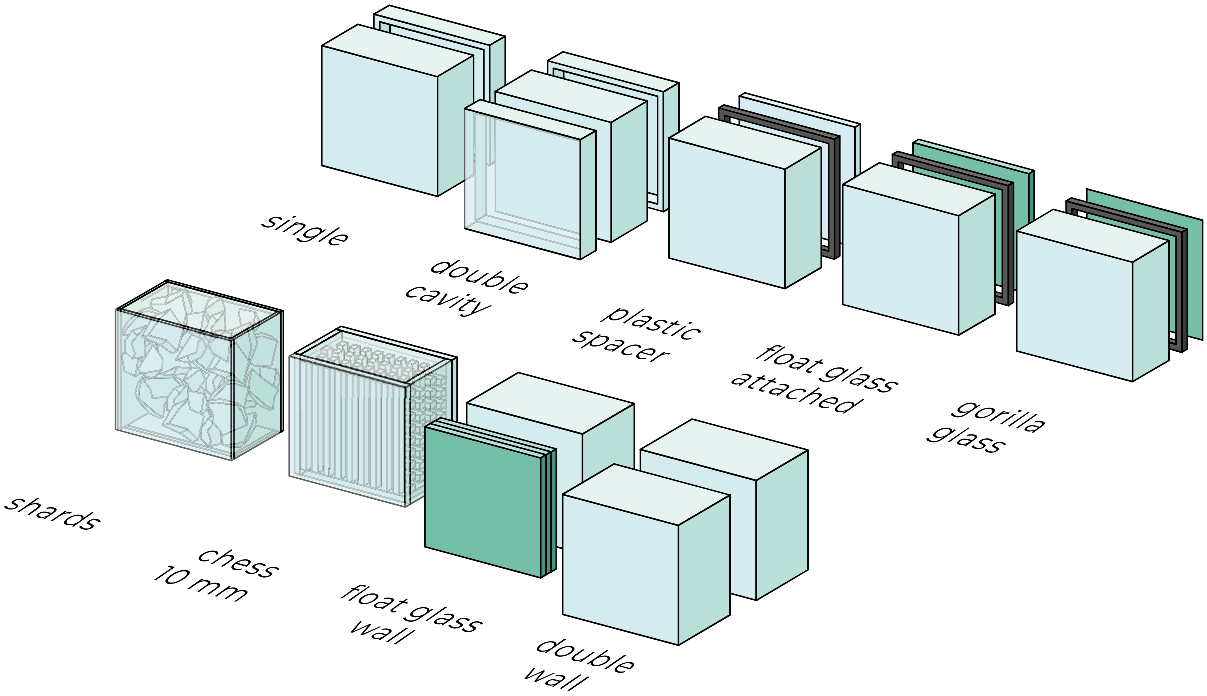


Figure 80 Design overview

As a design starting point, two extremes are illustrated; on one hand, a **strong and structural solid brick**, with the poorest thermal performance and on the other hand a more fragile yet better **insulating hollow glass brick**. In principle, the more air, the better the thermal performance and the more glass, the better the structural performance. The focus of this thesis is the thermal performance and in specifically the investigation of the **impact of cavities** on the thermal performance and the development of a relevant **production method** for cavity cast glass bricks. The thermal conductivity of air increases with the total dimensions in which the air is encapsulated. Air currents influence the convection within the pockets and therefore the conductivity. Smaller cavities have little airflow and therefor insulate better per millimetre of air.

In Figure 81 the results of the thermal simulations in TRISCO are presented, in which it is clear that in the first millimetres, the cavity influences the thermal performance tremendously (steep-slope), whereas the slope flattens with the increasing cavity depth. This is also clearly visible when comparing 'single cavity' with 'double cavity', the cavity is simply split in two, with a glass plane in between, and the performance difference is significant.

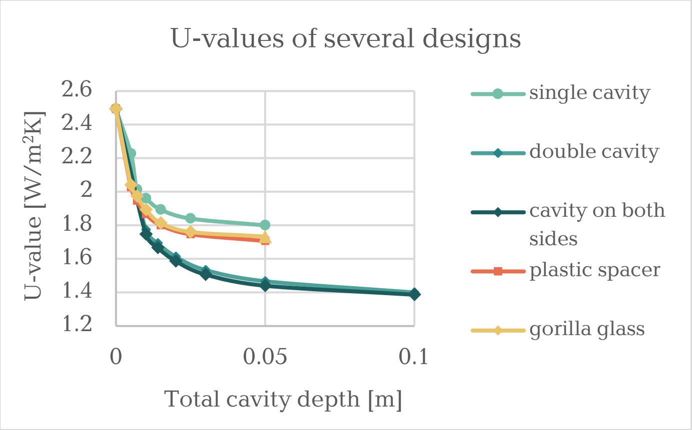


Figure 81 The influence of air pocket size on the thermal transmittance

Introducing **multiple air chambers** will automatically lead to the introduction of thermal bridges (by glass). However, continuous glass geometries are necessary for structural performance. A **balance** must be found, where the continuity of glass is interchanged with air pockets. Based on this principle, the 'chess' brick was designed. By lengthening the 'path' the heat must go through, using non-direct glass paths and the increased depth of a brick, it will still lead to an improved thermal performance. The connected glass strips provide structural strength. A second approach, which is less labour-intensive and allows for more types of glass waste, is by replacing the strips with recycled glass shards.

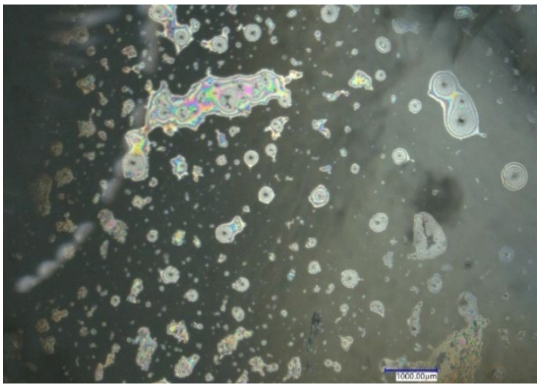
Producing this brick with current standard manufacturing techniques would require **glue**. Glueing is not very environmentally friendly. The glue is not easily (if not impossible) to remove and therefore the glass cannot be recycled when using this connection technique. The most ideal situation would be, to glue without glue. Research and art have shown the potential of fusing or **'tack fusing'** glass. This 'tack fusing' is done at a temperature below the actual fusing temperature, where the glass still creates a permanent bond, without relaxation and shape loss. This temperature lies around the dilatometric softening point of glass. When optimising the firing schedule for the geometry and size, a fused brick can be produced.

If one aims to model the structural resistance of these bricks, the strength of the connection must be known. The **shear strength of this fusing technique** is not yet validated. Therefore, the feasibility of tack fused glass connections needed to be investigated. **Shear tests** were performed from three types of samples: two different series of tack fused specimens at 650˚C (1hr, 3hr dwell at top temperature) and one series of glued samples (DELO 4468) to be used as a reference. DELO4468 is a high-performance glue, which is mostly used for its high strength.

Figure 82 shows a microscopic image, in which the bonding of the two surfaces is visible. Dirt is encapsulated in these 'bubbles'. All samples showed these imperfections, which will influence the strength. The DELO has a wider spread in results, due to the inaccurate application of glue (adhesive thickness varies between the samples). The thickness highly influences the strength. With this specific production process and this loading, the shear stress of the fused surface (resp. 5.96 and 6.53 MPa) is roughly **half of the DELO4468 shear strength** (resp. 11.67 MPa). The remaining fusing strength might prove sufficient for certain applications since it is still considerably more than for example structural silicone. Structural silicone is currently widely applied in certain applications. The shear strength is cannot precisely be determined since it is a non-linear elastic and complex material. Often only the tensile stress is referred to, but the shear strength is estimated between 0.5 and 1.5 MPa. The tensile strength for the DELO4468 provided by the producer is 20 MPa. Additionally, the strength might increase when tack fusing occurs in more regulated and controlled environments while optimising the firing schedule. (*Product Datasheet Sikasil SG-500*, 2020; *Technical Datasheet DELO PHOTOBOND 4468*, 2020)

The firing schedule will depend on the size and shape of the design. The quality of the connection will be influenced (among other things) by the maximum temperature and the dwell time. Longer dwelling leads to improved strength but can lead to shape inaccuracies due to sagging. For each design, a new firing schedule must be adapted. The quality of the bonds within the brick has not been tested yet. It is important to ensure bonding throughout the entire brick. If the geometry or the size is not compatible, it might lead to different bonding specifications within a single brick. It can be problematic if there are zones without bonding.

An interesting spin-off from this technique is the **replacement of aluminium spacers** in insulated glass units with fused glass strips. could increase transparency and solve the recycling issue of IGUs. If this is feasible, it could revolutionise the recyclability and transparency of double glazing.



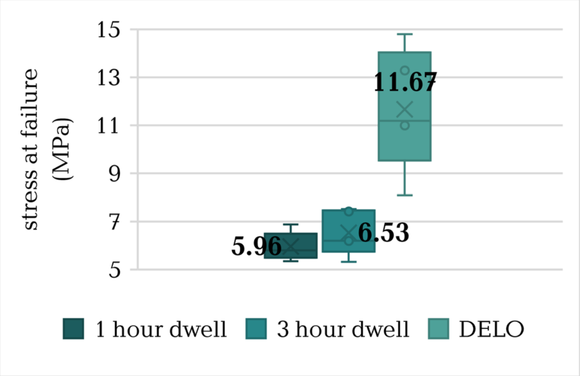


Figure 82 [left] Unbonded zones in fused samples and **Figure 83** [right] Average stress and spread of test results

One of the design alternatives is a shard-filled brick, from which the thermal transmittance is yet unknown. Modelling this would prove difficult since the geometry is not straightforward and randomly organised. For this reason, it was decided to investigate the thermal performance with an experiment. This **heat flow experiment** recreates a temperature differential between two surfaces of the prototypes. Sensors will measure the temperatures and the heat flow, which then can be translated into a U-value.

Ideally, all experimental heat flow graphs would convergence into one value, which can be converted to a corresponding thermal transmittance (U-value). This was however not the case for these tests, due to several uncontrolled variables. The **accuracy** of these tests was not ideal and therefore several tests were performed, from which an estimated guess is done for the thermal transmittance of the shard brick. Important to note is the dependency of this performance on the shard size and arrangement.

The increased thermal performance of cast glass brick walls is required to meet higher insulation standards, **compared to current standard building practice.** An insulated glass unit has a thermal transmittance of roughly 3.0 and an HR++ IGU of approx. 1.2 W/m^2K. A hollow glass block ranges from 3.0 to 1.5, depending on the gas filling. This thesis aimed to increase the 2.94 W/m^2K of a solid glass block of 100 mm depth. The double-wall reached 1.6 W/m^2K, the chess brick approx. 2.0 W/m^2K and the shard brick, depending on the shard size and distribution, reached in this configuration 1.8 W/m^2K. These values improved significantly and provide potential.

If one aims to design a fused glass brick, based on these principles, **further research is required**. Playing with the intervals of voids and sizes in the chess brick or the chunk size and porosity of the shard brick will influence both structural and thermal performance. The brick needs to be customized according to the design requirements. A multi-story façade in a tropical climate will result in a different ratio than a single storey, low load façade in a cold climate. Structural analyses can be performed with the given connections strength. The **tools** are given to adapt per individual design. The designs are a starting point, from which it can be adjusted. An interesting thesis proposal would be the **optimisation of strength and thermal performance**, for one specific brick design. After which the strength needs to be validated according to full-scale tests, to verify the firing schedule.

The exploration ended with a **multi-criteria analysis**, in which several designs are tested under multiple criteria. The sole outcome of this is not one solution, but the insights in which solutions are promising. The most innovative design would be the brick with fused shards. The structural performance and the optimal production sequence are yet to be investigated but could **revolutionize the waste glass industry**. Assumably, this would not be applied in high-strength facades, since it is expected that the structural performance is not extraordinary. For high-strength applications, either the double-wall or the fused cavity wall might be interesting. The solid brick will provide strength, while the cavity provides thermal performance. There is **not one perfect solution** since each façade has different performance requirements, but these results do provide insights for an improvement from the current technologies.

Recommendations

Tack fused glass connections

The most interesting additional application of tack fused glass surfaces is the replacement of aluminium spacers in insulated glass units. If this is feasible, it could revolutionise the recyclability and transparency of double glazing. Within the department, interest already arose to investigate this further. The foundation of this application still lies in further development and trying to optimise the bonding quality.

- The maximum feasible bonding area is yet unknown. An increased surface area might lead to more residual stresses in the glass due to unequal cooling rates.
- The fusing temperature and dwell time are not optimised. The impact of this on the sagging and the strength is an interesting research topic. The temperature should be high enough to bond, yet low enough not to sag. The dwell time should be long enough for the entire sample to heat up accordingly, while not allowing relaxation in the material (which again results in sagging).
- When float glass is produced, one side is exposed to air and one side rests on tin. The microstructure of the two sides differs, which might also result in different bonding characteristics. One could research if tin-to-tin, tin-to-air or air-to-air have different bonding strength or if the difference is neglectable.
- Especially interesting for IGU applications is the sealing capacity of the fused surface. How water and airtight is this? IGUs are mostly filled with argon and some applications even have vacuum cavities, which required proper sealants. If the glass fusing can replace both spacers and sealants, it does not require additional materials and thus improves the recyclability.

Architectural exploration

Cast glass provides lots of architectural potentials since it allows the designer to play with shapes, colours and arrangements. A flat float glass façade has no room for this playfulness. An interesting approach to the use of recycled cullet is coloured cullet. An entire brick could be coloured, which allows for arrangements or patterns in the entire façade or the patterns can be created within a single brick. This playfulness of completely coloured blocks can already be found in hollow glass blocks. The fused glass bricks will provide more texture and complexity. Mock-ups show the potential of this colour arrangement, but tests and design explorations can maximise this potential.

The detailing of this brick could prove complex, yet interesting. The detailing was not within the scope of this thesis. Interlocking cast glass bricks exist but are rarely used yet in common practice. Is it feasible to create interlocking bricks of fused shards? How will these bricks behave in such conditions? Also, is it desirable and possible to eliminate the 'glass box' in which the shards are now produced? The perimeter 'box' is now made of float glass, cut into specific rectangles, but if this can be eliminated, it eliminates the need of (intact) float glass pieces. If these bricks need to be glued together, how is this achieved?

Figure 84 Tetris coloured hollow glass brick wall [picture 1] (Eternal Tanelorn - TETRIS Glass Block Window, n.d.) and mock-ups of coloured shard/marble brick suggestions [picture to 2 to 4]

Experimental evaluation of thermal resistance

In paragraph 7.2 'Trial test runs and findings' some uncertainties and inaccuracies are discussed. The experimental evaluation of the thermal resistance of prototypes proves more difficult than anticipated. Many variables were unknown, which made concluding accurate results almost impossible. A thorough investigation is needed, in what the influence is of each uncertainty. Only then, when these can be eliminated, a clear analysis can be done. In paragraph 0, additional recommendations are given to minimise the inaccuracies. Merely the uncertainties, rather than the inaccuracies are interesting fields of study.

- The measured data will be analysed according to conductivity heat principles. However, if the glass is heated due to radiation, it can influence the outcomes. A light bulb always produces radiation, so what is the best way to prevent the radiation from influencing the results?
- The size of the prototype influences the orientation of the heat flow. In the corners, edge effects occur. If the size of the prototype is too small, the heat flow will not be two dimensional and thus not predictable. A minimum required size must be determined.

Structural performance vs. thermal performance

For enabling the application of hybrid glass blocks, thorough investigation of their structural performance is required. The shard brick proved interesting in terms of thermal performance. However, there should be a balance between thermal performance and structural performance. The denser the brick, the better the structural performance and the opposite applies for the thermal performance. What is the ideal porosity range, which provides both structural capacity and yet sufficient thermal resistance?

Interesting to investigate is the effect of local stress concentrations on the overall performance. If the cullet size increases, load paths with a high relative stiffness are likely to occur. Stiff paths attract more load, which might result in failure at much lower loading conditions than if the stiffness is evenly distributed.

Two factors influence the strength and the thermal performance. The cullet size is proportionate to the cavity size and the firing schedule will influence the deformations of each shard. A higher fusing temperature (with potentially a shorter dwell time) will mean that the glass will sag more and the contact surfaces will increase. A lower temperature with longer dwell time will lead to sharper corners and less sagging.

A strategy to investigate the structural and thermal performance would start with creating batches of prototypes with increasing cullet size. The best structural performance per cullet size will be reached if the firing schedule is optimised for that specific size of cullet. Each batch should be first tested for thermal performance and then for structural performance. Similar cullet size prototypes will still have a relatively wide spread in strengths, due to the random nature of the arrangement of the cullet shards.

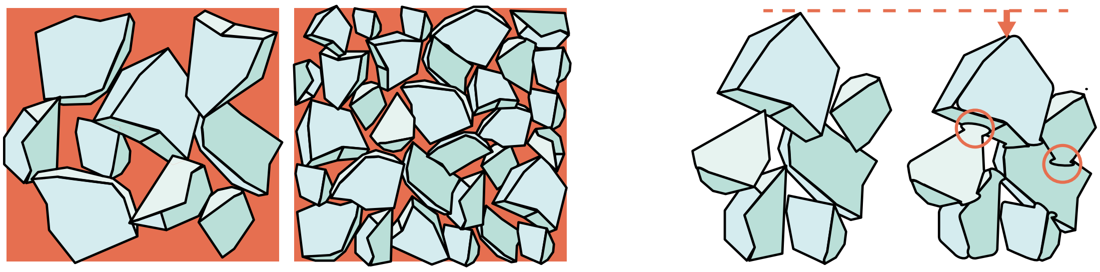


Figure 85 Cullet size and temperature deformation

Cavity walls

A double-wall or single cavity design is based on the idea of the solid brick, which has sufficient structural performance with an additional piece that provides thermal resistance. However, it could prove that the dimensions of the solid brick can be reduced, due to cooperation between the two surfaces. It is yet unknown what this benefit is and how much the second wall depth can be reduced.

Normally, cavity walls are tied together with metal ties. These ties activate the cooperation between the two walls. Glass cavity walls would not ideally be tied together with metals, due to the non-transparent nature and the hard contact surfaces. An interesting concept is either creating a 'bridging brick' made of glass which connects the two walls or designing an acrylic tie.

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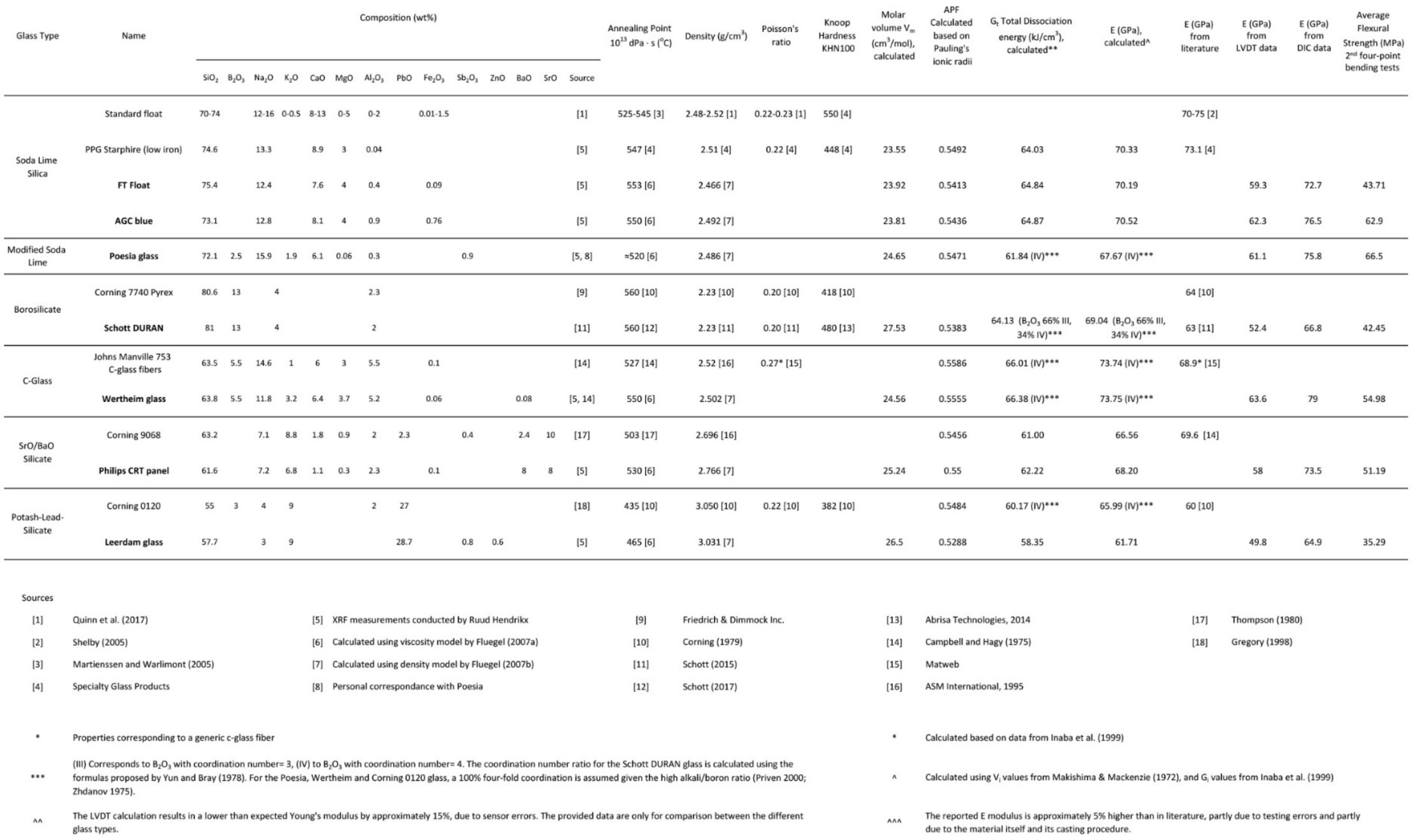
List of tables and figures

Appendix A: Properties of glass



Glass Type	Name	Composition (wt%)														Annealing Point 10^{13} dPa · s (°C)	Density (g/cm^3)	Poisson's ratio	Knoop Hardness KHN100	Molar volume V_m (cm^3/mol), calculated	APF Calculated based on Pauling's ionic radii	G_t Total Dissociation energy (kJ/cm^3), calculated**	E (GPa), calculated^	E (GPa) from literature	E (GPa) from LVDT data	E (GPa) from DIC data	Average Flexural Strength (MPa) 2nd four-point bending tests
		SiO_2	B_2O_3	Na_2O	K_2O	CaO	MgO	Al_2O_3	PbO	Fe_2O_3	Sb_2O_3	ZnO	BaO	SrO	Source												
Soda Lime Silica	Standard float	70-74		12-16	0-0.5	8-13	0-5	0-2		0.01-1.5					[1]	525-545 [3]	2.48-2.52 [1]	0.22-0.23 [1]	550 [4]					70-75 [2]			
	PPG Starphire (low iron)	74.6		13.3		8.9	3	0.04							[5]	547 [4]	2.51 [4]	0.22 [4]	448 [4]	23.55	0.5492	64.03	70.33	73.1 [4]			
	FT Float	75.4		12.4		7.6	4	0.4		0.09					[5]	553 [6]	2.466 [7]			23.92	0.5413	64.84	70.19		59.3	72.7	43.71
	AGC blue	73.1		12.8		8.1	4	0.9		0.76					[5]	550 [6]	2.492 [7]			23.81	0.5436	64.87	70.52		62.3	76.5	62.9
Modified Soda Lime	**Poesia glass**	72.1	2.5	15.9	1.9	6.1	0.06	0.3			0.9				[5, 8]	≈520 [6]	2.486 [7]			24.65	0.5471	61.84 (IV)***	67.67 (IV)***		61.1	75.8	66.5
Borosilicate	Corning 7740 Pyrex	80.6	13	4				2.3							[9]	560 [10]	2.23 [10]	0.20 [10]	418 [10]					64 [10]			
	Schott DURAN	81	13	4				2							[11]	560 [12]	2.23 [11]	0.20 [11]	480 [13]	27.53	0.5383	64.13 (B_2O_3 66% III, 34% IV)***	69.04 (B_2O_3 66% III, 34% IV)***	63 [11]	52.4	66.8	42.45
C-Glass	Johns Manville 753 C-glass fibers	63.5	5.5	14.6	1	6	3	5.5		0.1					[14]	527 [14]	2.52 [16]	0.27* [15]			0.5586	66.01 (IV)***	73.74 (IV)***	68.9* [15]			
	Wertheim glass	63.8	5.5	11.8	3.2	6.4	3.7	5.2		0.06			0.08		[5, 14]	550 [6]	2.502 [7]			24.56	0.5555	66.38 (IV)***	73.75 (IV)***		63.6	79	54.98
SrO/BaO Silicate	Corning 9068	63.2		7.1	8.8	1.8	0.9	2	2.3		0.4		2.4	10	[17]	503 [17]	2.696 [16]				0.5456	61.00	66.56	69.6 [14]			
	Philips CRT panel	61.6		7.2	6.8	1.1	0.3	2.3		0.1			8	8	[5]	530 [6]	2.766 [7]			25.24	0.55	62.22	68.20		58	73.5	51.19
Potash-Lead-Silicate	Corning 0120	55	3	4	9			2	27						[18]	435 [10]	3.050 [10]	0.22 [10]	382 [10]		0.5484	60.17 (IV)***	65.99 (IV)***	60 [10]			
	Leerdam glass	57.7		3	9				28.7		0.8	0.6			[5]	465 [6]	3.031 [7]			26.5	0.5288	58.35	61.71		49.8	64.9	35.29

Sources

[1] Quinn et al. (2017)
[2] Shelby (2005)
[3] Martienssen and Warlimont (2005)
[4] Specialty Glass Products
[5] XRF measurements conducted by Ruud Hendrikx
[6] Calculated using viscosity model by Fluegel (2007a)
[7] Calculated using density model by Fluegel (2007b)
[8] Personal correspondance with Poesia
[9] Friedrich & Dimmock Inc.
[10] Corning (1979)
[11] Schott (2015)
[12] Schott (2017)
[13] Abrisa Technologies, 2014
[14] Campbell and Hagy (1975)
[15] Matweb
[16] ASM International, 1995
[17] Thompson (1980)
[18] Gregory (1998)

* Properties corresponding to a generic c-glass fiber

*** (III) Corresponds to B_2O_3 with coordination number= 3, (IV) to B_2O_3 with coordination number= 4. The coordination number ratio for the Schott DURAN glass is calculated using the formulas proposed by Yun and Bray (1978). For the Poesia, Wertheim and Corning 0120 glass, a 100% four-fold coordination is assumed given the high alkali/boron ratio (Priven 2000; Zhdanov 1975).

^^ The LVDT calculation results in a lower than expected Young's modulus by approximately 15%, due to sensor errors. The provided data are only for comparison between the different glass types.

* Calculated based on data from Inaba et al. (1999)

^ Calculated using V_i values from Makishima & Mackenzie (1972), and G_i values from Inaba et al. (1999)

^^^ The reported E modulus is approximately 5% higher than in literature, partly due to testing errors and partly due to the material itself and its casting procedure.

Figure 86 Table showing glass properties (Bristogianni et al., 2020)

Appendix B: Microscopic pictures

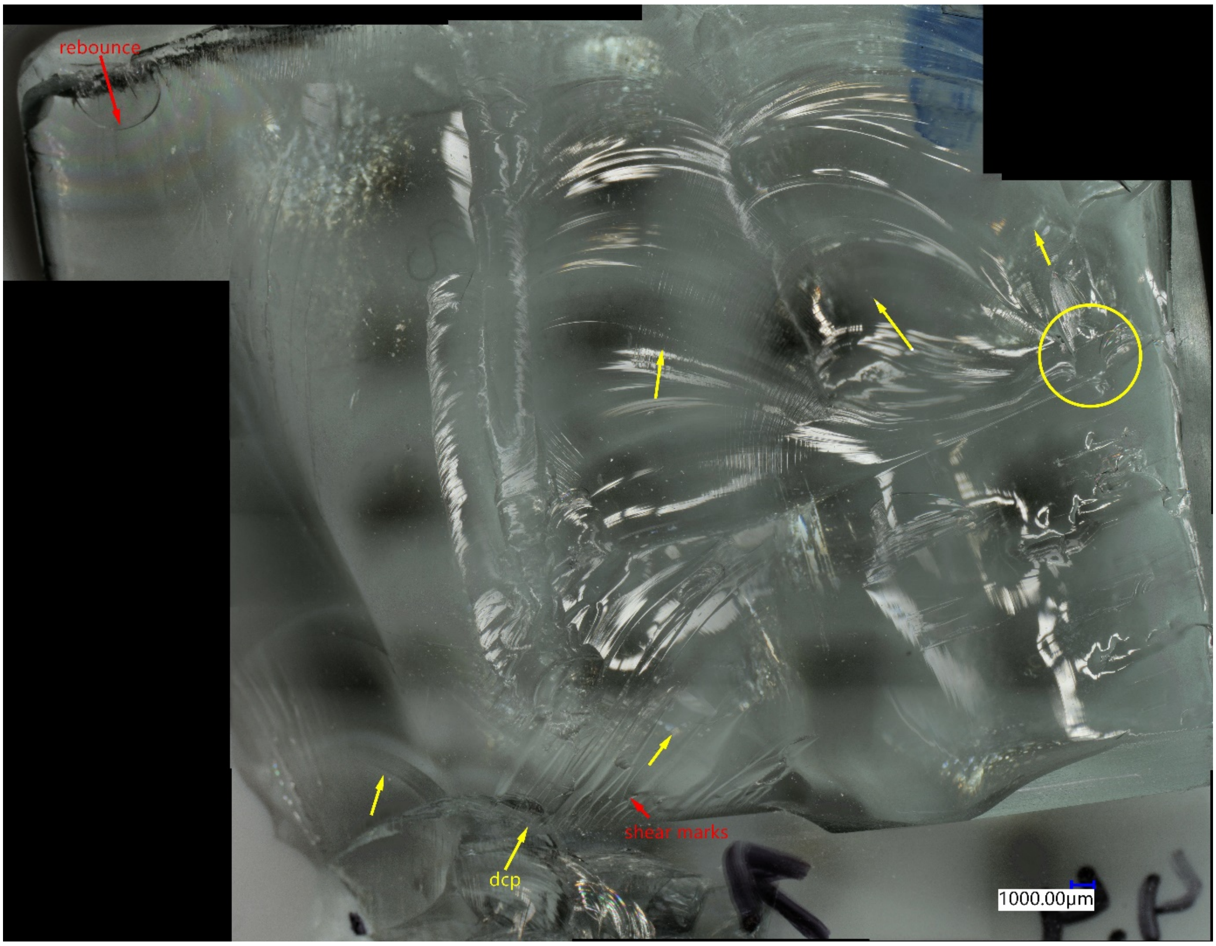


Figure 87 Direction of crack propagation of trial test run sample 4

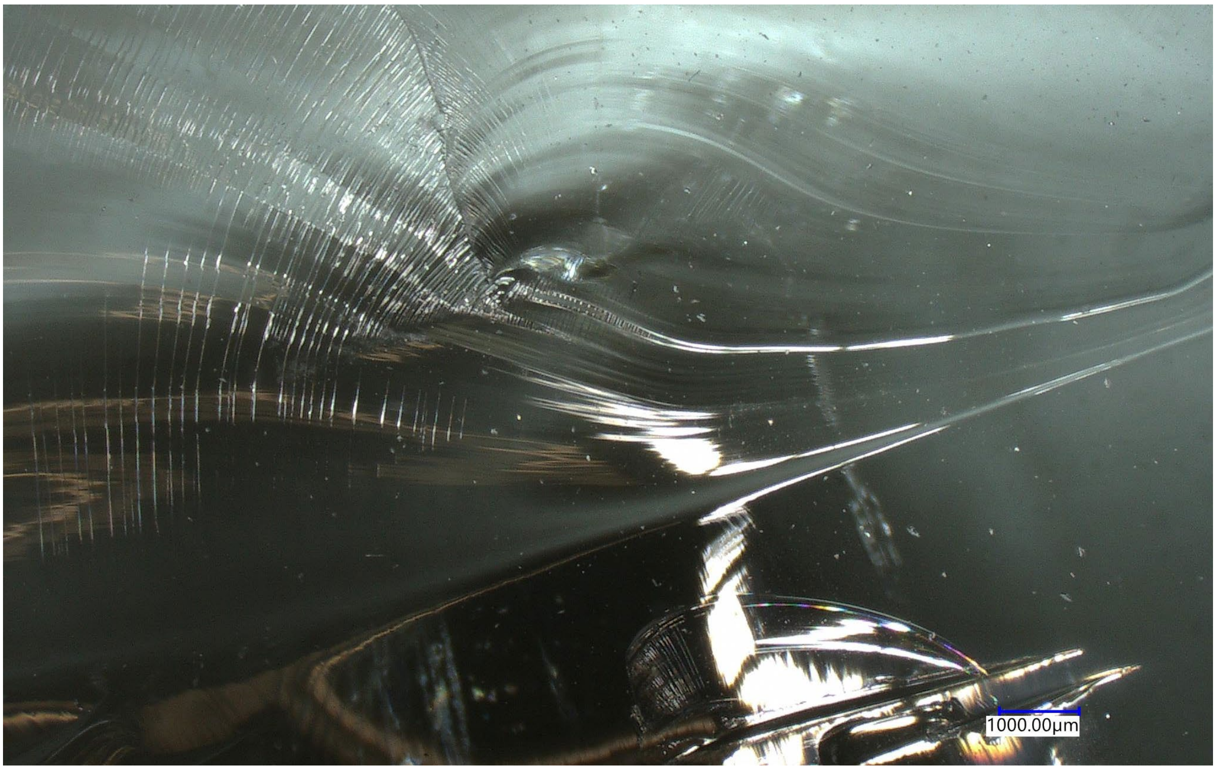


Figure 88 Shear marks of trial test run sample 4

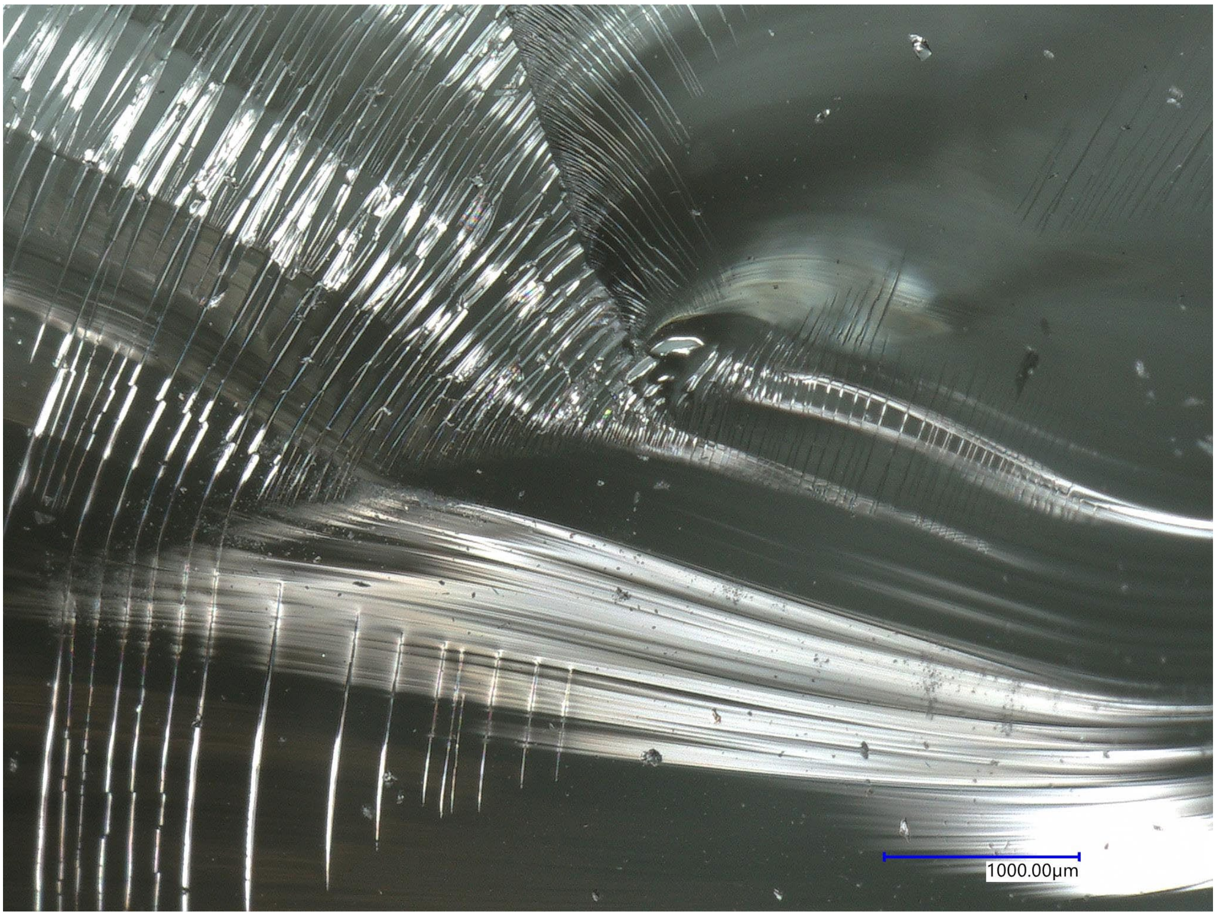


Figure 89 Close up of shear marks of trial test run sample 4

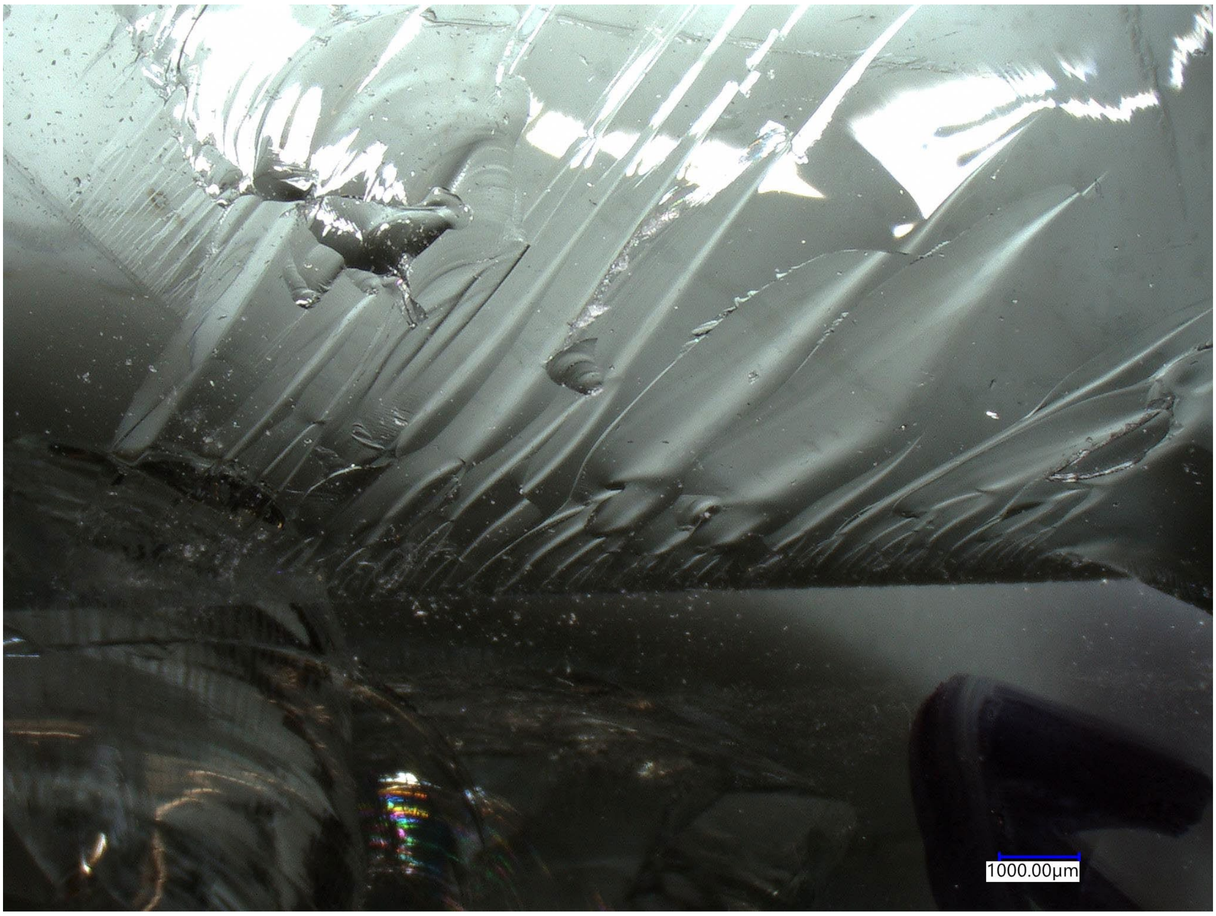


Figure 90 Facture origin of trial test run sample 4

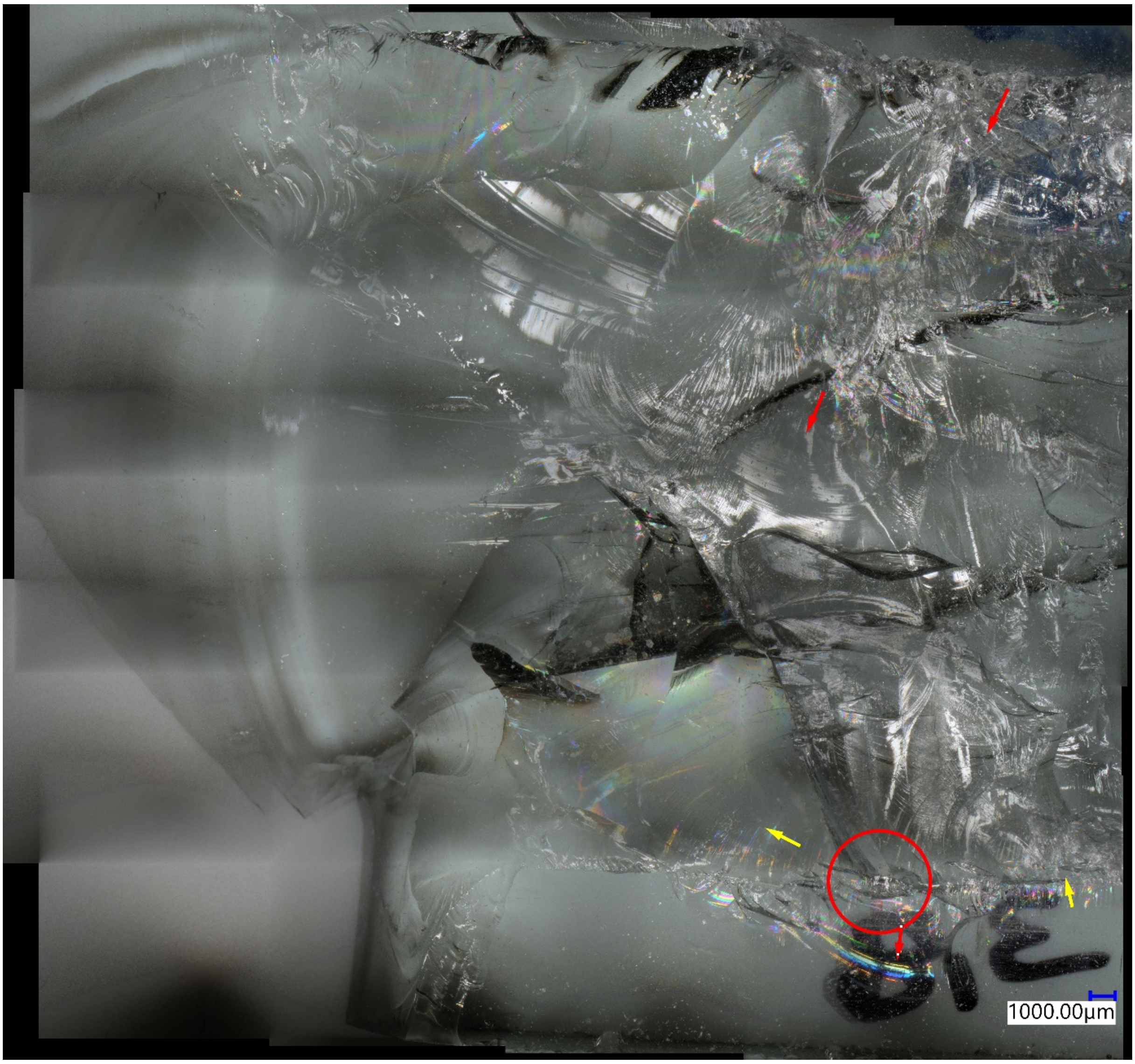


Figure 91 Direction of crack propagation of trial test run sample 5

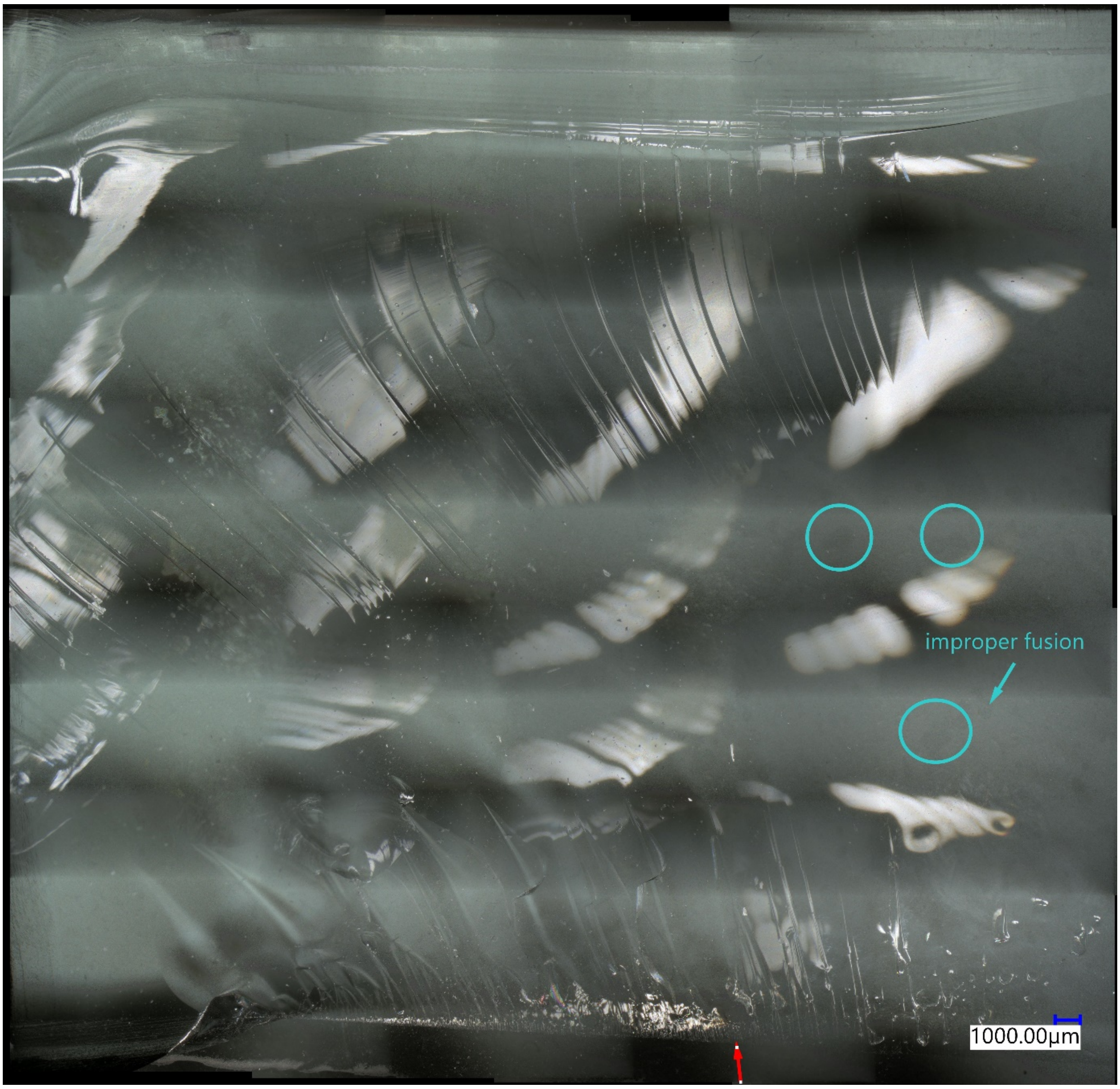


Figure 92 Improper fusion and crack origin of trial test run sample 6

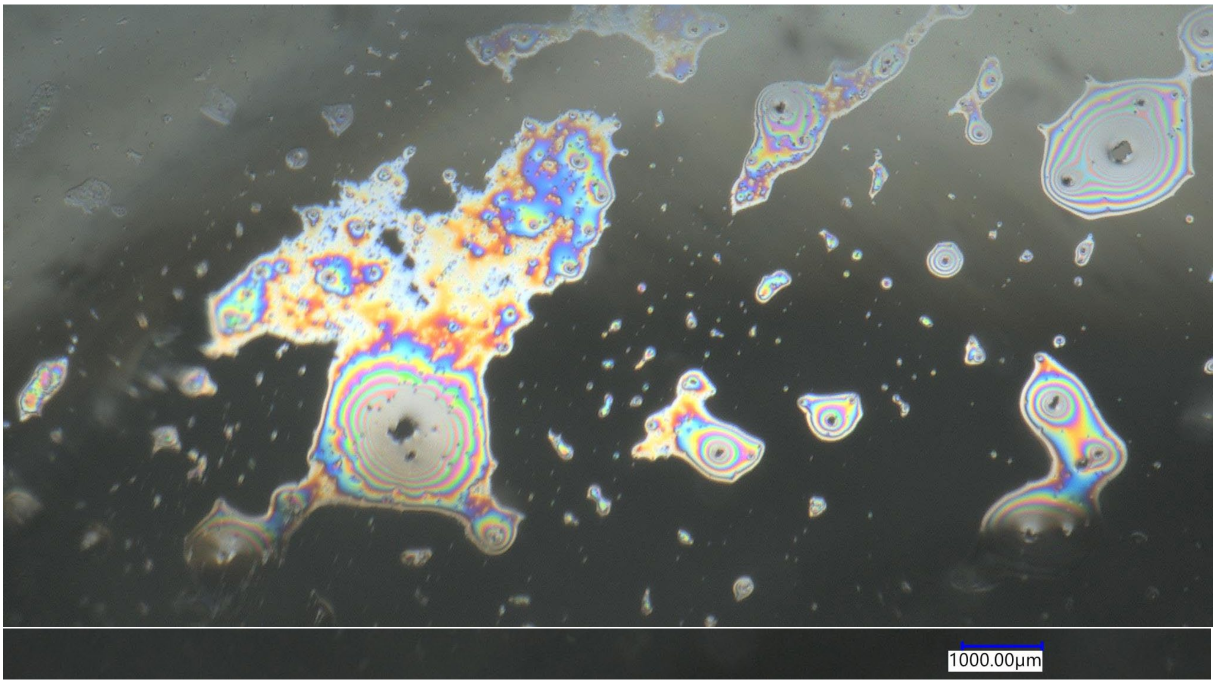


Figure 93 Improper fusion and crack origin of trial test run sample 6

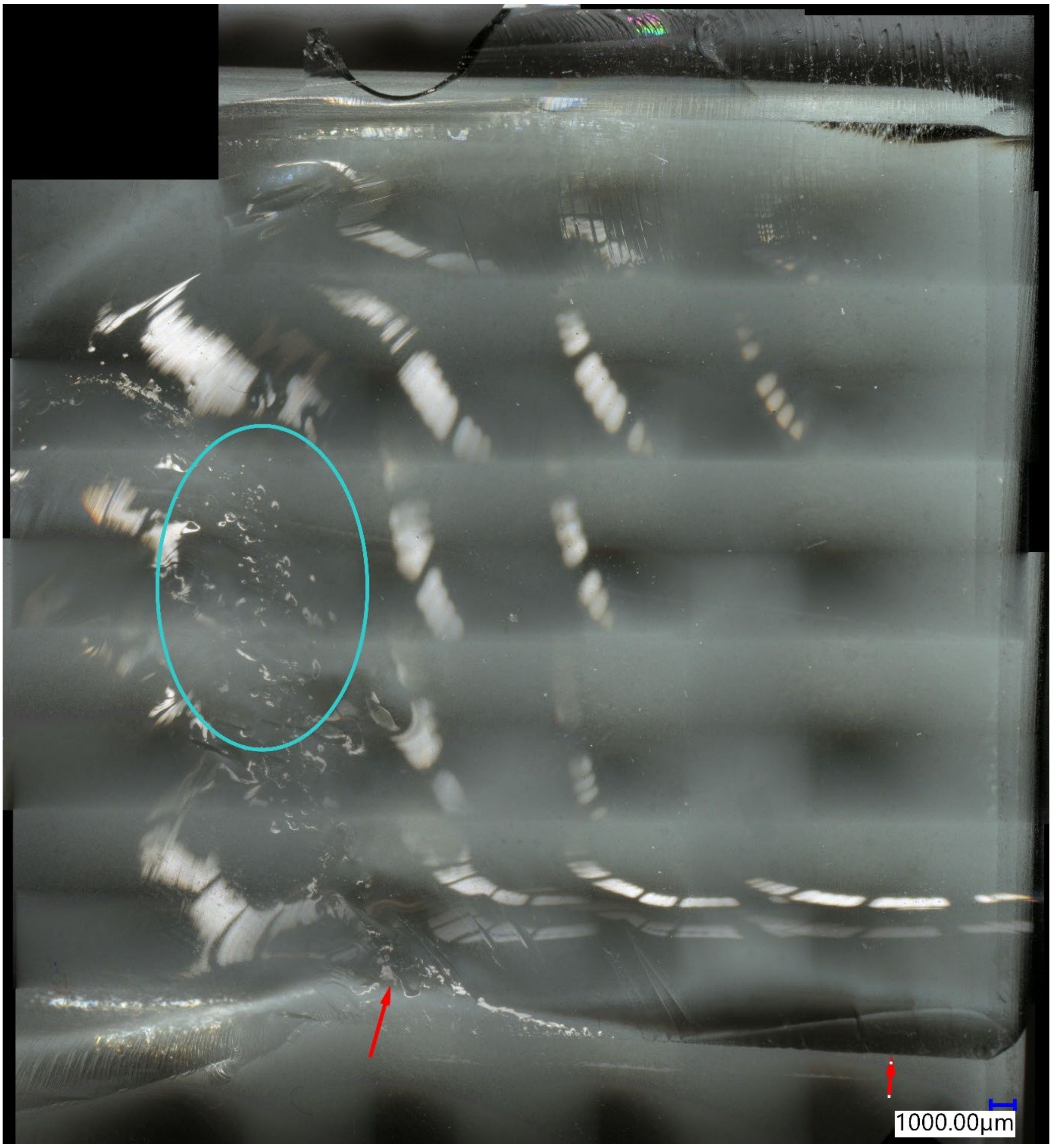


Figure 94 Facture origin of trial test run sample 7

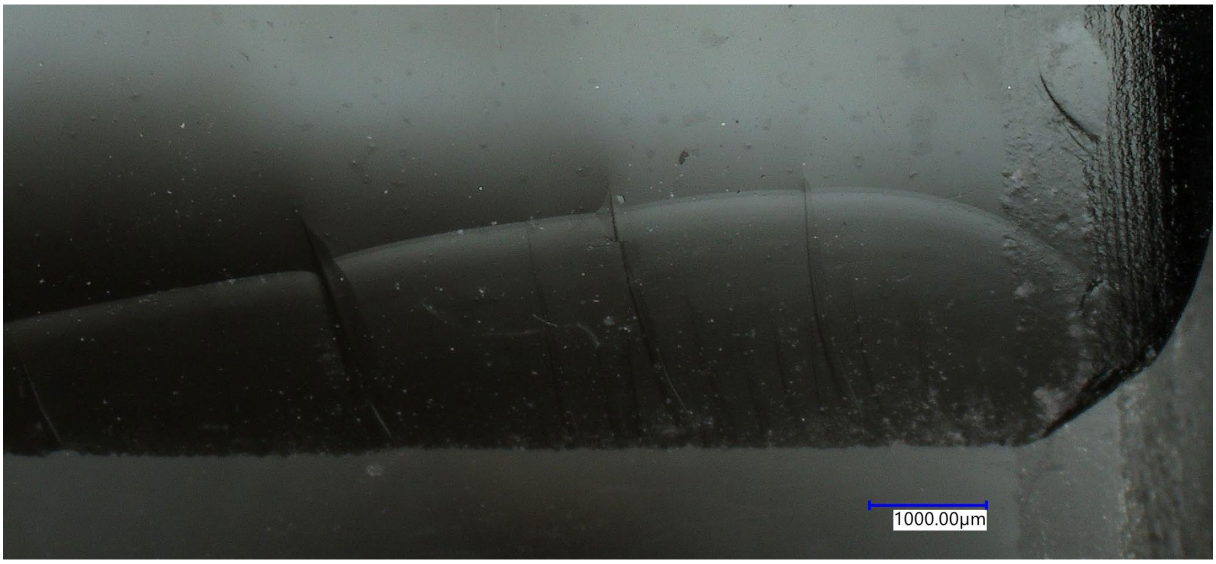


Figure 95 Bottom fusing surface edge of trial test run sample 7

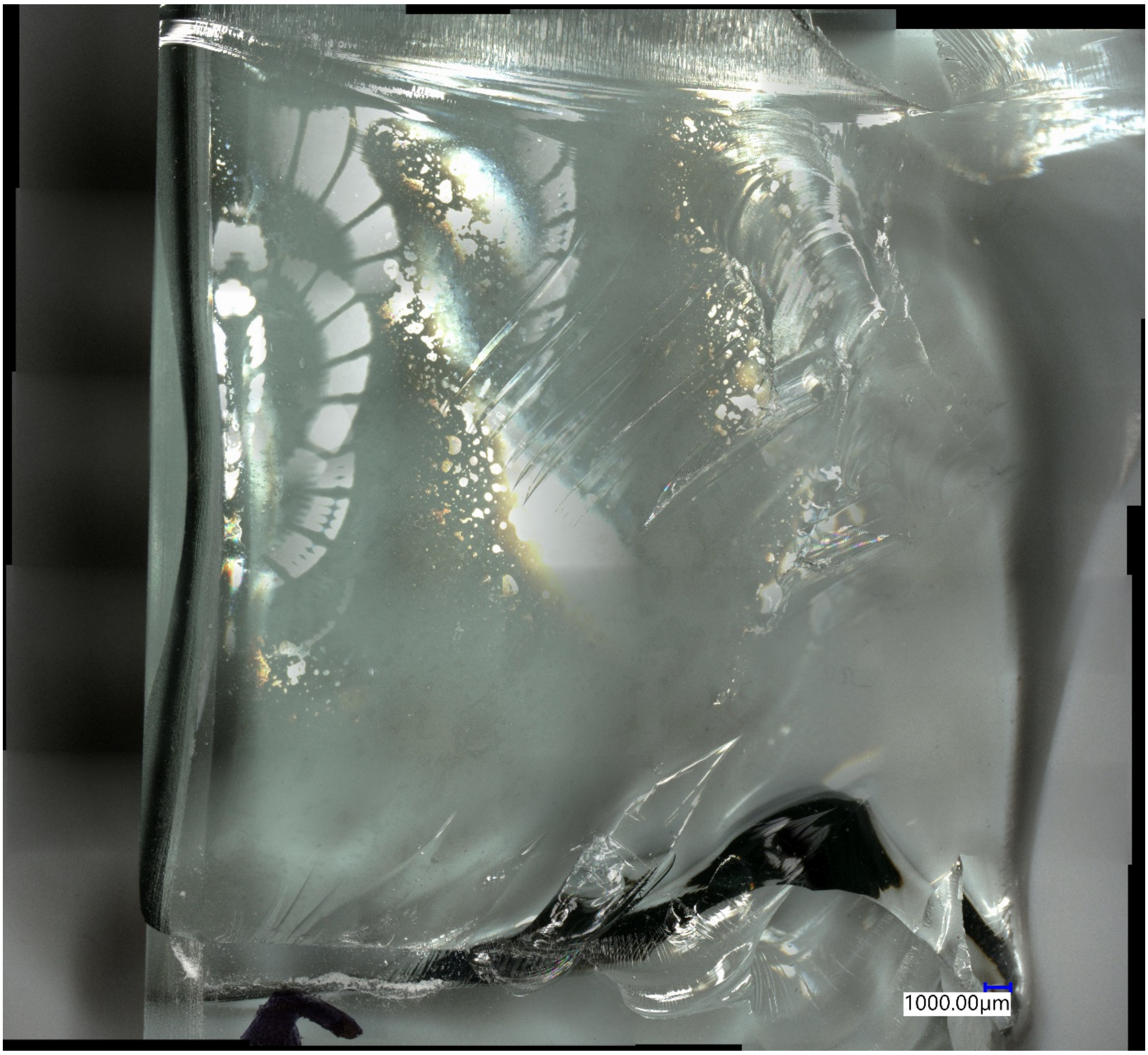


Figure 96 Bottom corner of trial test run sample 7

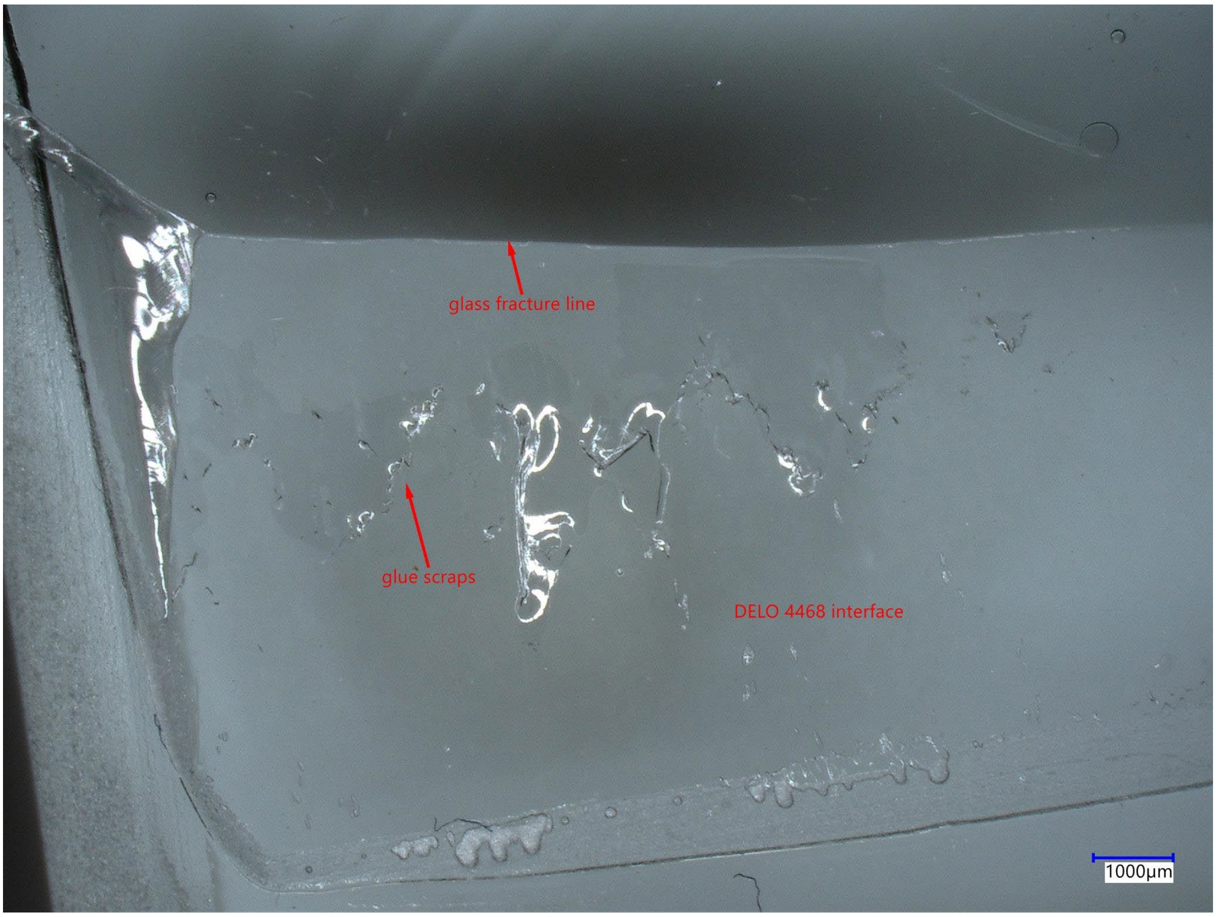


Figure 97 Failure surface of sample DELO 1

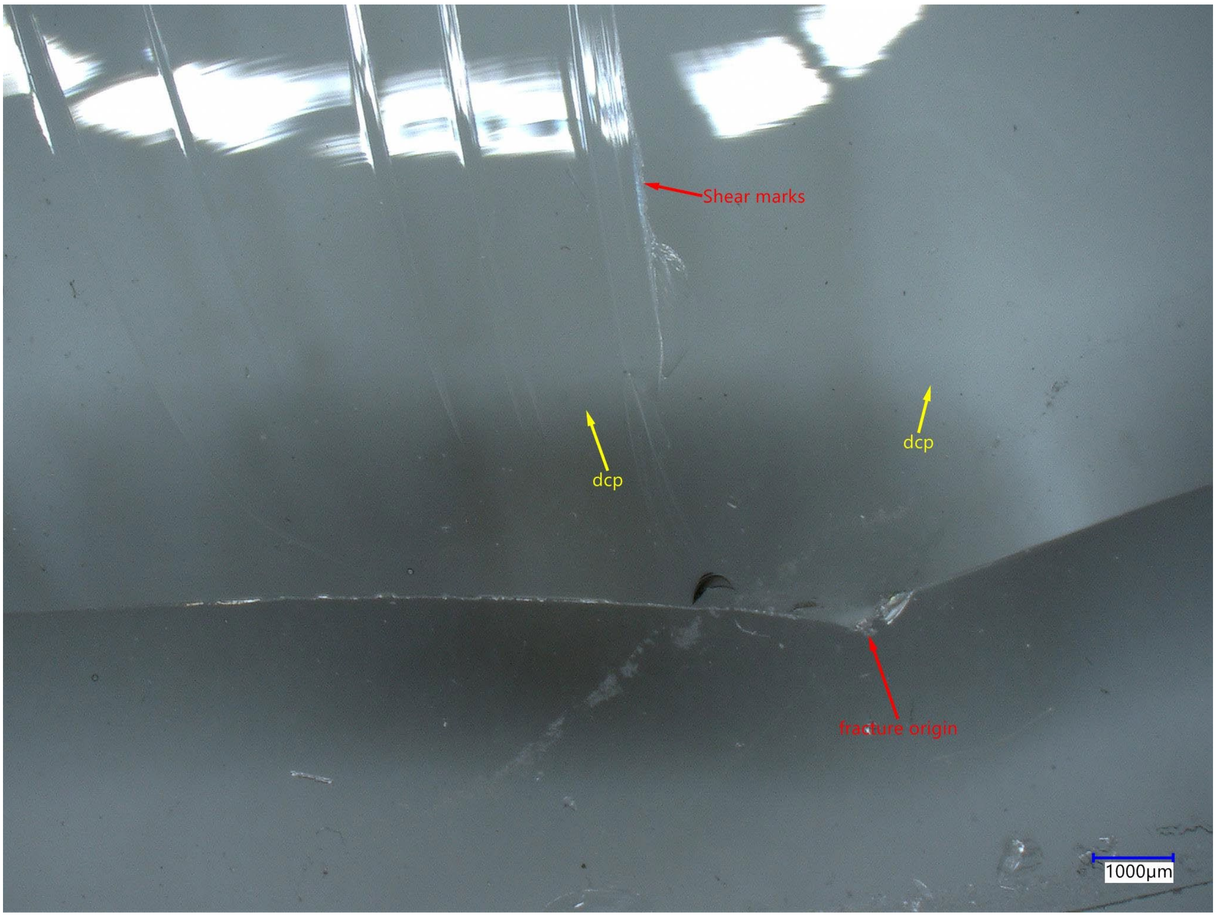


Figure 98 Failure origin of sample DELO 1

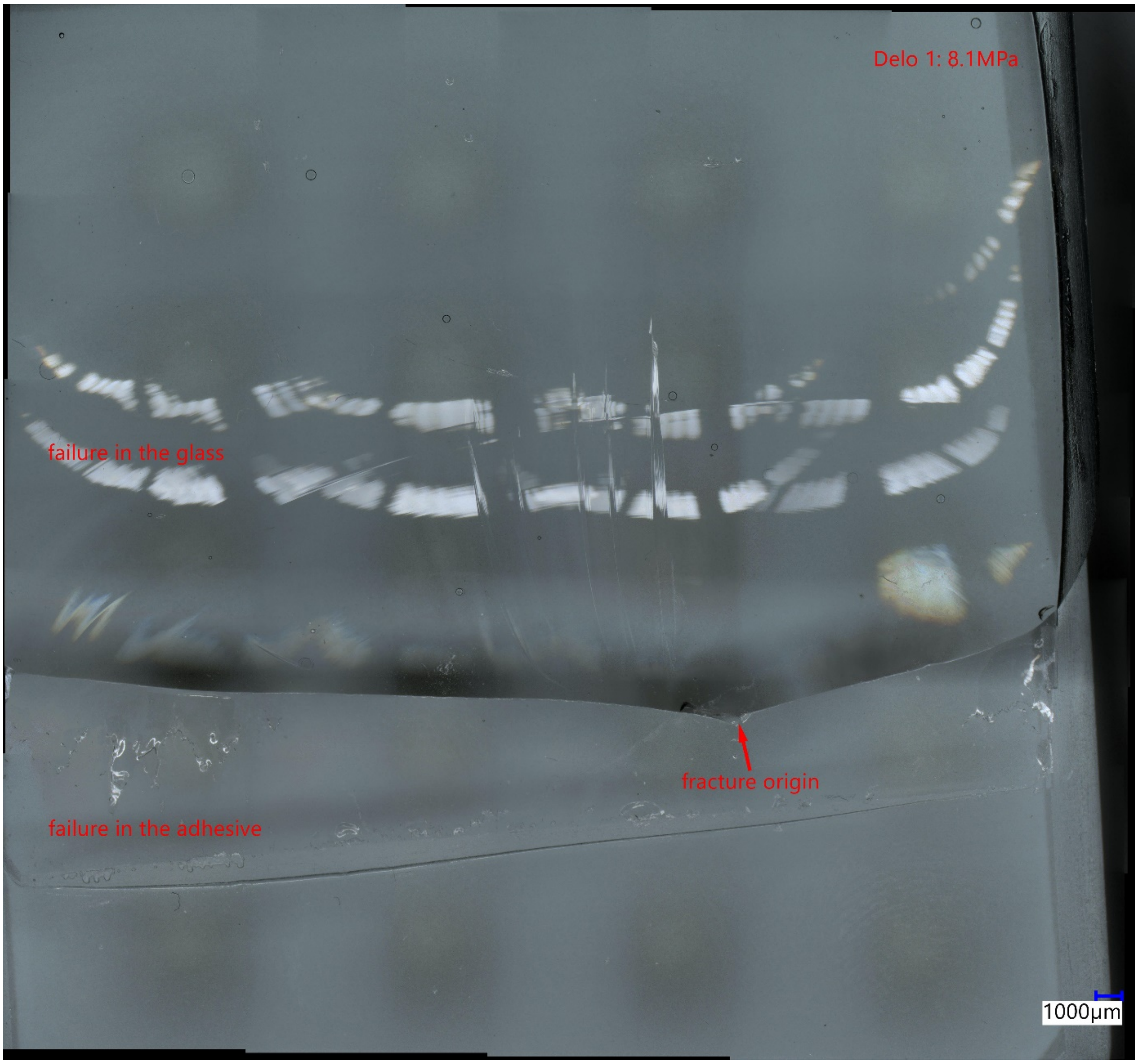


Figure 99 Complete overview of sample DELO 1

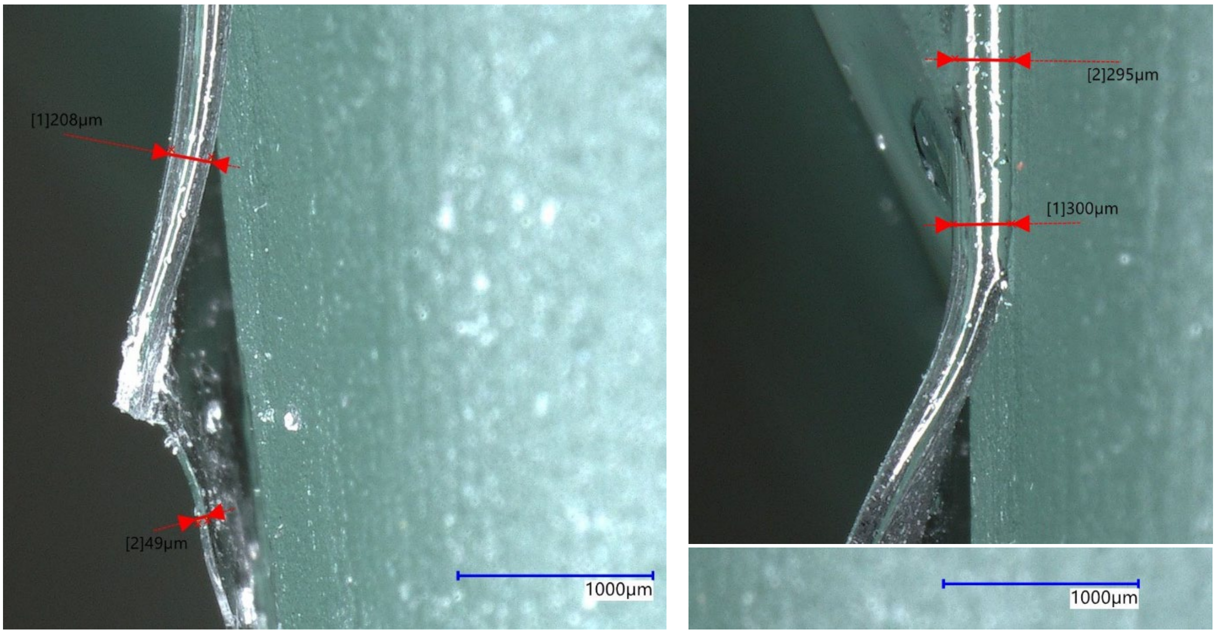
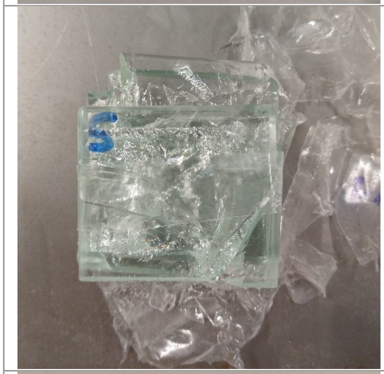
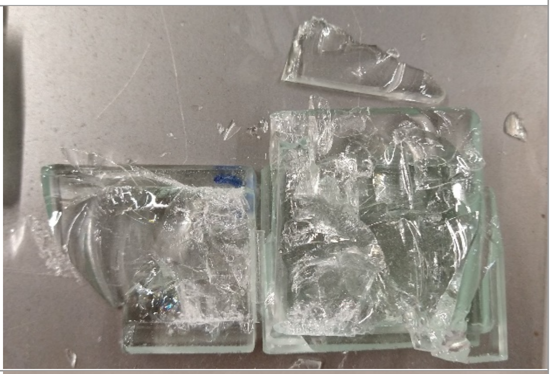
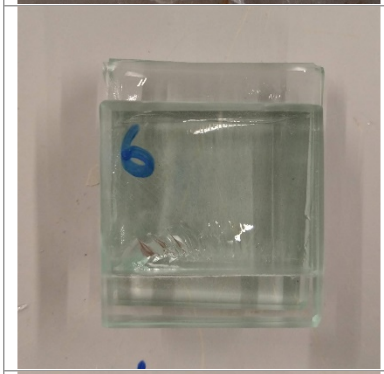
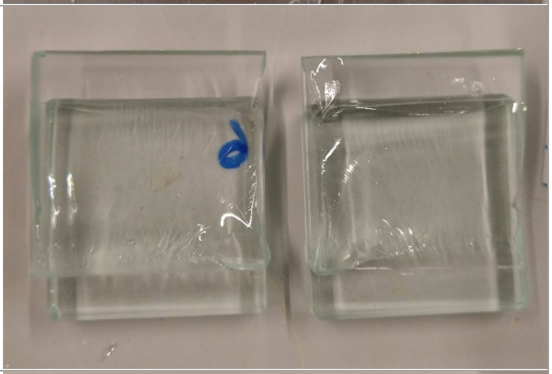
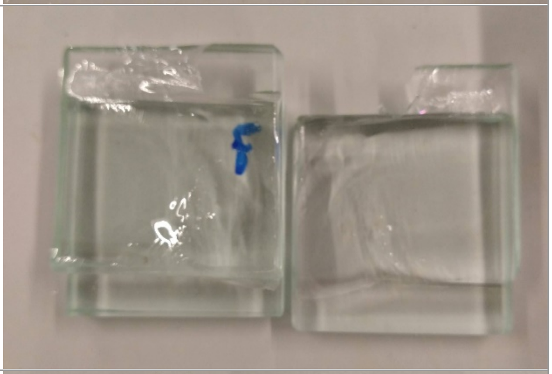
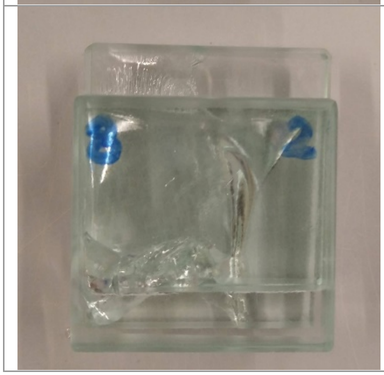
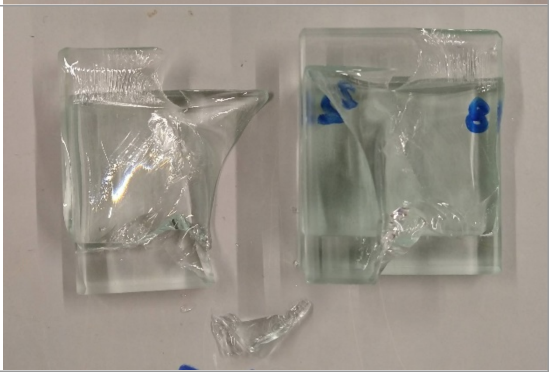


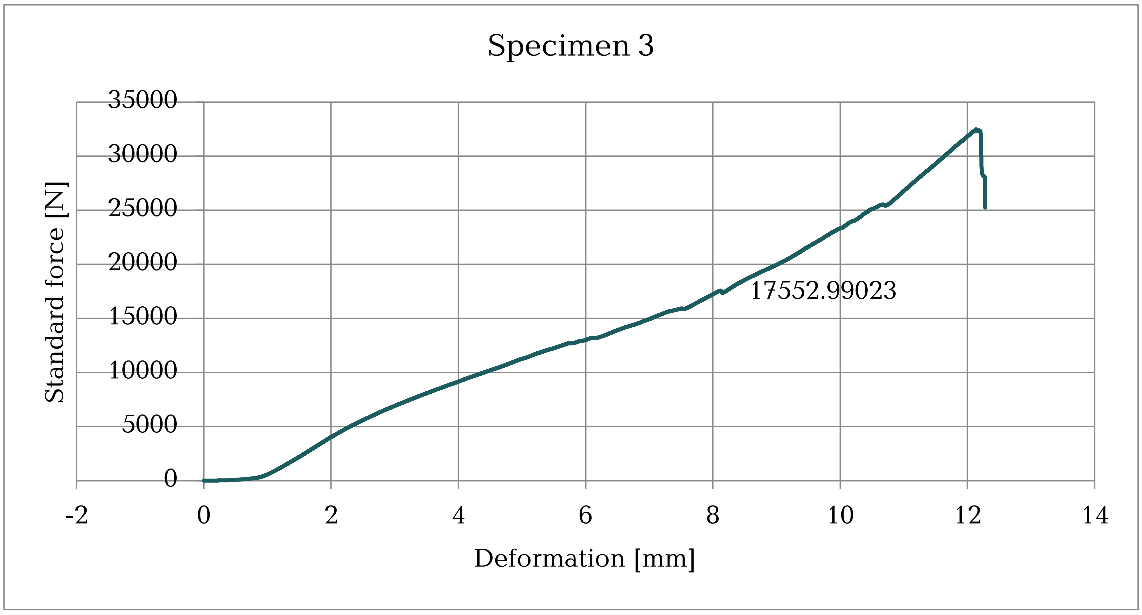
Figure 100 Glue depth of sample DELO 1

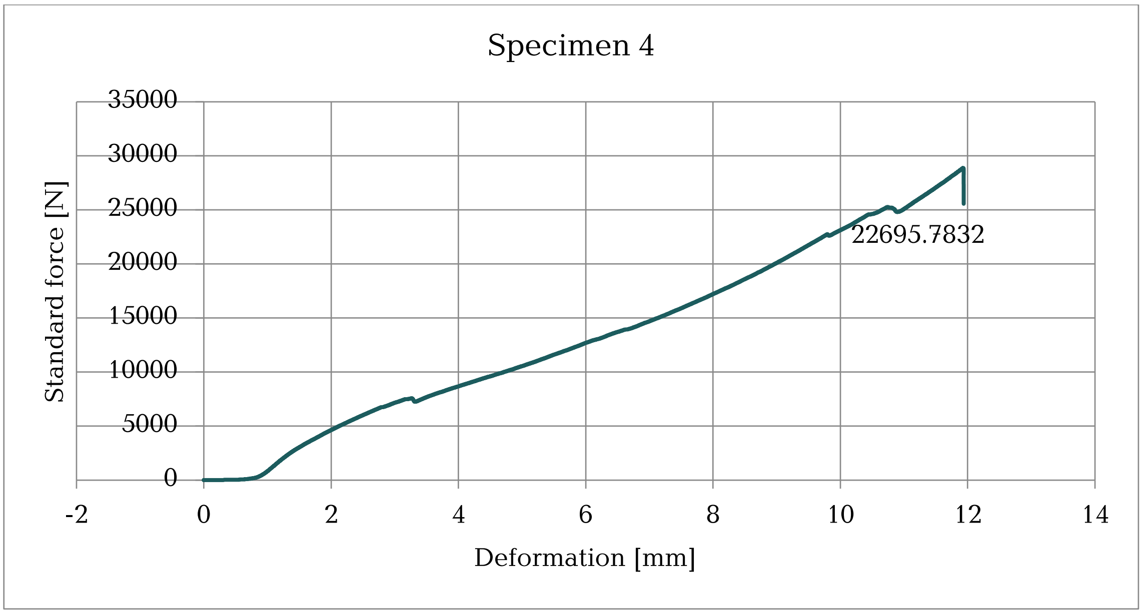
Appendix C: Failed shear tests, initial run

Table 37 Pictures of failed samples

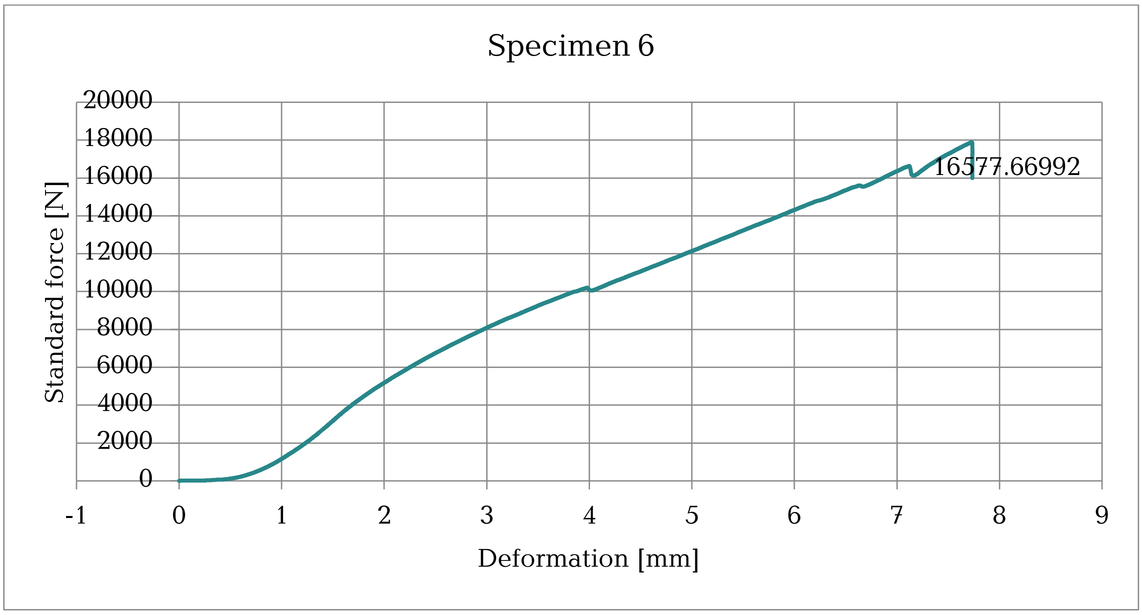
Front view	Side view	Folded open
		
		
		
		
		

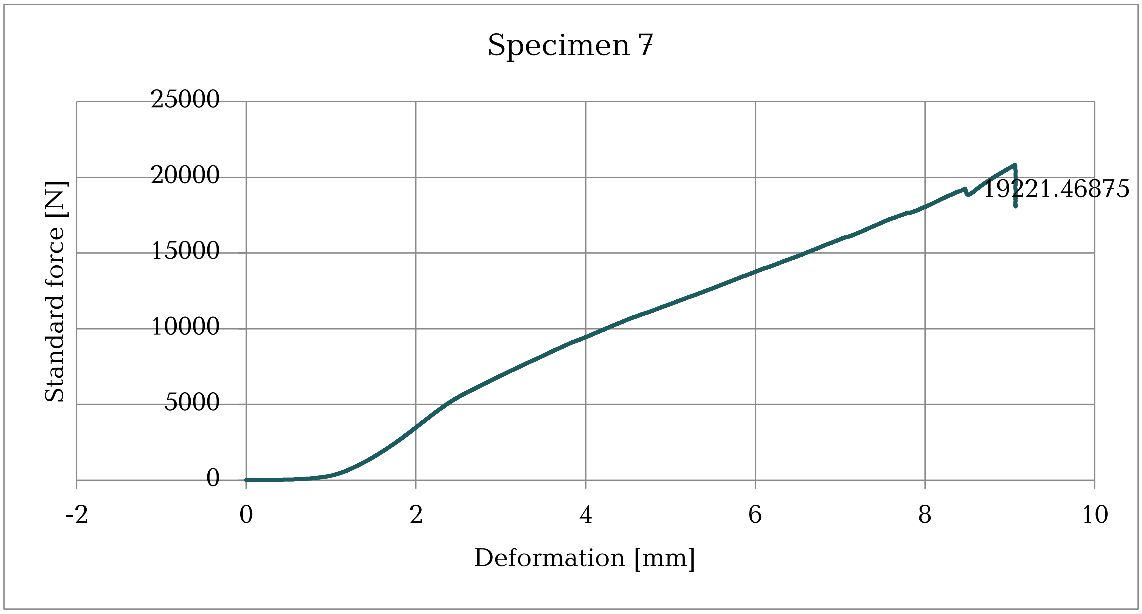
Appendix D: Shear test graphs



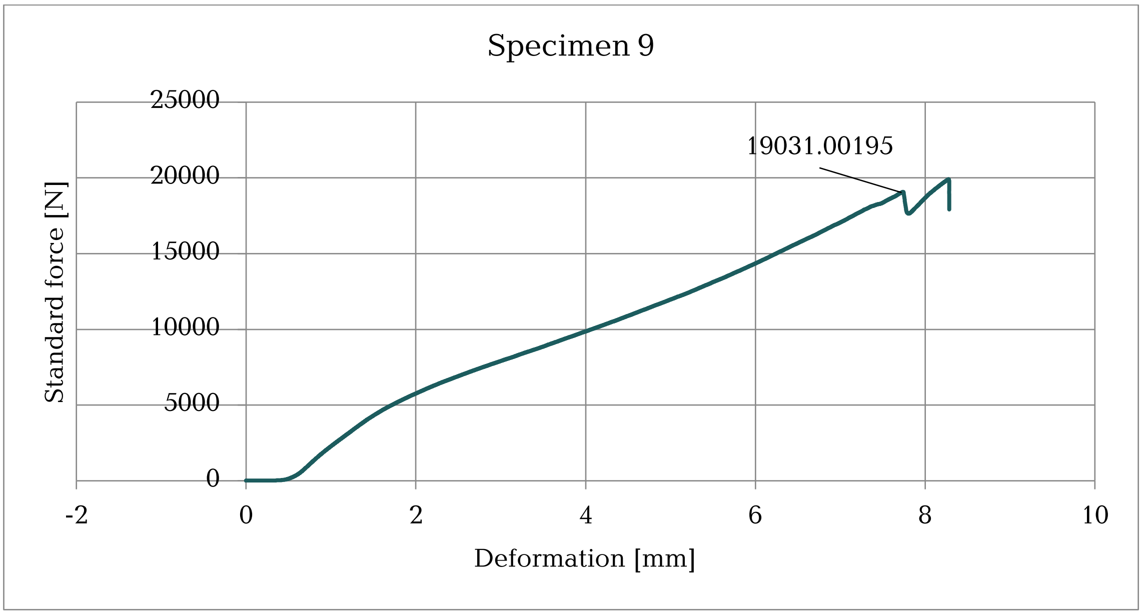

Specimen 4
Standard force [N]
35000
30000
25000
20000
15000
10000
5000
0
-2
0
2
4
6
8
10
12
14
Deformation [mm]
22695.7832


Specimen 5
Standard force [N]
25000
20000
15000
10000
5000
0
0
2
4
6
8
10
Deformation [mm]
20164.23633


Specimen 6
Standard force [N]
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
-1
0
1
2
3
4
5
6
7
8
9
Deformation [mm]
16577.66992


Specimen 7
Standard force [N]
25000
20000
15000
10000
5000
0
-2
0
2
4
6
8
10
Deformation [mm]
19221.46875


Specimen 8
Standard force [N]
30000
25000
20000
15000
10000
5000
0
0
2
4
6
8
10
12
Deformation [mm]
25084.51367


Specimen 9
Standard force [N]
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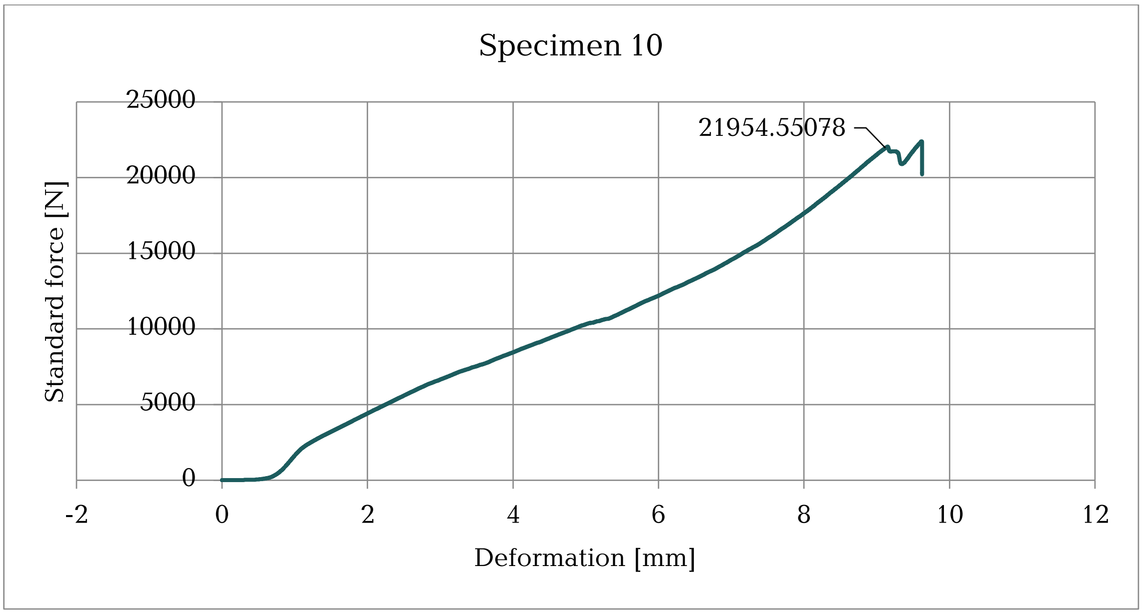
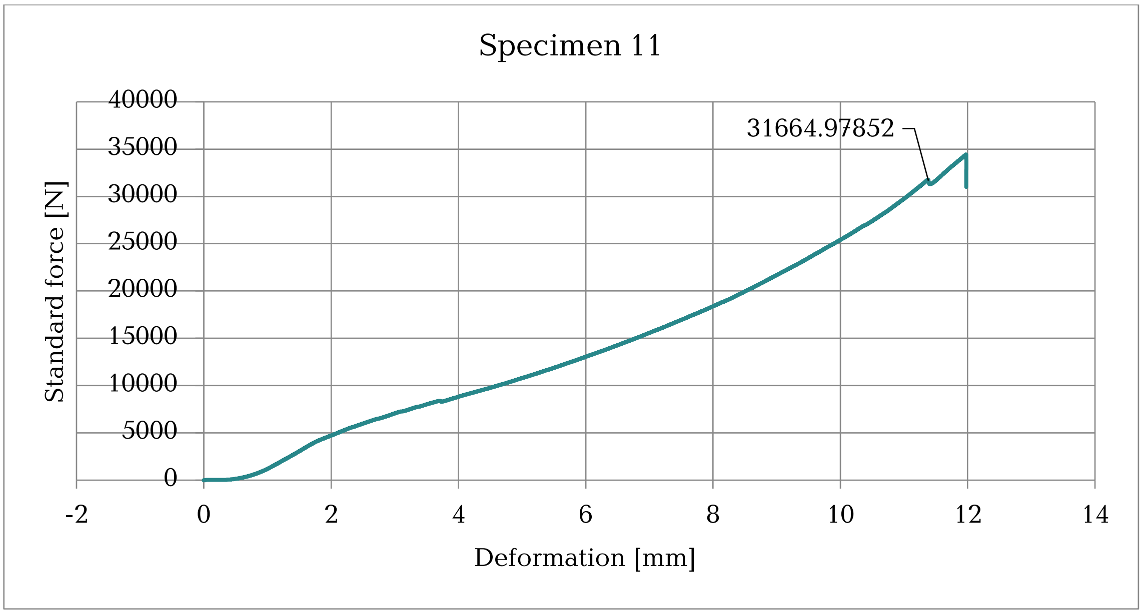
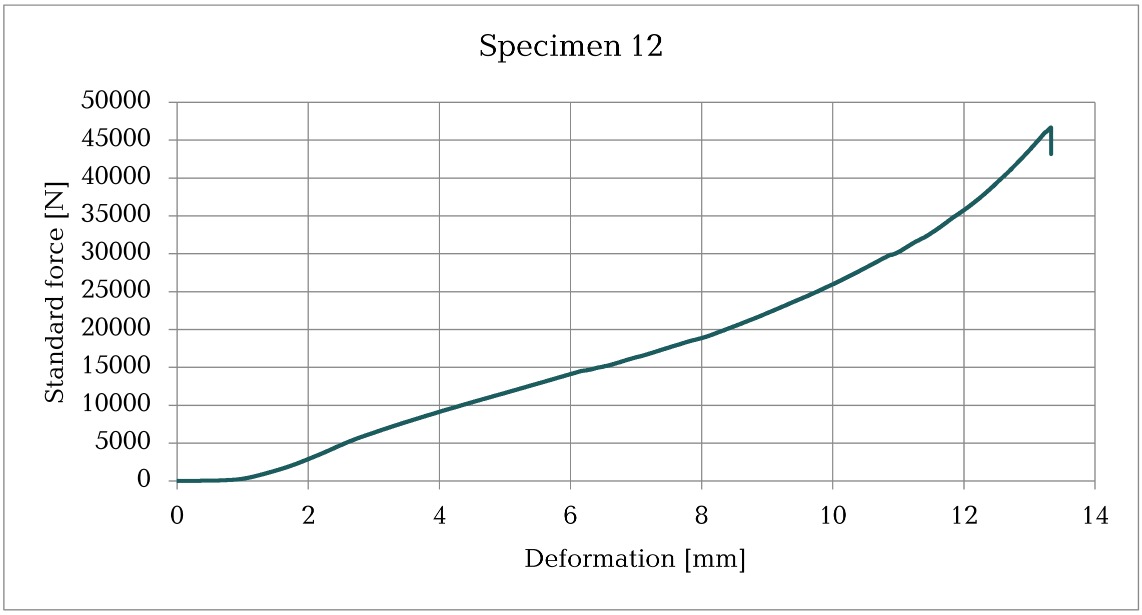
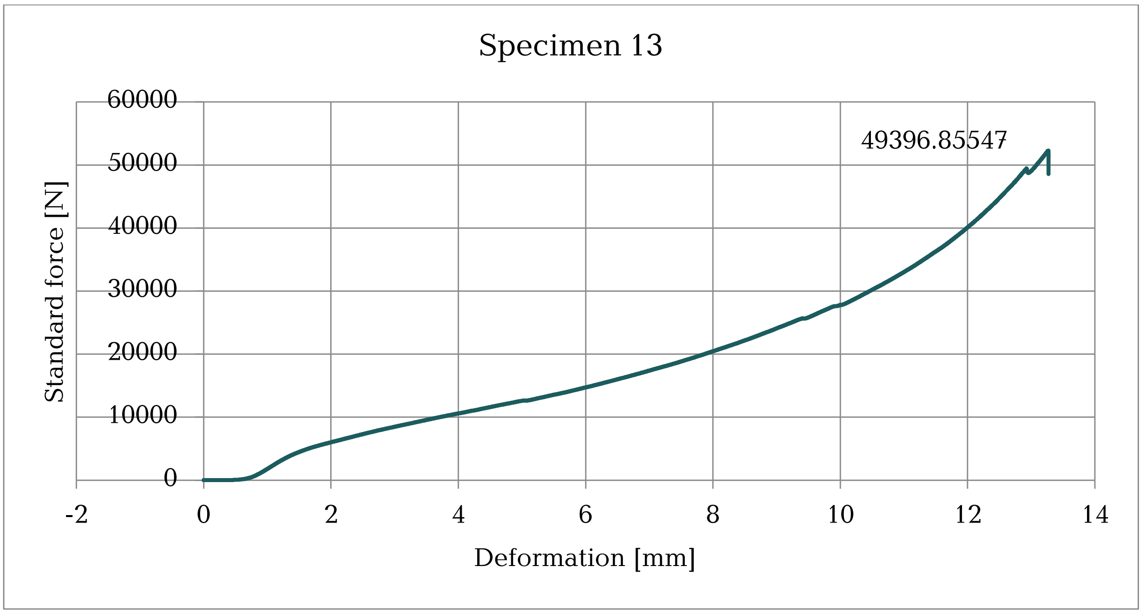
20000
15000
10000
5000
0
-2
0
2
4
6
8
10
Deformation [mm]
19031.00195

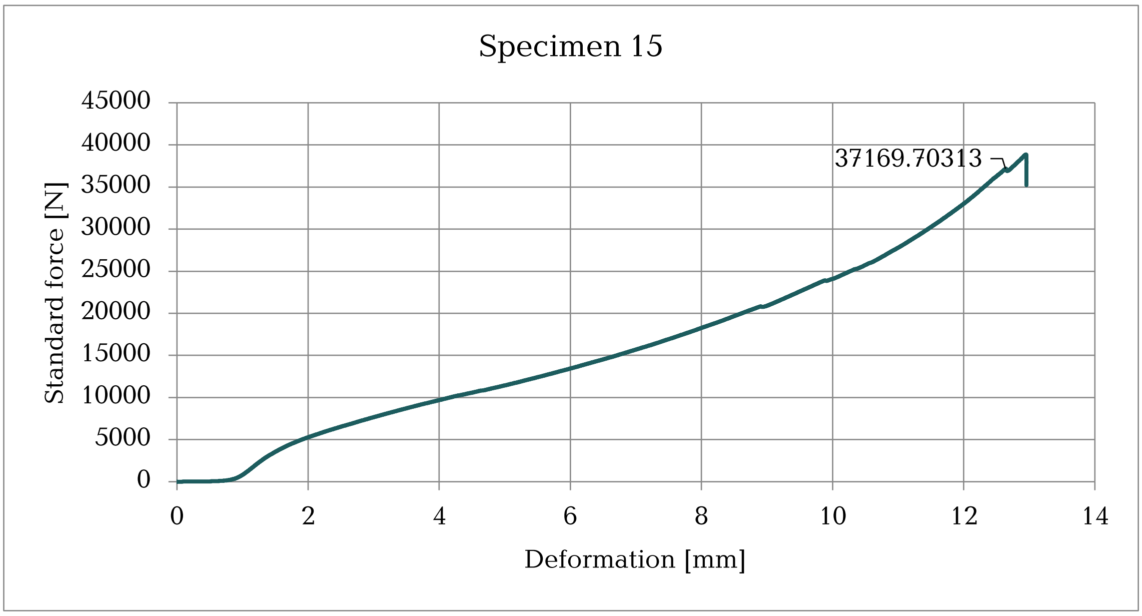

Specimen 10
21954.55078
Standard force [N]
0
5000
10000
15000
20000
25000
Deformation [mm]
-2
0
2
4
6
8
10
12


Specimen 11
31664.97852
Standard force [N]
0
5000
10000
15000
20000
25000
30000
35000
40000
Deformation [mm]
-2
0
2
4
6
8
10
12
14


Specimen 12
Standard force [N]
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000
Deformation [mm]
0
2
4
6
8
10
12
14


Specimen 13
49396.85547
Standard force [N]
60000
50000
40000
30000
20000
10000
0
-2
0
2
4
6
8
10
12
14
Deformation [mm]

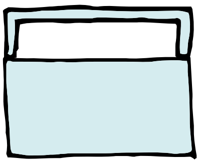

Specimen 14
35117.85547
Standard force [N]
40000
35000
30000
25000
20000
15000
10000
5000
0
0
2
4
6
8
10
12
14
Deformation [mm]


Specimen 15
37169.70313
Standard force [N]
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
2
4
6
8
10
12
14
Deformation [mm]

Appendix E: Explanation of design alternatives

Design 1: single cavity

The first concept follows from hollow blocks; half a hollow block will be fused or glued to a structural brick. Each block will have at least one air chamber, which will act as the thermal barrier. Fusing has the advantage over glueing that there is no need for other materials, and it is easier to recycle. On top for that, it is an airtight seal. However, this will result in some residual stresses within the brick due to the uneven cooling down.



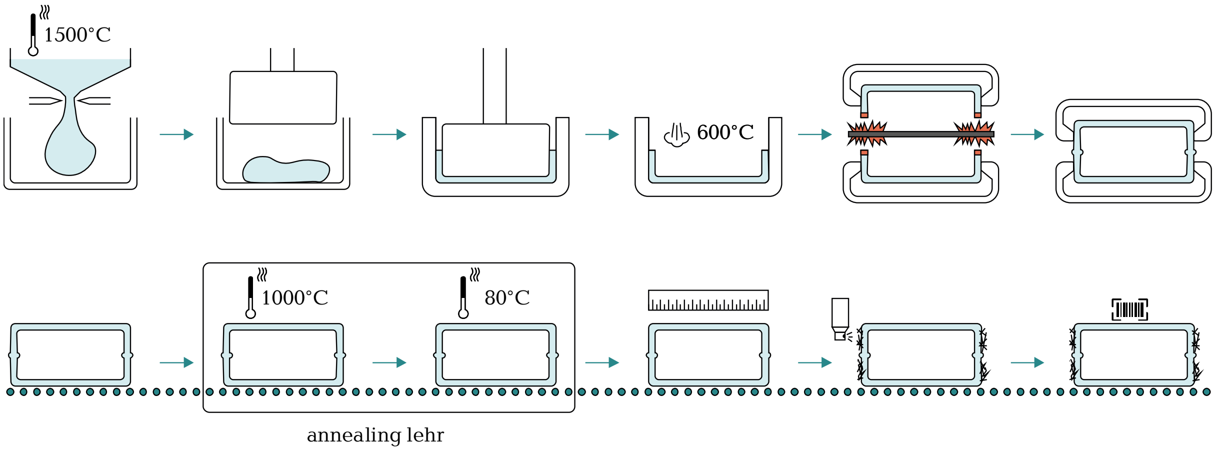
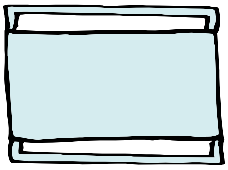


Figure 101 Production of hollow glass bricks

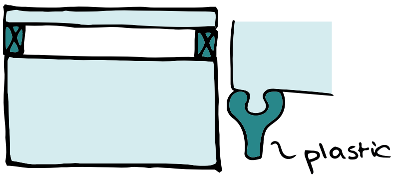
Design 2: double cavity

The second concept is based on the idea that the thermal resistance of cavities is not linearly increasing with the depth. Convection will reduce the resistance. If an air chamber is split in two, the thermal resistance will be more than the equivalent thickness of a single chamber with the same total thickness. Because two chambers on one side can be more difficult to produce, the third design places two chambers on opposite sides of the brick. This can be beneficial for the production complexity, while still profiting from a double cavity.



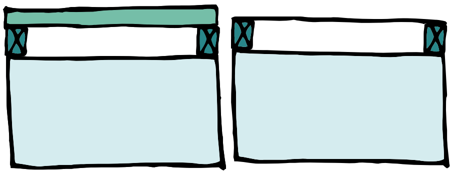
Design 3: single cavity with spacers

The fourth design tries to reduce the thermal bridging occurring in the former designs. Optional in this design, is trying to make the plastic interlock with the glass. With this innovative system, a dry connection can be made which can easily be taken apart again to recycle each part separately. This is possible because of the form-freedom of cast glass.



Design 4: float glass piece attached + Design 5: Gorilla glass

Design number five and six follow from the same principle of trying to reduce the thermal bridge by using another material as a spacer, i.e. plastic. When doing this, the additional glass piece has a simple rectangular geometry. This can also easily be executed with float glass or even something very thin like gorilla glass. This layer does not contribute to the vertical load-bearing capacity and if placed on the inside, will not take any wind loads. This does, however, introduce a different glass production type, which is not preferable in terms of recycled waste glass usage.



Design 6: double brick wall

Similar to clay bricks, two walls can be constructed with an air cavity in between. This will not result in a change of design for the bricks themselves. If a secondary wall is created, the depth of each layer can be minimized, if the two walls can collaborate structurally. For this, some ties are needed to provide stability for out-of-plane loads on the slender wall. These ties are common practice in clay brick walls and are dealt with in the Eurocode, but will need modification to work in glass brick walls. Transparent acrylic ties could generate more transparency, but its structural integrity has to be analysed and tested.

Another way to approach these ties is by designing a glass connector piece, that functions as a tie. This could be an interesting design, in which no additional materials will be introduced.

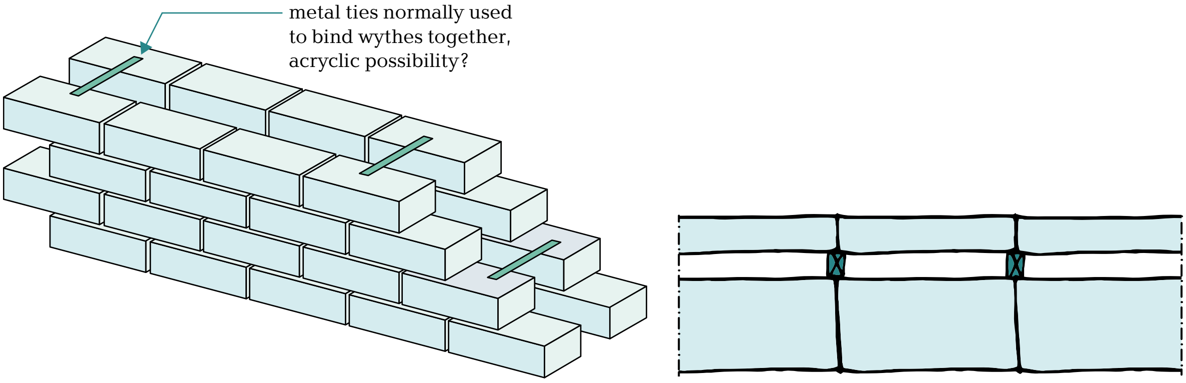


Figure 102 Secondary brick wall design

Design 7: secondary float glass wall

Current insulating facades mostly consist of float glass panels, forming an IGU. Creating an insulation air layer with a float glass layer is feasible. However, this does not fully align with the goal of this thesis. To lengthen the life cycle of float glass waste, the possibility is researched to recycle it into bricks. Introducing a new layer of float glass does not follow this concept. Additionally, the bricks are modular, each element can be used to create several systems, and thus façade sizes. Float glass panels have a fixed size and are thus not generally applicable.

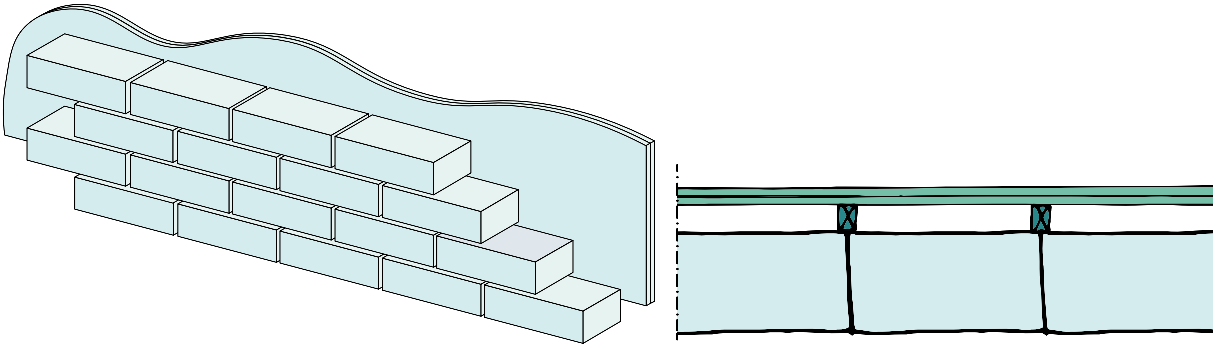


Figure 103 Float glass + brick wall combination

Design 8: chess brick

During the development of the prototypes, an interesting concept arose. Incorporating air bubbles can be a tricky process, especially with bubbling agents. It leaves the outer surface irregular with many imperfections. What if it would be possible to create bubbles only in desired places, with a predetermined shape. In art, the answer can be found, for example in the art of Joan Mitchell (Mitchell, n.d.). In her art, the glass is heated until a viscosity where the glass fully fuses with itself.

However, at lower temperatures, tack fusing might prove sufficient. The lowered temperature will increase the sustainability by the less amount of energy required. An investigation has to be made, at which temperature the material can stick to itself, without sagging much.

Figure 104 Fused glass art (left) and tack fused glass in mould (right)

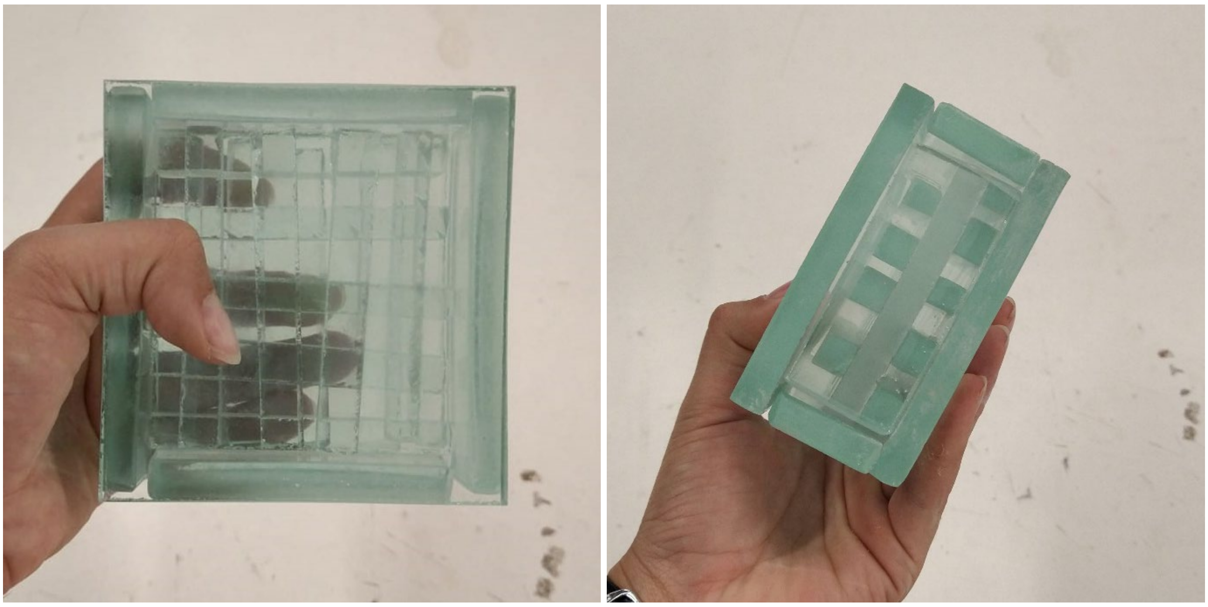


Figure 105 Chess brick with 10mm float glass on sides

It is produced with float glass strips in the right size, placed in a mould (to maintain shape) and then heated up in the oven. This can also be executed with a thinner float glass on the sides.

Design 9: shard brick

It is produced with float glass strips in the right size, combined with glass shards, placed in a mould (to maintain shape) and then heated up in the oven. This can also be executed with a thicker float glass on the sides.

Figure 106 Shard brick with 4mm float glass on sides