BONDLESS INNOVATION

EVALUATING DIRECT ADHESION IN A CONCRETE-GLASS INTERFACE
FOR FREE FORM TRANSPARENCY.

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EVALUATING DIRECT ADHESION IN A CONCRETE-GLASS INTERFACE
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Graduation Thesis Report

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"design is thinking made visual "

- Saul Bass

PREFACE

This report represents my Master's thesis for Building Technology at TU Delft. The past two years have been pivotal in my education and personal development. The passion of all the students to make the world of tomorrow a bit more beautiful through architecture has been both inspiring and invaluable. Working on this project over the last eight months has been the most enriching experience of my master's program. Although there were physical challenges during this period, none of this would have been possible without the help of many people.

First and foremost, I would like to thank my mentors, Faidra Oikonomopoulou and Marcel Bilow. They always encouraged and guided me in the right direction, especially when I felt a bit lost. Their innovative ideas and proactive approach have been a positive influence on me. I would also like to extend my gratitude to Telesilla Bristogianni, who was always available in the lab to assist with any questions, no matter what they were.

Lastly, and most personally valuable, I want to express my love and gratitude to my family, friends, and girlfriend, who have always been there for me. Without their support, believe, and love, I would not be where I am today.

ABSTRACT

Key words: Cast glass, Concrete, Free-form transparency, Hybrid, Interface design, Interlocking, Surface roughness, Facade panel

This thesis explores the potential for creating a hybrid facade panel with free-form transparency by combining concrete and glass without the use of adhesives or interlayers. The research focuses on optimizing the direct interface between these materials to enhance adhesion and structural performance. Key parameters investigated include material composition, interlocking geometry, and surface roughness. Experimental testing revealed that a self-compacting concrete with lower alkalinity and a belly-shaped interlocking form with a roughened glass surface yielded the best results in terms of interface strength and adhesion. Design guidelines were established based on these findings, defining the areas within a facade panel where the glass-concrete interface can be placed to minimize stress concentrations. The proposed hybrid panel offers a sustainable solution by enabling disassembly and recycling of the materials at the end of the panel's service life. This research represents an initial step towards realizing a new architectural design language that combines the opacity of concrete with the transparency of glass in a free-form manner. Further research is recommended to refine the material compositions, optimize the interface design, and explore additional applications for this innovative hybrid system.

00
RESEARCH FRAMEWORK

01
RESEARCH FRAMEWORK

1.1 PROBLEM STATEMENT

Glass, glass, glass. Todays city skyline is dominated by all-glased buildings. The widespread use of glass in architecture has surged in recent years, resulting in a skyline defined by transparency (NESEA Blog | The All-Glass Building, z.d.). The fascination for glass goes back as far as the Romans. Not only due it's functionality but also the artistic and philosohic purpose of this unique material has captivating the build environment (Thimmarajakalyan, 2017).

The glass innovation, partly due to the mastering of the float glass process by the *Pilkington Brothers* in 1959, gave architects the freedom to use glass in a scale they have only dreamed about (Bricknell, 2010). This technical revolution in combination with the architectural and artistic fascination led to increasement in todays all glass buildings.

The rising popularity of fully glazed facades brings about a downside: too much sunlight flooding indoor spaces. This lack of control leads to discomfort as shading systems obstruct the outside view, leaving occupants without visual relief. Furthermore, when these shading systems aren't utilized, glare issues and overheating become prevalent problems for those inside (Valitabar et al., 2022).

Also from the perspective of passersby, the skyline becomes monotonous due the presence of high-rise buildings characterized by a rectangular grid pattern consisting of glass panels. While innovation in the glass industry provides freedom in using glass as a facade material, this doesn't necessarily translate into architectural expression in design. The panel-based curtain wall systems introduce an obstruction to free-form design.

The performance of the facade plays a crucial role in the energy consumption of buildings (Akšamija, 2013). The Energy consumption of non-residential high-rise building have an increasement in energy consumption by 74% in the last 20 years (BPIE source). Energy saving options have been widely discussed. Research have shown the potential in decreasing energy demands by reducing the percentage of glass in facades (Shaik et al., 2021).

Figure 1: Full-glazed offices (Vinoly tower) are taking over the skyline of Amsterdam (Zuidas).

1.2 POTENTIAL INNOVATION

Energy-efficient building facades possess several key properties. These include facilitating daylight penetration while preventing excessive solar heat, retaining heat within wall masses, enhancing insulation to prevent heat transfer, blocking air and moisture infiltration, and enabling natural ventilation for interior cooling. Facades generally fall into two categories: opaque and transparent (Brookes, 1998). Opaque facades are benefitical in higher mass, insulation and have a increased heat capacity. Conversely, as discussed before, glazed facades allow daylight entrance, enhanced views for occupants, and reduced structural loads when compared to their opaque counterparts (Akšamija, 2013).

Facade panels are gaining popularity in construction for their versatility and efficiency. They come as fully opaque or transparent curtain wall systems. Why not combine these two facade categories? Innovative material composites for facades with glass surfaces allow a significant improvement in usability, stability and residual load-bearing capacity (Knaack et al., 2015). Innovative hybrid panel element made from an opaque and transparent material has significantly improved performance characteristics compared to conventional carrier panel systems (Murray, 2013).

By replacing full glazed curtain wall systems with hybrid facade elements, It not only reduces the percentage of transparency in the facade, it also gives opportunity and potential to stop the monotomy design obstructions. Creating free-form transparency in a hybrid form introduces a new design language for architects.

The potential innovation in hybrid elements, blending transparency with opacity, faces challenges due to the current restrictions on design freedom for transparent facades. A critical gap exists in research focusing on connections for hybrid systems, hindering the realization of versatile and aesthetically pleasing building components.

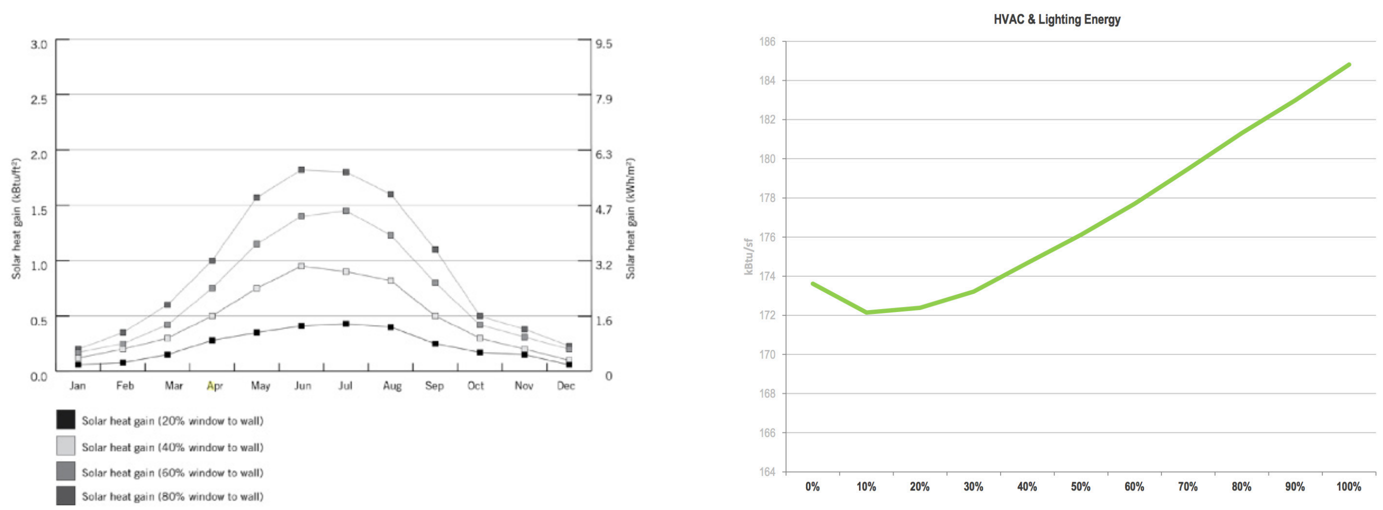


Figure 2: Left: increasement in window percentage leads to solar heat gain. Right: The most efficient percentage window is around 20% in terms of electricity

1.3 RELEVANCE

1.3.1 SOCIAL & SCIENTIFIC

Full transparency and an aesthetically high-quality appearance achieved through the use of glass have become the new standard for many buildings. The connection between the interior and exterior, along with the spatial qualities that light brings, is increasingly valued by building occupants. Thanks to advancements in innovative technologies and a rapidly growing knowledge base in the material, glass is now employed in various applications.

However, the complete transparency of facades can have drawbacks. Occupants may experience issues such as glare, heat gain, and the need for extensive sun shading systems due to the size of the glass facades. Furthermore, fully glass buildings often lack aesthetic tension and architectural innovation due there monotony.

For these reasons, the objective of this research is to create a new design language with no distinct zones of transparency and opaqueness. This study explores the challenge of creating a self-supporting panel with a hybrid connection between concrete and glass, a combination with minimal existing research. By casting solid glass elements, it becomes possible to achieve free forms with high transparency and high compressive strength, enclosed within a concrete framework. Despite the shared material property of brittleness and different expansion coefficients, the collaboration between the two materials, considered unrealistic, introduces this hybrid partnership as a novel building material composite.

This research goal serves as one of the first introductions to this hybrid collaboration. Until now, experimental work has been conducted separately for each material. The data, encompassing performance and structural development of both materials, can serve as a guideline and aid in the research.

The outcome of this experimental study provides new insights into the collaboration between concrete and glass on various fronts. Beyond structural benefits, the final product offers architectural opportunities. It provides architects with the choice and possibility to select transparency in a free form way as a facade material. The interplay between light and dark, open and closed, transparent and opaque, brings significant aesthetic value to the field of architecture.

1.3.2 SUSTAINABILITY RELEVANCE

Technological advacements and material innovations has been a growing trend in the build environment. More and more hybrid (embedded) elements have been created to achieve enhanced properties or functionalities. Despite the growing prevalence of hybrid materials, there is a notable absence of provisions for recycling these elements.
In addition to the soctial en scientific relevance, this thesis intension is also to achieve a reversible connection that allows recovery of the two materials and their eventual recyclability. Hence, the experimental process will be guided by the design for assembly approach.

If, ultimately, an interlocking embedded connection between glass and concrete can be established through the research, it could also be applied as a solution for other products utilizing hybrid materials (without the use an interlayer).

1.4 RESEARCH QUESTION

MAINQUESTION:

In what way is free-form transparency possible in a hybrid facade panel, consisting of a transparent and opaque material?

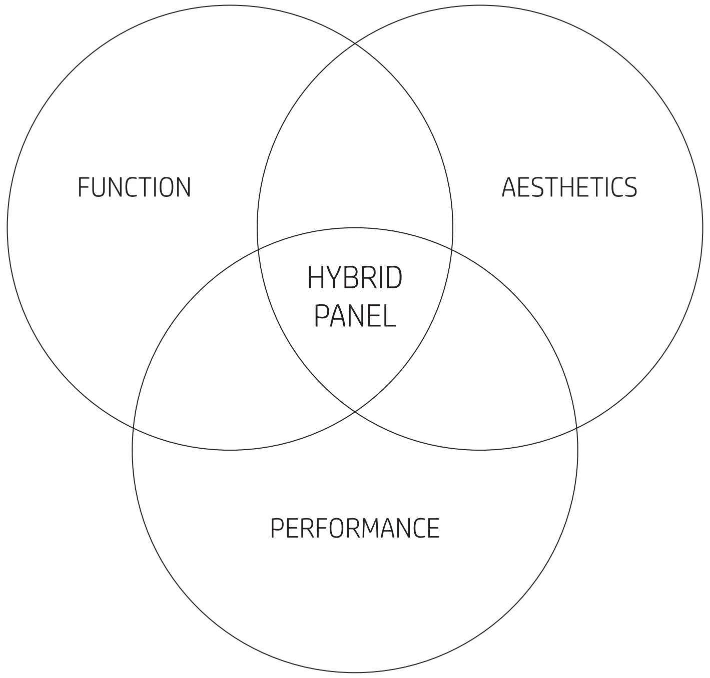
SUBQUESTIONS:

Every chapter has there own subquestion which helps define the design considerations allowing for free-form transparency is a hybrid composition.

1.5 METHODOLOGY

This thesis is divided into 5 parts:

- Literature research
- Experimental research
- Research by Design
- Design refinement
- Conclusion & Discussion



I LITERATURE REVIEW

The focus is on understanding the fundamental principles of a hybrid components and choosing a transparent and opaque material (by making a matrix of all various materials possible) to pick the most suitable materials for my research. The second investigations is about the general information of both selected materials and to make a comparison and selection in composition, fabrication method and production processes for the experiment research part of this thesis.

II EXPERIMENTAL RESEARCH

In this phase, background information will first be reviewed through literature research, followed by experimental testing of various important design considerations for an interface design. The results of the different interface aspects will serve as input for the next phase: research by design. The experimental research aims to identify the best concrete composition for this design, evaluate the structural integrity of interlocking forms in a hybrid composition, and assess the impact of surface roughness on adhesion strength.

III RESEARCH BY DESIGN

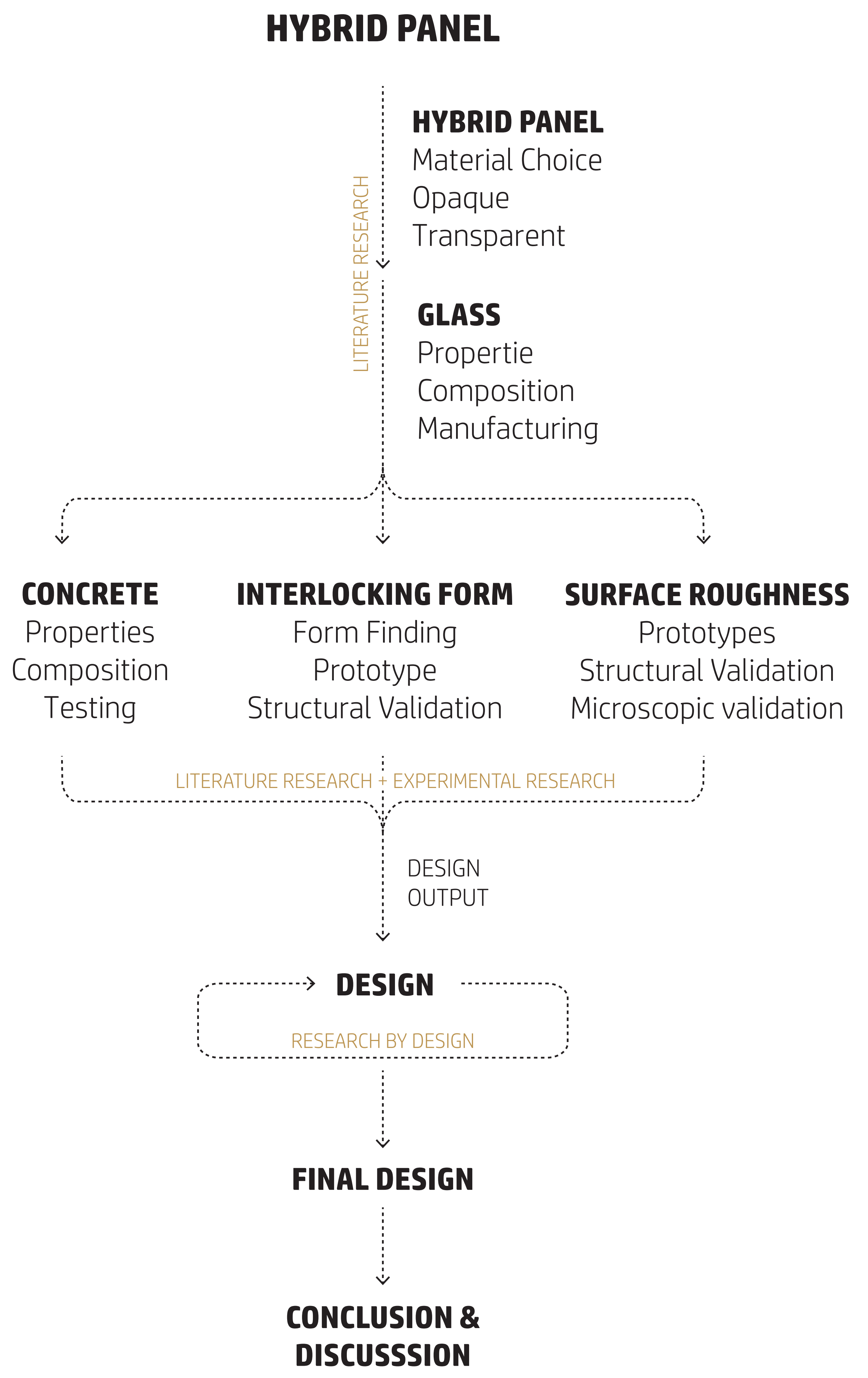
Here, the results of the experiments for the interface design are consolidated. By making prototypes, which also assess the manufacturability, research can be done by looking into the various designs and their possibilities and limitations. Different hybrid connections will be experimentally tested in the lab to assess structural performance. The main focus will be the interlocking interface design of the two materials.

IV DESIGN REFINEMENT

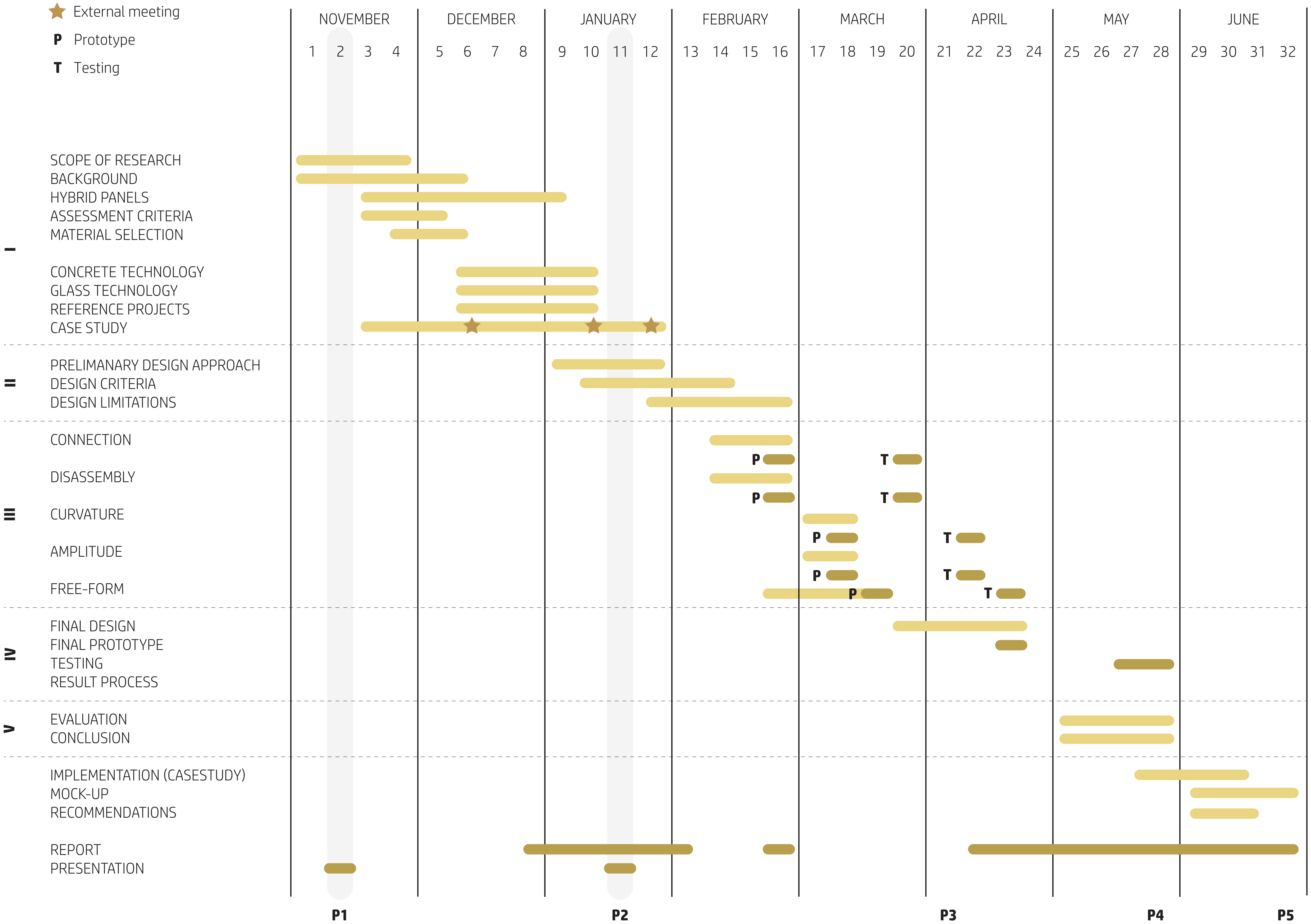
All the tests and design research is done and qualitative results are calculated or tested. To arrive at a final design concept, considerations are made regarding the advantages and limitations. The ultimate design is thoroughly developed and detailed into a cohesive whole. This process also involves a close examination of the manufacturing and assembly steps for facade implementation. Once the entire concept is finalized, the final prototype is created. This prototype is intended to depict how the design should appear in real-life applications.

V EVALUATION & CONCLUSION

After making the final prototypes and all the testing results are done, a full evaluation will be made. There will be an comparison assessment with the casestudy.
In the conclusion, all aspects are summarized and the feasibility and potential real-life applications are examined. Recommendations are provided to support further research in hybrid panels, all limitations are discussed, and the research demonstrates the potential of the study.



1.6 PLANNING


External meeting
P Prototype
T Testing
NOVEMBER
DECEMBER
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
I
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GLASS TECHNOLOGY
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DESIGN CRITERIA
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02
HYBRID PANEL

In what way can we assess the choices of materials for a hybrid composition in a panel allowing for a balance between transparency and opacity in a free-form manner?

2.1 INTRODUCTION

According to the Oxford Dictionary, hybird is “a thing made by combining two different elements”. The act of merging two or more pre-existing monolithic materials to integrate their individual properties is referred to as hybridization. (Ashby, 2003). The ultimate goal of such hybrids is to leverage the strengths of each constituent material, strengthen one another. In the envisioned hybrid facade panel, this concept can be described as a fusion of opaque and transparent materials, forming a seamless integration that empowers architects in a new architectural design language.

To design such a hybrid, it’s imperative to deconstruct it and conceptualize it as a fusion of materials (or material and space) within a defined geometry (Ashby, 2003).

Defined as a combination of two or more materials within a specific geometry and scale, a hybrid material optimally serves distinct engineering purposes (Kromm et al., 2002). This concept can be paraphrased as “A + B + shape + scale.”

Creating successful hybrids presents significant challenges, both in terms of complexity and cost. These challenges arise from the multitude of choices involved: selecting appropriate materials, determining the suitable process for their integration, and defining the internal geometry and topology of the constituent materials. Additionally, these choices must align with a set of design requirements, striking a balance between feasibility and optimization

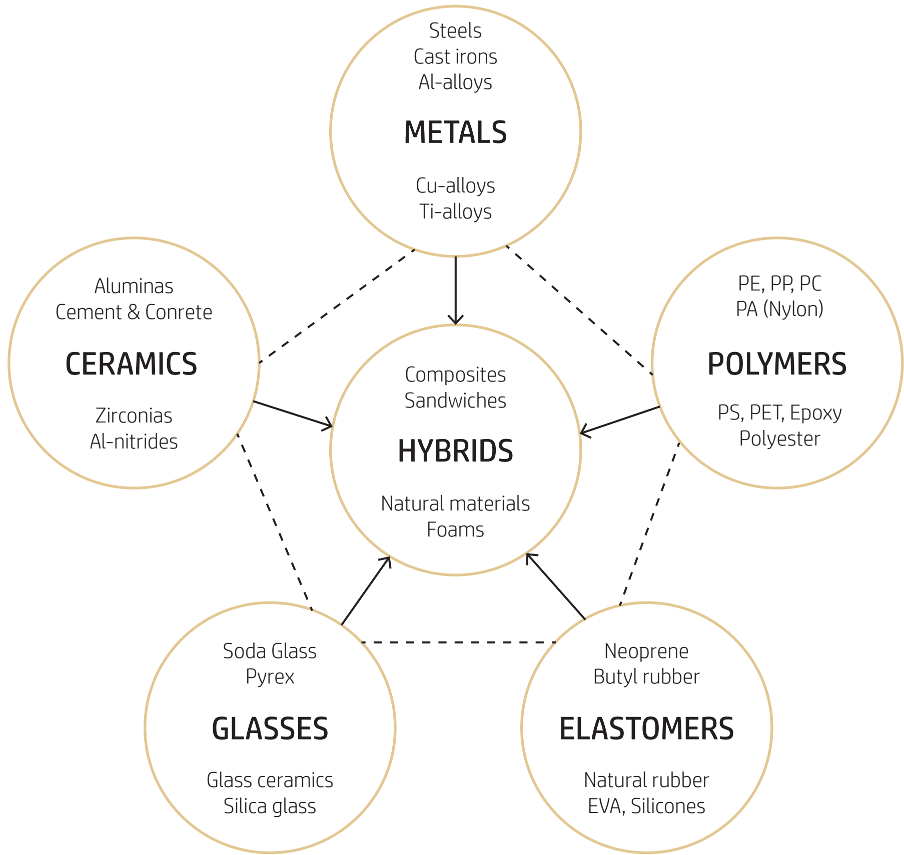


Figure 3: In this thesis a hybrid is chosen between the properties of a (non-technical) ceramic and the properties of glasses.

2.2 CHOICE OF MATERIALS

The primary role of a facade is the separation of the outside and inside climates (Knaak et al., 2008). However, contemporary facade technology goes beyond achieving a favorable climate balance. It encompasses the entire process of designing, constructing, and implementing building facades, which are the external surfaces or coverings of a structure. These facades serve a dual purpose, contributing to both aesthetic appeal and functional performance. The evolution of facade technology necessitates a multidisciplinary approach that integrates architectural, engineering, and material science principles to attain optimal outcomes (Source).

To select the most suitable materials for a free-form hybrid facade panel, a decision-making table employing a multi-criteria decision-making (MCDM) method is employed. MCDM methods prove effective in striking a balance among various design objectives (Saviz et al., 2020). The study compares the eight most commonly used opaque facade materials and the five most prevalent transparent materials in the built environment. Table 1 outlines the multidisciplinary performance criteria that guide the selection process. Notably, this research focuses specifically on a hybrid free-form panel, which entails assigning varying levels of importance to specific criteria within an integrated design. Each performance criterion is consequently assigned an importance factor, with distinct intensities detailed in the accompanying table (Figure 4).

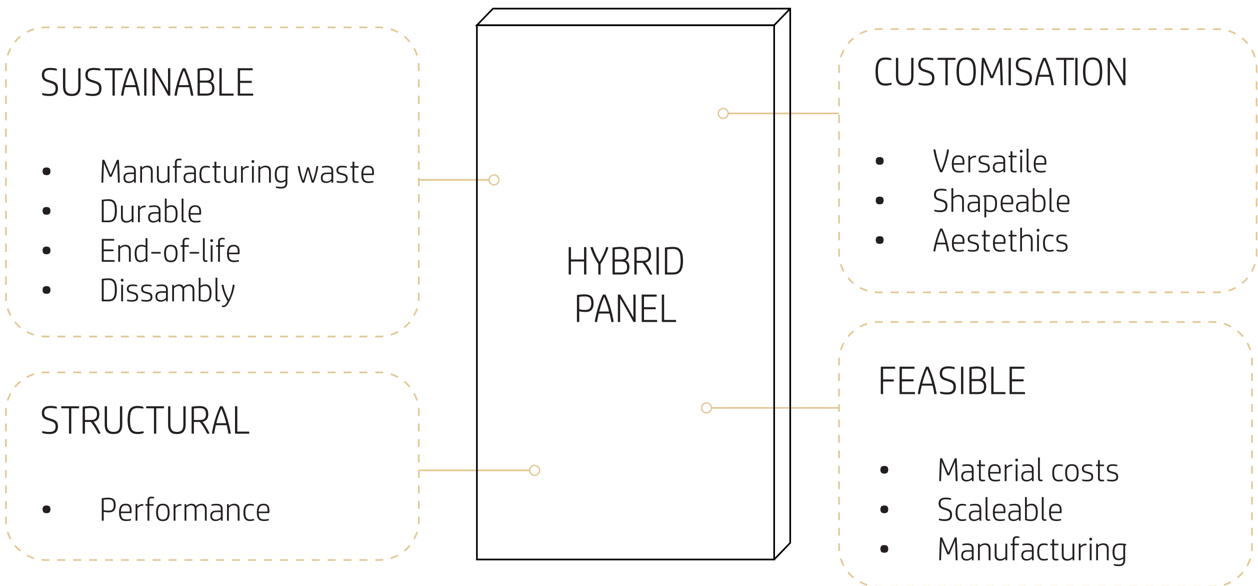


Figure 4: Hybrids are a combionation of properties of two monolithic materials. In this thesis a hybrid is chosen between the properties of a (non-technical) ceramic and the properties of glasses. Edited from (Ashby, 2003).

OPAQUE MATERIALS

In the process of selecting an opaque material, an evaluation is conducted among the eight prevalent building material categories. The majority of these properties are derived from Granta Edupack 2022. These categories are distinguished by their average material composition, encompassing characteristic properties and performances.

The categories are as follows:
1) minerals & stone
2) fired clays
3) cement & concrete
4) polymer composites
5) thermoplastics
6) natural materials
7) alloys (non-ferrous)
8) metals (ferrous)

An overview of the material properties of the 8 most common buidling materials can be find in the Appendix.

TRANSPARENT MATERIALS

For the transparent section of the hybrid facade panel, a similar MCDM analysis is performed. This analysis involves the comparison of five distinct transparent materials commonly utilized in facade technology. The evaluation is based on average values and properties associated with these materials. The transparent materials under consideration can be seen on the right and are as follows:

1) Glass
2) Polycarbonate
3) Acrylic
4) ETFE (Ethylene Tetrafluoroethylene)
5) Epoxy (resin)

In the comparison matrix, you will notice an additional performance criterion, namely aesthetics. This refers to how transparent a material is. Given that transparency is a crucial aspect, this allows for a comparison of the aesthetic value of the transparent materials.

PERFORMANCE CRITERIA FOR FREE-FORM FACADE MATERIAL SELECTION				
STRUCTURAL	PHYSICAL	CHEMICAL	SUSTAINABLE	EFFICIENCY
Density	Thermal conductivity	Combustibility	Embodied energy	Material costs
Tensile	Expansion coëfficient	Weather resistance	Recyclable	Shape ability
Yield	Heat capacity	UV-resistance	Durability	Accessible
Compressive			Manufacturing waste	Aesthetics *

Figure 5: Overview of the material properties that are being analysed for a comprehensive overview of the most common opaque and transparent materials in the build environment.

SUSTAINABLE

Sustainability is a topic that cannot be ignored in today's world, particularly in the building industry. This industry stands as one of the largest emitters of greenhouse gases and end-of-life waste generators, with building envelope accounting for 10-30% of the total emissions (Arup & SGG, 2022; Hartwell et al., 2021).

When creating a new building element, it's essential to consider sustainable design principles. For the design of a hybrid panel, the following sustainability criteria are addressed: disassembly, durability, waste generation, and end-of-life. These criteria are all interrelated, both directly and indirectly.

The **durability** of a panel determines its lifespan and thus forms part of the product's life cycle. If the product no longer meets functional or aesthetic requirements, it's crucial that it doesn't end up in a landfill but instead finds a new purpose at the end of its **life cycle**. Circular design aims to close the loop of materials in the building sector. This is only achievable if materials can be separated from each other for recycling, which involves the **disassembly** of the element (See figure 6).

Waste generation also looks at how much waste is produced during both the initial and subsequent production stages, emphasizing the importance of minimizing waste throughout the manufacturing process. By optimizing production methods and **reducing waste generation**, the environmental footprint of building materials can be significantly reduced (Bertin et al., 2022).

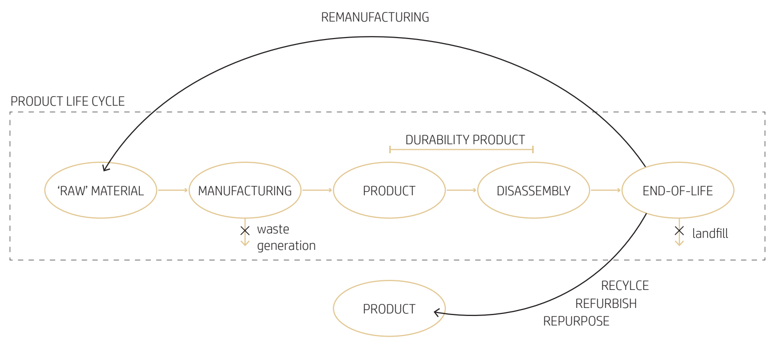


Figure 6: Illustration of recycling opportunities with design for dissassembly.

CUSTOMISATION

The concept of the hybrid panel presented in this thesis aims to provide an opportunity and potential to overcome the monotonous design limitations of contemporary window systems. By offering designers the freedom to create transparency in virtually any form, a new design language is established.

Creating free-form transparency requires **shapeable** materials. These materials can either be molded or cut and processed into specific shapes. However, cutting has the drawback of generating manufacturing waste and imposes design limitations due to the cutting or processing techniques. This applies to both transparent and opaque materials.

This study explores a hybrid panel that could potentially function as a façade panel. However, hybrid forms of transparent-opaque materials can serve multiple purposes. Therefore, it is crucial that the selected materials can be used in various universal locations and applications, ensuring **versatility** and overall visual appealing properties.

From an optical perspective, **aesthetic** value also plays a crucial role. For transparent materials, the degree of transparency is important, while for opaque materials, they must also be aesthetically pleasing, as this can influence occupant satisfaction and perception of the space.

STRUCTURAL

An essential aspect of a hybrid panel is its overall structural performance. Given that the panel must function as a single unit, the hybrid form must ensure structural integrity. Pisarenko (2011) describes the structural strength of such material is not only the physical and mechanical properties but also its ability to resist external influences when elements of an appropriate size and shape are made. Rodichev (2018) divides this into three factors influencing the **structural strength** of a material:

- Structural: Mechanical properties of the materials
- Operational: External factors such as heat, wind, time, etc.
- Technological: Overall dimensions, shape (of the interface), and production.

FEASIBLE

Feasibility is crucial for creating a new hybrid material, because it ensures that the material can be practically and economically produced, implemented, and maintained. Assessing feasibility helps identify potential technical, financial, and logistical barriers early in the development process, ensuring that the new material can meet performance standards. To ensure that a product is not only innovative but als practical and economoically viable the materials selected must be **cost-effective**, which includes considering the availibilty and the long-term cost stablityof the product.

The production process of the materials must be efficient. As earlier mentioned, the **manufacturing** methods should minimize waste and optimize the use of materials to enhance overall efficiency and sustainability. Easily accessible materials have significant scalability potential due to advancements in material production technologies. These technologies enable the efficient and cost-effective mass production of materials, ensuring consistent quality and availability on a large scale.

2.3 CHOSEN MATERIALS

In conclusion of the assessment criteria and the material properties presented in Appendix .... Two materials, Concrete and glass are selected based on on the performance criteria. A description why glass and concrete is given below:

CONCRETE

Concrete, chosen as the opaque material, is primarily selected due to its casting method in production, providing excellent shapeability and zero manufacturing waste. Coupled with its cost-effectiveness and durability, it emerges as the most suitable material in terms of design flexibility and production. Concrete is often seen as an 'ugly' material, but together with glass it can achieve an aesthectically appealing look.

GLASS

As for the most suitable transparent material, Glass is the choice. Glass is known for its superior optical clarity and durability, particularly over time as other materials may degrade.

Glass offers greater design flexibility. Glass can be molded, bent, and shaped into a variety of configurations to achieve free-form designs while maintaining its structural integrity and transparency.

While the production of glass does have environmental considerations, it may be perceived as more sustainable than some alternatives like epoxy, which may contain harmful chemicals, or ETFE, which requires significant energy input for manufacturing. Additionally, glass is highly recyclable and can be reused in various applications, contributing to its overall sustainability.

HYBRID

Concrete and glass, while common in construction, are not always the most sustainable materials due to their environmental impact and are known for their relatively poor adhesion when compared to other materials.

However, when it comes to sustainability and disassembly, this weak adhesion can actually be advantageous. The weak adhesion between concrete and glass can support these goals by facilitating the separation and recycling of components at the end of a building's life cycle.

Concrete is aslo able to align with the thermal expansion characteristics of glass, which is essential for hybrid panels where both materials share load transfer duties (more in Chapter 4).

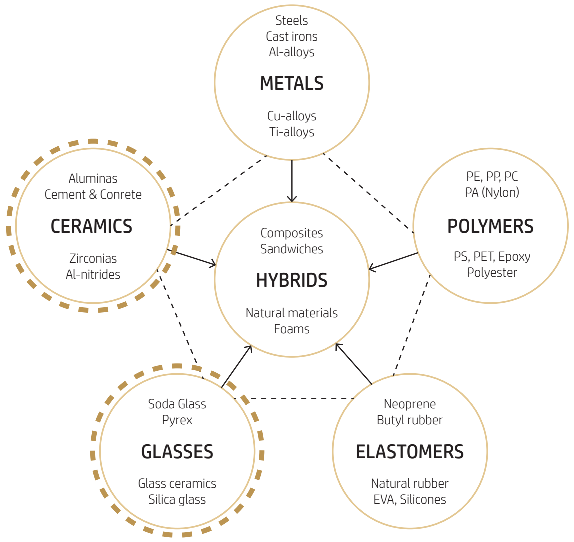


Figure 7: In this thesis a hybrid is chosen between the properties of a (non-technical) ceramic and the properties of glasses.

2.4 PERSONAL INSPIRATION

A glass-concrete hybrid form is not frequently encountered in the built environment. In 2017, TU Delft conducted a feasibility study for a glass and concrete hybrid panel for MVRDV. Upon encountering this project, my personal interest was sparked. To gain a better understanding of a glass-concrete interface, this project will be briefly discussed to note its key findings for this own research project.

In Kuala Lumpur, MVRDV undertook the development of an innovative facade for Bulgari (Figure 8).

The conceptualization of the facade initially aimed at creating a concrete-cast glass panel. TU Delft collaborated on the project, contributing experimental design options and ideas for prototypes in conjunction with ABT. Given the inherent challenge of achieving adhesion between glass and concrete, an exploration into a hybrid structure combining both materials for a panel ensued (Figure 10).

Due time limitation in structural validation of a hybrid sctructure between concrete and glass, MVRDV continued the realisation of the project with TensoForma. The final product is a hybrid panel consisting of a concrete (GRC) and resin. The utilization of Glass Reinforced Concrete (GRC) played a pivotal role in this architectural endeavor. Precisely cut GRC, infused with resin, was strategically illuminated using amber LED lights. The resin was applied atop a stainless steel sheet, seamlessly concealing panel joints within the vein pattern (MVRDV, z.d.) (Figure 9).

From two materials that had the potential to be used as self-supporting facade materials without adhesives, a system was chosen in which epoxy resin was used as an adhesive between the concrete and the stainless steel back construction that absorbs the forces.

Figure 8: Feasibility study by ReStruct group TU Delft of a concrete-glass panel.

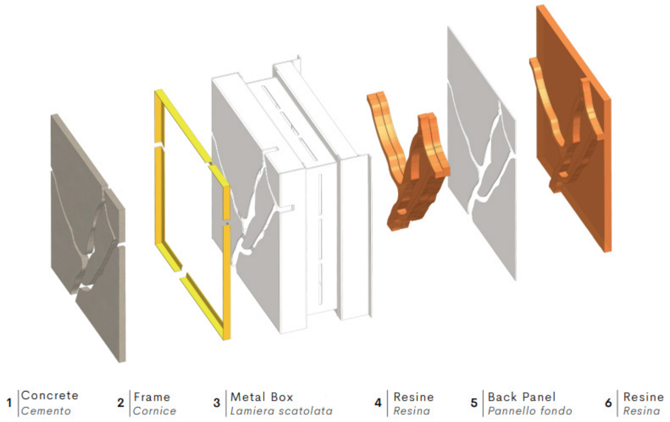


Figure 9: Feasibility study by ReStruct group TU Delft of a concrete-glass panel.

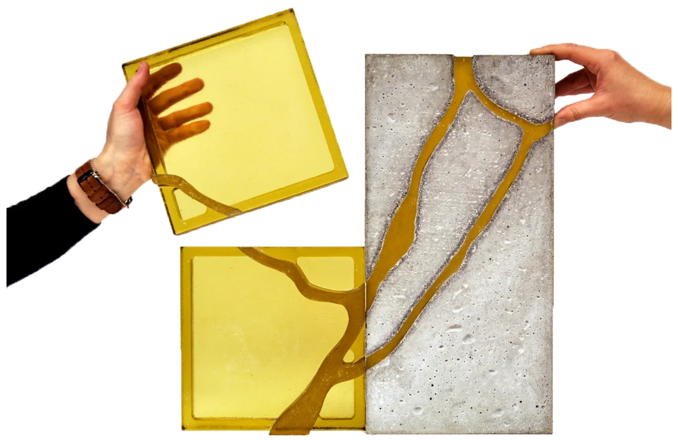


Figure 10: Feasibility study by ReStruct group TU Delft of a concrete-glass panel.

During the initial investigation conducted by TU Delft, various approaches were explored to achieve complex-shaped glass and structurally combine glass with concrete. Three structural configurations of the element were conceived (see figure 11).

The first configuration utilizes a composition where concrete serves as the load-bearing element, poured beyond the thickness of the glass. However, the drawback of this system lies in the reduced transparency due to the underlying layer of concrete.

The second option involves a hybrid load-bearing system, with the glass positioned between layers of concrete. The glass component can consist of either cast or laminated glass. While this structure maintains transparency, the interface between glass and concrete presents a challenge due to hybrid load transfer resulting from the attachment of the two materials.

The third option proposes a construction where glass serves as the load-bearing element, a trend increasingly observed in both laminated and cast glass applications. Oikonomopoulou et al. (2018) effectively demonstrate in her work the potential of cast glass in structural applications in architecture. However, the downside of using glass as a load-bearing structure lies in the excess material usage and more challenging production processes. In terms of sustainability and weight considerations, a hybrid form would be more desirable, although the glass provides a significantly larger contact surface for adhesion.

For a hybrid panel consisting of concrete and glass, this thesis advocates for a hybrid structure due to sustainability, aesthetic, and production considerations.

Unfortunately, further research on the direct bonding and adhesion strength of a glass-concrete interface has not been conducted by TU Delft.

Until now.

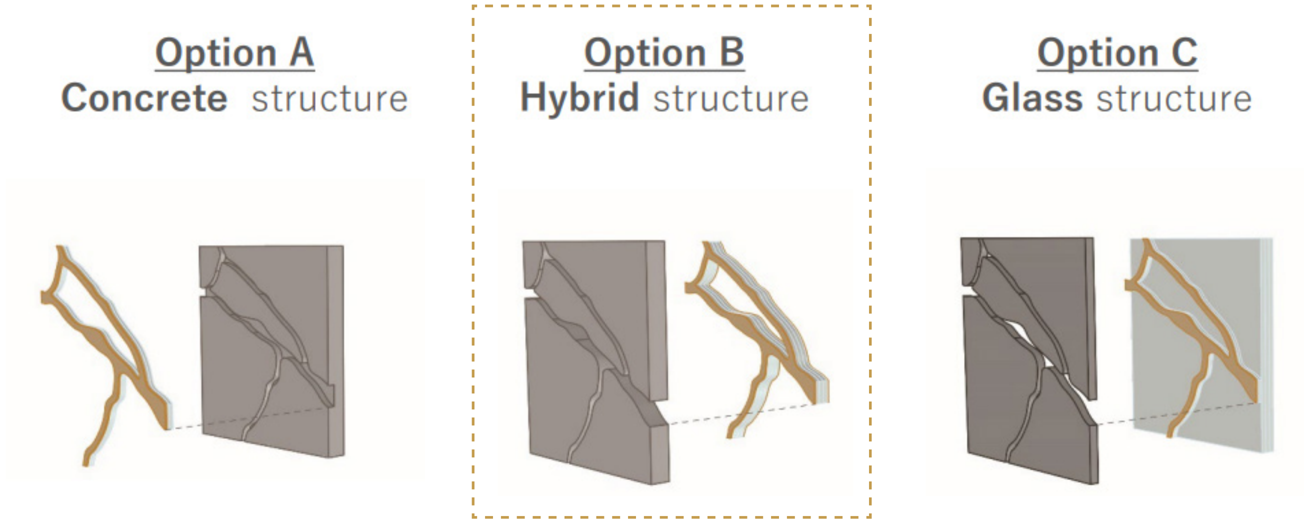


Figure 11: Feasibility study by ReStruct group TU Delft of a concrete-glass panel. Three structural scenarios are tested.

2.5 INTERFACE

Interfacial adhesion occurs when two different materials are combined, blended, or mixed. This combination may create the better dispersion of materials into the matrices. Usually, to achieve better interfacial adhesion, the combination of materials must have the same properties (Taib, 2019)

Glass and concrete both having unique properties were which can be extracted to be taken advantage of depending on the design. In the table below an overview of physical properties of the materials are given (Figure 12). The have similar density but glass performance better structurally. Glass is stiffer and higher in both tensile and compressive strength, there is possibility to use the mechanical strength of glass in a hybrid connection between both materials. This can lead to material savings of concrete where glas will be the load-bearng part instead of the concrete

PROPERTIES		GLASS (Soda-lime)	CONCRETE (C25/30)
Young's Modulus	[N/mm²]	70,000	27,000
Poisson's ratio	-	0.2	0.2
Tensile strength	[N/mm²]	20	2.2
Compressive strength	[N/mm²]	200	30
Density	[kg/m³]	2500	2500
Coefficient of thermal expansion	[K^1]	$8.6x10^6$	$10x10^6$
Thermal conductivity	[W/mK]	1	1

Figure 12: Physical properties of glass and concrete. Source: Author (EduPack Software 2022)

When combining two distinct materials in architectural applications, the interaction at their interface becomes a critical consideration. This interface serves as the boundary where the two materials meet and interact with each other. One common challenge that comes along with interfaces is managing the differences in mechanical properties and thermal expansion coefficients between the materials.

To address these challenges, interlayers are often employed between the interface to absorb loads and accommodate the differential thermal expansion of the materials. These interlayers act as buffers, helping to distribute stresses and prevent potential issues such as cracking or delamination.

However, in some cases, such as when pouring concrete against another material, adhesive bonding occurs naturally between the materials. This adhesive bonding can eliminate the need for interlayers and offer advantages in terms of simplifying construction processes and reducing material costs.

In the context of concrete and glass interfaces, research has been conducted to evaluate the adhesive bonding between these materials (Figure 13). The bond strength between glass and concrete is not as robust as desired (Figure 15), with an average bond strength of approximately 1 N/mm² (Gilabert et al., 2016). This relatively low bond strength poses challenges in structural applications where strong adhesion between the materials is essential for long-term performance and durability.

Efforts to improve the bond strength between glass and concrete continue through ongoing research and development. Innovations in adhesive technologies and surface treatments may offer potential solutions to enhance the adhesive bonding between these materials, thereby expanding their practical applications in architectural design and construction. Further investigation into the factors influencing the

bond strength, such as surface preparation methods, adhesive formulations, and curing conditions, is crucial for advancing our understanding and improving the performance of concrete and glass interfaces in architectural practice.

While interfacial bonding between concrete and cast glass offers potential benefits such as enhanced aesthetics and structural performance, overcoming the technical, durability, cost, and regulatory challenges is necessary to promote its widespread application in the construction industry. Continued research and development efforts in materials science, construction technology, and design innovation may eventually lead to advancements that facilitate the practical implementation of this construction method.
While not intended for mainstream construction, they contribute valuable insights to the field of architectural innovation.

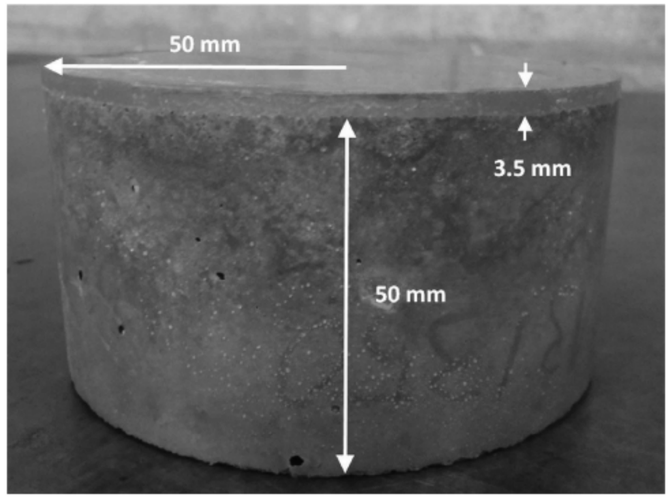


Figure 13: Prototype for testing interfacial bond strength. Source: (Gilabert et al., 2016)

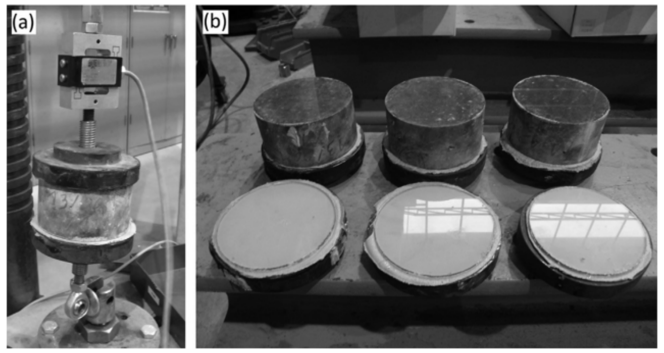


Figure 14: Test set-up with 6 samples. Source: (Gilabert et al., 2016)

Bond strength of a glass-concrete interface.

Sample	Bond strength [N/mm^2]
I	1.15
II	0.92
III	0.70
IV	0.79
V	0.82
VI	1.36
Average	0.96 ± 0.09

Figure 15: Results of bond strength of a glass-concrete interface of the 6 samples. Source: (Gilabert et al., 2016)

2.6 ALKALI-SILICA REACTION

When creatring a hybrid connection between concrete and glass an alkali-silica reaction (ASR) is something to take in mind. An ASR can happen when using glass aggregates in concrete composites, mostly applied in glassfibre reinforced concrete.

Concrete, a composite material formed from various components (see chapter 4), contains alkali elements, primarily Sodium (Na) and Potassium (K), which are predominantly found in the cement mixture (Schroeyers & Kovalchuk, 2020). Upon mixing, micro-pores within the concrete can be filled with a highly basic fluid (pH>12) containing dissolved alkali hydroxides (Thomas, 2013). The presence of siliceous aggregates in the concrete introduces the potential for alkali-aggregate reactions, notably the Alkali-Silica Reaction (ASR).

ASR occurs when alkalis from the concrete pores interact with siliceous aggregates and water, initiating the formation of a gel. This gel formation leads to expansion and increased pressure within the concrete matrix, potentially resulting in cracking if the pressure exceeds the material's capacity (Figure 16).

Several factors influence the rate of ASR, including the alkali content of the cement, the potential alkali reactivity of the aggregates, and the amount of water present in the concrete. Glass, known for its high silica content, can face the problems of ASR when used as aggregates in concrete mixtures, potentially leading to cracks (Schroeyers & Kovalchuk, 2020).

To mitigate ASR, various material and engineering solutions can be employed. Material solutions include the use of low alkali cement, supplementary cementitious materials such as fly ash or silica fume, careful aggregate selection, control of water content, and the utilization of chemical admixtures. Engineering solutions involve incorporating expansion joints into the design to accommodate any potential expansion caused by ASR (Folliard et al, 2003).

When making a hybrid connection between glass and concrete, it is important to consider ASR and explore suitable composite materials that effectively address this chemical reaction to ensure the structural integrity and durability of the resulting material. By implementing preventive measures and selecting appropriate materials, the ASR effect can be mitigated, ensuring the long-term performance of concrete structures.

When considering glass compositions for direct adhesion with concrete, particularly to minimize the risk of alkali-silica reaction (ASR), the suitability largely depends on the chemical composition of the glass. The ASR is a reaction between the alkali hydroxides in the cement paste and the reactive silica in the glass. Therefore glasses with high silica (SiO2) content are more chemically inert and less likely to participate in ASR because the content reduces the proportion of other reactive components that might contribute to ASR.

Also glasses with a low alkali content are preferable because these alkalis can promote ASR. Glasses with low sodium (Na_2O) and Potassium (K_2O) helps in mitigating the risk of ASR.

Figure 16: Sequence of Alkali-Silica Reaction (ASR) in concrete. Source: (Al-Neshawy, 2013)

2.7 OVERVIEW

Concrete and glass have been selected to create a free-form hybrid facade panel, capitalizing on their high shapeability and design potential. Concrete offers advantages such as zero manufacturing waste and cost-effectiveness, while glass provides high transparency and compatible mechanical properties that closely align with the thermal expansion coefficient of concrete.

However, the creation of a concrete-glass hybrid panel entails certain limitations and design considerations. The interface of the two materials is known for a low adhesion strength. To make a hybrid panel the structural integrity lies in the interface design. Therefore a refined main research question is:

To what extent can design considerations ensure the structural integrity of a hybrid interface incorporating direct adhesion between concrete and glass?

When no additional materials or interlayers are employed between concrete and glass, additional limitations arise. Designing an interface between concrete and glass requires careful consideration of their respective physical properties to ensure mutual reinforcement. Thermal expansion must be closely matched to prevent cracking due to differences in expansion during thermal fluctuations. The occurrence of alkali-silica reaction (ASR) is a potential concern when alkali cement composite and silica glass parts are in contact, underscoring the importance of understanding material composition for both thermal expansion and ASR mitigation.

In the next chapters the interface design is being structurally validated by literature and experimental research. The following design aspects are important and will be further discussed:

- Materials compostion and production: Ensures compatibility between concrete and glass, optimizing adhesion and structural integrity.
- Surface roughness: Affects the mechanical bond strength; appropriate roughness enhances the adhesion between the two materials.
- Interlocking form: Increases mechanical interlock, enhancing the overall strength and stability of the hybrid panel.
- Manufacturing by design: Allows for efficient, waste-free production and customization of hybrid panels, optimizing material usage and ensuring high-quality construction.

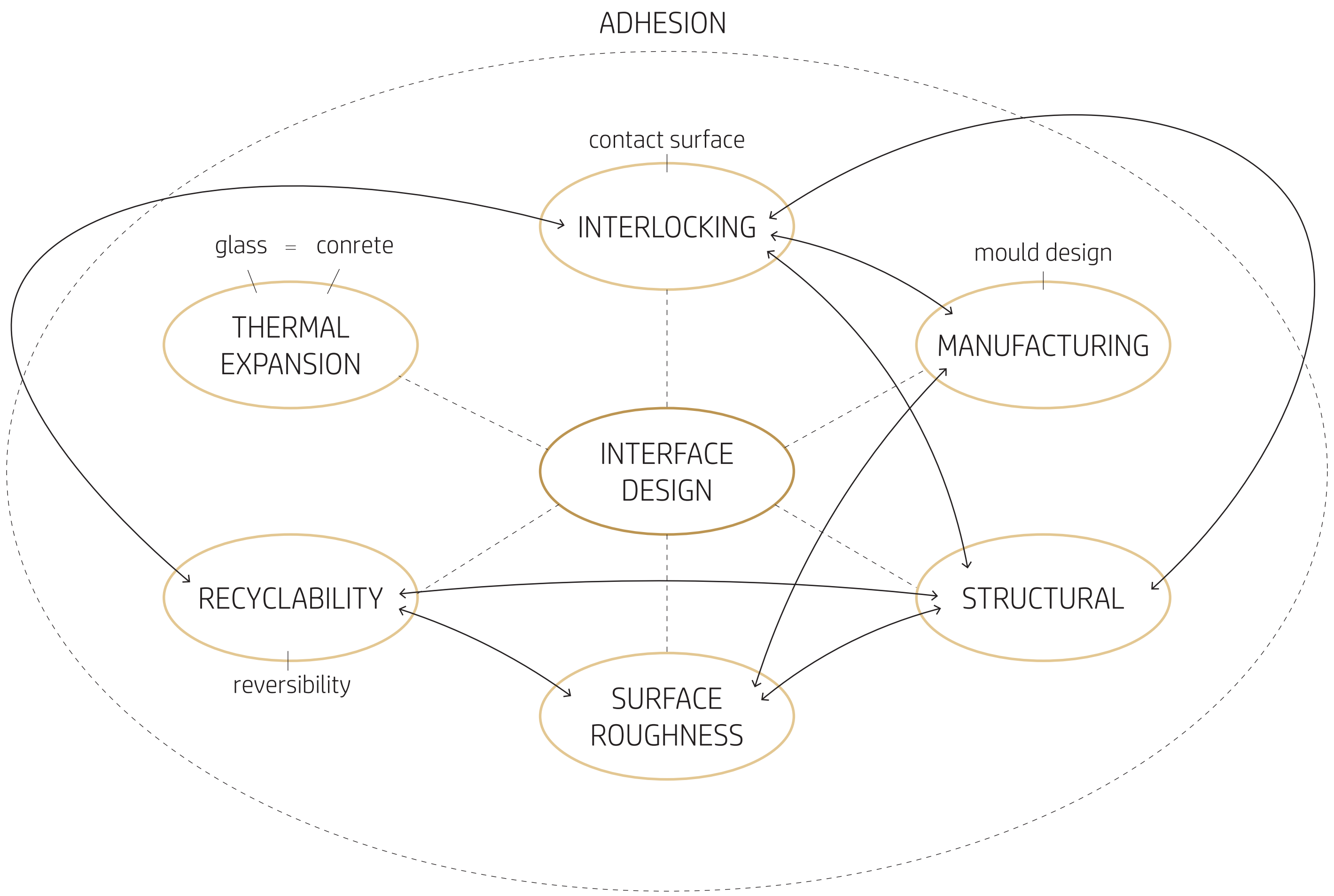


Figure 18: Illustration of different design aspects for creating a hybrid interface.

03

GLASS TECHNOLOGY

What are the design considerations for glass when creating free-form transparency with a concrete interface?

3.1 INTRODUCTION

Glass has been crafted by humanity for centuries, with ancient civilizations like the Egyptians and Romans pioneering its use for various purposes. From colored glass jewelry crafted by the Egyptians to the Romans' development of the first clear glass for glazing, its utility has spanned across cultures and time periods. Today, glass remains a focal point of research worldwide, with continual advancements shaping its evolution as a material (O'Regan, 2014).

Known for its transparency, glass has become together with architectural innovation, reshaping the relationship between indoor and outdoor spaces. Glass not only meets the need for sunlight but also connects to nature, an important aspect for occupants. Its ability to integrate with surroundings while allowing natural light to enter interiors and while having an unique aesthetical performance.

Nowadays, glass can be found across a diverse range of industries and applications, thanks to its versatility and adaptability. From towering skyscrapers to intricate laboratory equipment, glass manifests in forms, sizes, colors, and thicknesses. These variations all have to do with the interplay of material properties, composition, and production techniques employed in glass manufacturing.

Figure 19: Production of a COVID vaccin vial . Source: (https://www.nationalgeographic.com/premium/article/glass-revolution-innovation)

3.2 PROPERTIES

COMPOSITION
Glass is a material formed through the heating of a mixture containing silicon oxides, alkaline oxides, and alkaline earth elements. As it undergoes this process, its molecular structure becomes randomized, resulting in the absence of crystalline bonds upon solidification, achieved through rapid cooling to bypass crystallization (Douglas & Zallen, 2016).

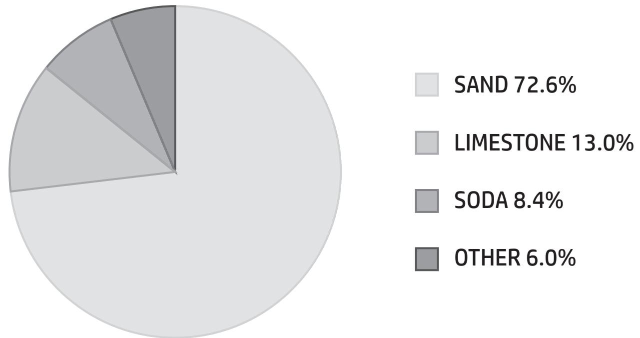


Figure 20: Proportions of raw materials. Source: (Weller, 2009)

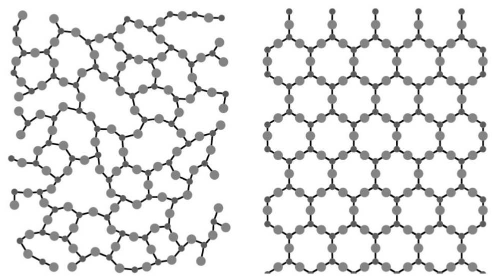


Figure 21: Molecular structure amorphous solid; glass [left] and crystalline solid; quartz [right]. Source: (Weller, 2009)

AMORPHOUS ISOTROPHY
Notably, glass exhibits amorphous isotropy, meaning its properties remain consistent in all directions (Schittich & Lenzen, 2007). This intrinsic characteristic contributes to its versatility in various applications.

TRANSPARENT

Transparency is a defining feature of glass, with its optical properties dependent on factors such as thickness, chemical composition, and applied coatings. The structural composition of the glass component can also influence its degree of transparency.

In glass, there are big gaps in the energy levels where electrons can't be. This allows visible light photons, with wavelengths between 400 to 700 nanometers, to pass through because they don't have enough energy to be absorbed or reflected (Varshneya, 2016).

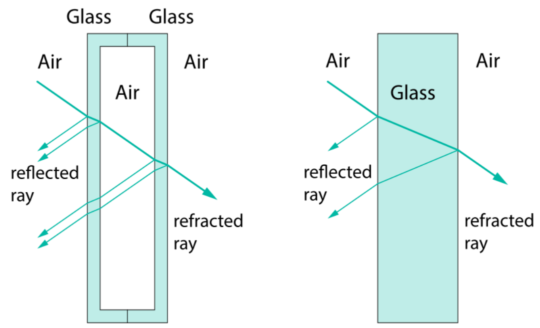


Figure 22: Transition of light through a hollow glass block and solid blocks. Source: (Oikonomopoulou, 2019)

BRITTLENESS

Glass is brittle. While it may exhibit some elastic deformation, it lacks plastic yielding behavior due to the nature of its covalent bonds between atoms (Figure 23). Once these bonds are broken, they cannot repair themselves, leading to its classification as a brittle material (Veer, 2007). Mechanical flaws on the material's surface, lowering the tensile strength of glass, is therefore a crucial aspect for its brittleness. (Figure 24) (Balkow, 1999).

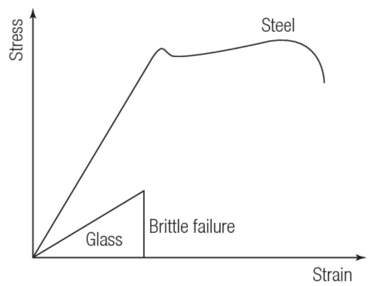


Figure 23: Stress-strain curve showing brittleness of glass compared to steel. Source: (Weller, 2009)

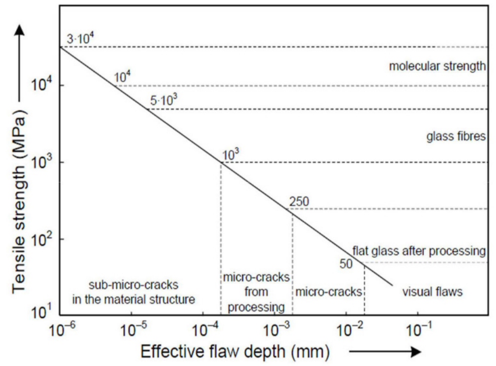


Figure 24: Rough estimated ratio between tensile strength and effective flaw depth. Source (Balkow, 1999)

SUSTAINABLE

Moreover, glass is recognized for its sustainability, durability and resistance to alkaline solutions, which prolongs its lifespan and reduces the need for frequent replacements. Additionally, glass is highly recyclable (Figure 25), meaning it can be recycled endlessly without losing its quality, thus reducing the demand for raw materials which lead to a environmental friendly impact. This recyclability contributes to conservation efforts and promotes a circular economy, making glass an environmentally friendly choice (Figure 26).

Figure 25: Glass prototypes made from recycled car windshields (left), containers (middle) and oven-doors (right). Source: (Bristogianni, 2022)

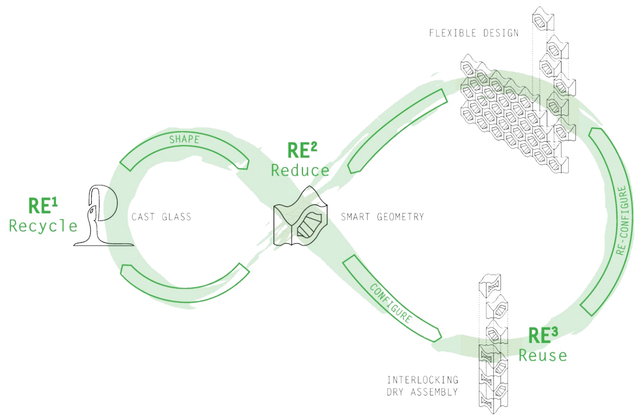


Figure 26: Circularity potential of cast glass elements by ReStruct group TU Delft. Source: (Oikonomopoulou & Bristogianni)

3.3 TYPES & COMPOSITION

Glass can be categorised in six main families based on their composition; aluminasilicate, borosilicate, fused quartz glass, high silica glass, lead glass and soda-lime glass (Oikonomopoulou, 2019).

ALUMINOSILICATE GLASS

Aluminosilicate is known for its high strength, excellent thermal resistance, and chemical durability. It contains a combination of two main components: Silicondioxide and Aluminiumdioxide. Silicondioxode provides the glass of it's basic structure where aluminiumdioxide (20-40%) provides the strength and durability of the glass. It can tolerate temperatures above 800⁰ Celsius. Therefore it is more difficult to melt then other glass compositions.

BOROSILICATE GLASS

Borosilicate glass must contain at least 5% boron oxide. In a common composition the amount of boron oxide is 13% and is gives the glass its characteristic low coefficient of thermal expansion. This makes it highly resistant to thermal shocks and ideal for applications with rapid temperature changes. Borosilicate glass has a higher melting point compared to other types of glass, which is responsible for its higher heat resistance, but makes it also more expensive. Additionally it is has an excellent chemical resistance except for a range of alkalis. Borosilicate glass has wide range of application and stand out in its scientific and medical laboratories.

FUSED QUARTZ GLASS

Fused quartz glass, also known as fused silica or quartz glass, is a high-purity glass made from crystalline silica, found in sand and rock crystal, through a specialized manufacturing process (electrical or flame fusion). Due its high fusion temperature of 1650º C its manufacturing process is very difficult and expensive. Fused quartz glass is mainly used for aerospace applications due its high heat resistance.

HIGH SILICA GLASS

High silica glass contains an averga of 96% silica. This is done by melting down the glass until almost all non-silicate elements are gone. High-purity silica as a raw material and a deformation temperature of 1700º C, results in a expensive and difficult manufacturing process which is a limiting factor for a wide range application. Despite its facrication limitations high silica glass has a relatively low thermal expansion, good chemical durability and excellent optical clarity.

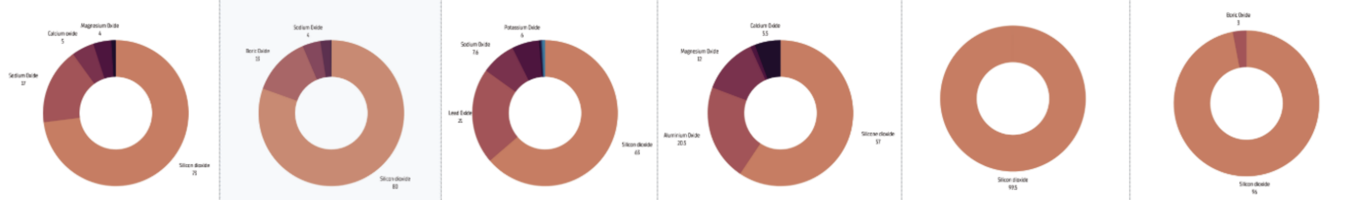
LEAD GLASS

Lead glass, also known as lead-oxide glass, contains lead(II) oxide (PbO) as a major component, imparting unique optical and physical properties. Lead glass has a higher refractive index, greater brilliance, and increased density compared to regular glass. These characteristics make it ideal for fine glassware, optical lenses, and decorative items. Manufacturing involves melting raw materials at high temperatures, forming the desired shape through blowing or molding, and then annealing for strength. However, the use of lead in glass has raised health and environmental concerns, leading to the development of lead-free alternatives.

SODA-LIME GLASS

Soda-lime glass, the most common type of glass, is composed of silica (sand), soda ash, and limestone. This glass is known for its transparency, durability, and ease of production. Its properties include a low melting point (around 1,600°C), good chemical resistance, and cost-effectiveness. Soda-lime glass is widely used in windows, containers, and everyday items due to its versatility and affordability. Therefore, 90% of all produced glass is soda-lime glass.

An overview of the six main glass types can be found on the next page (Figure 27).



	SODA LIME GLASS	BOROSILICATE GLASS	LEAD SILICATE GLASS	ALUMINOSILICATE GLASS	FUSED-SILICA GLASS	96% SILICA GLASS
GLASS TYPE	73% SiO2, 17% Na2O, 5% CaO, 4% MgO, 1% Al2O3	80% SiO2, 13% B2O3, 4% Na2O, 2.3% Al2O3, 0.1% K2O	63% SiO2, 21% PbO, 7.6% Na2O, 6% K2O, 0.3% CaO, 0.2% MgO, 0.2%, B2O3, 0.6% Al2O3	57% SiO2, 20.5% Al2O3, 12% MgO 1% Na2O, 5.5% CaO	99.5% SiO2	96% SiO2, 3% B2O3
OBSERVATIONS	Durable. Least expensive type of glass. Poor thermal resistance. Poor resistance to strong alkalis (e.g. wet cement)	Good thermal shock and chemical resistance. More expensive than sodalime and lead glass.	Second least expensive type of glass. Softer glass compared to other types. Easy to cold-work. Poor thermal properties. Good electrical insulating properties.	Very good thermal shock and chemical resistance. High manufacturing cost.	Highest thermal shock and chemical resistance. Comparatively high melting point. Difficult to work with. High production cost.	Very good thermal shock and chemical resistance. Meticulous manufacturing process and high production cost.
APPLICATIONS	• Window panes • Bottles • Façade glass	• Laboratory glassware • Household ovenware • Lightbulbs • Telescope mirrors	• Artistic ware • Neon-sign tubes • TV screens (CRT) • Absorption of X-rays (when PbO % is high)	• Mobile phone screens • Fiber glass • High temperature thermometers • Combustion tubes	• Outer windows on space vehicles • Telescope mirrors	• Furnace sight glasses • Outer windows on space vehicles
M.P	1350-1400 [°C]	1450-1550 [°C]	1200-1300 [°C]	1500-1600 [°C]	>>2000 [°C]	>>2000 [°C]
S.P	730 [°C]	780 [°C]	626 [°C]	915 [°C]	1667 [°C]	1500 [°C]
A.P	548 [°C]	525 [°C]	435 [°C]	715 [°C]	1140 [°C]	910 [°C]
ST. P	505 [°C]	480 [°C]	395 [°C]	670 [°C]	1070 [°C]	820 [°C]
DE.	2460 [kg/m3]	2230 [kg/m3]	2850 [kg/m3]	2530 [kg/m3]	2200 [kg/m3]	2180 [kg/m3]
C.E	8.5 [10^-6/°C]	3.4 [10^-6/°C]	9.1 [10^-6/°C]	4.2 [10^-6/°C]	0.55 [10^-6/°C]	0.8 [10^-6/°C]
Y.M	69 [GPa]	63 [GPa]	62 [GPa]	87 [GPa]	69 [GPa]	67 [GPa]

M.P. - Mean Melting Point at 10 Pa.s*, S.A.- Softening Point, A.P.- Annealing Point, ST.P.- Strain Point, DE.- Density, C.E.- Coefficient of Expansion 0°C - 300°C, Y.M.- Young's Modulus

Figure 27: Overview of the six main glass families. Source: (Sonar, 2022)

3.3.1 CHOSEN COMPOSITION

Among the different chemical compositions borosilicate glass can be considered as one of the best choices due to its balance of low alkali content and enhanced chemical stability and therefore minimizing the risk of ASR when having a direct adhesion with concrete.

The coefficient of thermal expansion (CTE) of soda-lime glass is closer to that of concrete compared to borosilicate glass. This compatibility reduces the risk of stress and cracking at the interface between the glass and concrete due to temperature fluctuations.

While ASR is a critical concern when using glass in concrete, the risk of failure due to thermal mismatch is often considered more significant in certain applications. Thermal mismatch can create stress fields that significantly impact material performance, often more immediately than the long-term effects of ASR (Sun et al., 2020; Xie et al., 2023)

In terms of economic and practical considerations, soda lime glass emerges as the preferred choice for various applications. Firstly, its widespread availability makes it easily accessible and an attractive option for large-scale projects and mass production (Pilkington, 2010). Additionally, its inherent durability ensures longevity and resistance to breakage, contributing to overall product reliability (Shelby, 2005). Furthermore, is soda-lime the least expensive type of glass which makes it an attractive option in terms of cost-effectiveness (Oikonomopoulou, 2020)

Despite the superior chemical stability and lower alkali content of borosilicate glass, **soda-lime glass is often preferred for direct adhesion with concrete** due to its thermal expansion compatibility, widespread availability, and lower cost.

3.4 PRODUCTION

FLOAT GLASS

The float glass production method revolutionized the glass industry, becoming the prevailing type in the building sector (Pilkington 1969). This technique, introduced by Pilkington in 1959, accounts for approximately 90% of flat glass production (Bourhuis, 2014). Known for its low cost, wide availability, superior quality, and ability to produce large sheets, float glass is the reason for todays (full glazed) modern architectural design.

In the float glass process, raw materials are melted at temperatures around 1500°C before being poured onto a bath of molten tin at approximately 100°C. The glass spreads out evenly across the surface, forming a continuous ribbon. The thickness of the glass is controlled by the speed at which it is drawn from the tin bath. As the glass exits the bath, it is gradually cooled down to around 600°C in an annealing lehr to relieve internal stresses. Finally, the glass undergoes a slow, controlled cooling process to room temperature, ensuring uniformity and preventing internal stresses that could compromise its structural integrity (Oikonomopoulou, 2019). The last step involves visual inspection and cutting to size, ensuring that the glass meets quality standards before being shipped to customers (Figure 28).

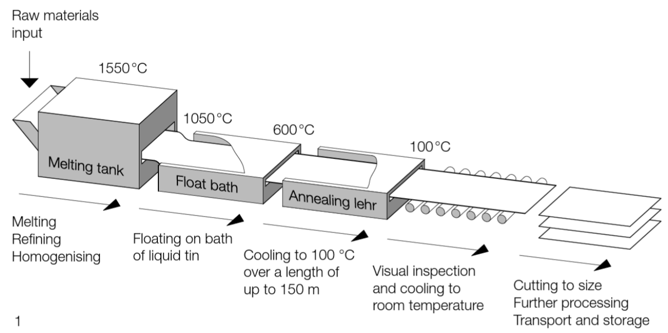


Figure 28: Schematic illustration of the float glass process. Source: (Weller, 2009)

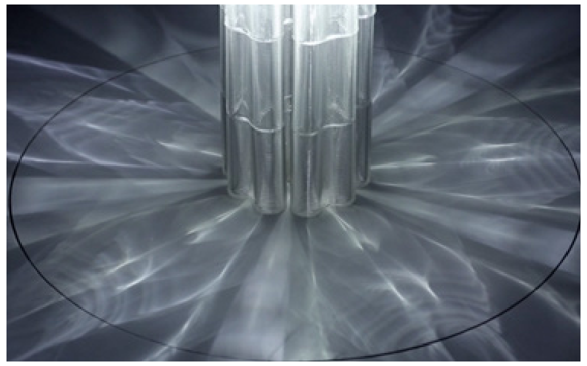


Figure 29: Large-size glass column printed by G3DP2 (invented by MIT). Source: (Inamura, 2018)

3D PRINTED GLASS

A Relatively recent innovation of glass casting emerges through AM. Three-dimensional structures are built layer by layer with the aid of computer-aided design. Pioneered by the Glass Lab of MIT Group, exemplified by the G3DP and G3DP2 systems, this method has thus far been confined to laboratory settings, showcasing its potential (Inamura et al., 2018). Recently, the G3DP2 successfully manufactured a large-size column (Figure 29).
There mainly two types of 3D printing glass, direct printing and indirect printing (Xin et al., 2023).
The main difference between direct and indirect printing lies in the approach to forming the object. Direct printing builds the object directly from molten glass or glass precursor material, while indirect printing creates a mold or pattern first, which is then used to form the final glass object. Each method has its advantages and limitations, depending on factors such as resolution, speed, complexity of shapes achievable, and material properties.

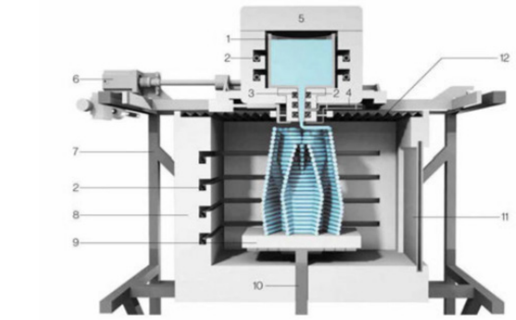


Figure 30: Dual chamber printer. Source: (Klein, 2015)

EXTRUDED GLASS

Extruded glass production entails the manufacturing of glass profiles with a consistent cross-section, primarily employed in non-structural applications. Extrusion is recognized for its cost-effectiveness and versatility in producing various types of hollow and full profiles (Pfaender, 2012). Extrusion methods such as the Danner process stand out as one of the most prevalent techniques in the industry (Figure 31).

In addition to the Danner process, alternative methods such as centrifuging and the Vello process offer solutions for specific production requirements. Centrifuging is particularly suited for the fabrication of large and non-rotationally symmetrical elements (Oikonomopoulou, 2019),

The Vello process involves the extrusion of molten glass through a channel, presenting another viable approach to extruded glass production. These methods collectively contribute to the wide array of techniques available in the extruded glass manufacturing landscape, each offering unique advantages tailored to various applications and design specifications.

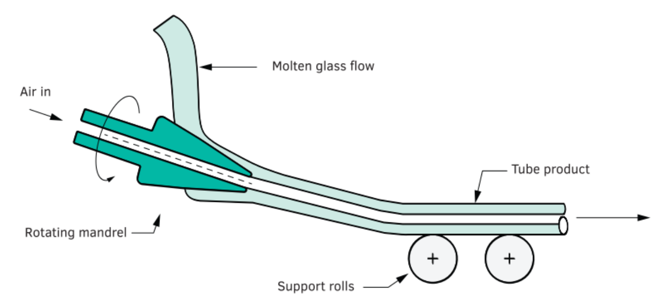


Figure 31: Principle of the danner process. Source: (Oikonomopoulou, 2019)

CAST GLASS

Casting is the oldest way of making glass. By pouring molten glass into moulds, 3D components of virtually all size and geometrical freedom can be made (Oikonomopoulou, 2019). Each type of glass composition has a specific melting point, which is a crucial factor in the casting process. After the molten glass is poured into a mould, the annealing process begins. The duration of annealing, a key step, is essential for minimizing stress within the cast glass element. If the size of the element increases, so does the required annealing time. This presents limitations in geometry during this phase (Watson, 1999).

After competing the annealing process, the cooled down glass can be removed from its mould. The level of surface quality, transparency and required post-processing depends per pouring method. A notable advantage of casting lies in the minimal production waste and shape ability and it can be concluded that cast glass is the only manufacturing method at present that allows for creation of glass element with a considerable cross-section in three dimension (Oikonomopoulou, 2019). The two casting methods are primary and secondary casting (figure 32).

Primary casting involves melting raw ingredients in a furnace at high temperatures, followed by pouring the molten glass into moulds and subsequent placement in a secondary annealing oven. This method, preferred for mass production, primarily employs hot-forming as its main process. On the other hand, secondary casting, also known as kiln-casting, utilizes a single furnace (kiln) for both melting the glass into moulds and the annealing process. Solid glass pieces are reheated in this method, which is favoured for customized production and operates at lower temperatures compared to primary casting.

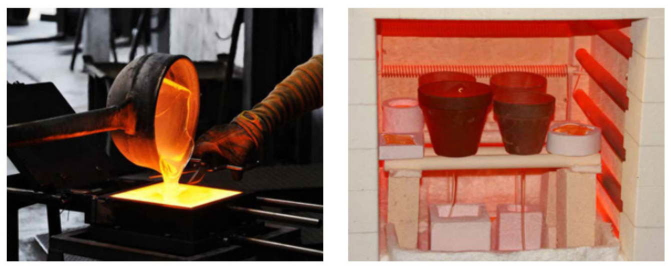


Figure 32: Primary casting [left] and secondary casting [right]. Source: (Oikonomopoulou, 2019)

3.5 POTENTIAL & CHALLENGES

In the context of creating hybrid panels, extruded glass is not a viable option. This chapter will delve into the potential and limitations of three alternative methods: float glass, cast glass, and 3D printed glass. for achieving desired outcomes in hybrid panel fabrication.

3.5.1 FLOAT GLASS

Since the introduction of the Pilkington float process, there has been significant innovation in panelized glass technology. With advancements in technology and manufacturing processes, float glass production now provides architects and designers with greater flexibility in creating planar glass elements for architectural applications (Figure 33). Panel sizes have increased while thickness has decreased (Figure 34), leading to widespread use in various architectural contexts. Following the fabrication of large flat sheets, the possibilities for application are virtually limitless. On the other side, the float glass method imposes limitations on design flexibility due to the inherent two-dimensional planar elements it produces (Oikonomopoulou, 2019).

After a flat sheet of glass is produced and manufactured glass can be cut into any size and shape. Cutting of glass can be cone by using a CNC machine or a abrasive waterjet (AWJ). Abrasive waterjet cutting is a manufacturing procedure using a high pressure water jet combined with abrasive material to cut material into sheets (ShivajiRao & Satyanarayana, 2020). Both are controlled by computer and therefore comes with optimal and precise cutting. The drawback of glass cutting lies in the production of cut-out pieces, resulting in a significant amount of discarded glass and inefficiency. If a flat sheet is cut into a desired size and elements the edges can be grinded and polished into various different edge finishes (Figure 35). Not only edge finishing can be done, also holes can be made in shapes (Figure 36). These procedures can introduce edge flaws, which then require subsequent inspection and treatment.

Figure 33: Apple's Fifth-Avenua glass cube . Source: (Apple)

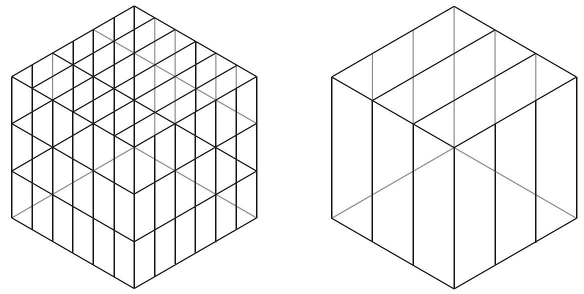


Figure 34: By using larger panels, Apple's store using just 15 panes instead 90. Source: (Apple)

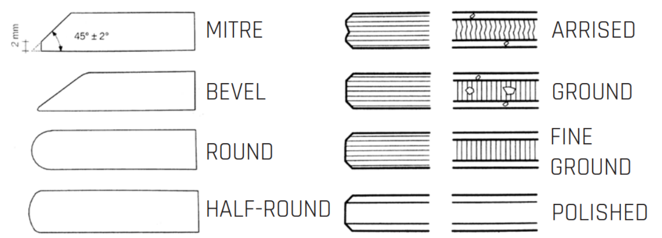


Figure 35: Edge work and bevelling [left] and edge types and finishing [right]. Source: (Wurm, 2007)

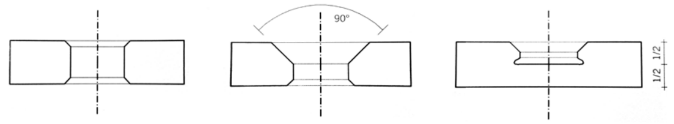


Figure 36: Different hole shapes. Source: (Wurm, 2007)

To strengthen a glass sheet, there are three options: tempering, heat or chemical strengthening, and laminating. Tempering involves putting the outer surfaces of the glass sheet into compression while the core is under tension, enhancing the overall strength due to glass's high compressive strength. Chemical strengthening immerses the glass sheet in molten potassium, creating a compressive layer on the surface while the interior is in tension. Laminating involves bonding multiple sheets together with an interlayer, offering increased safety and predictable behavior after failure. However, laminated glass elements are challenging to recycle due to adhesive interlayers, and there is a maximum limit to the number of glass layers, limiting design freedom.

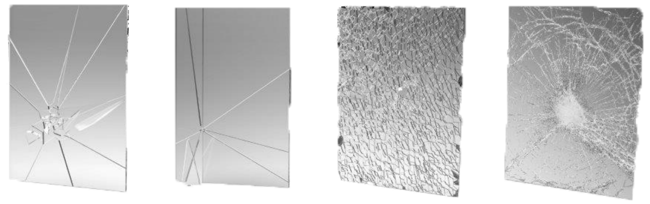


Figure 37: Strength type of glass. From left to right; Annealed, Heat-strengthened, Fully tempered and Laminated. Source: (Weller, 2009)

3.5.2 CAST GLASS

While casting glass has been practiced since ancient times, recent advancements have opened up new possibilities for its application in structural glass. These developments have expanded the traditional use of casting, transforming it into a cutting-edge method for creating innovative and durable glass structures with high precision (Figure 39). As a result, casting now offers architects and designers a new dimension in glass fabrication, allowing for the realization of free-form and visually stunning architectural designs that were previously unimaginable (Figure 38).

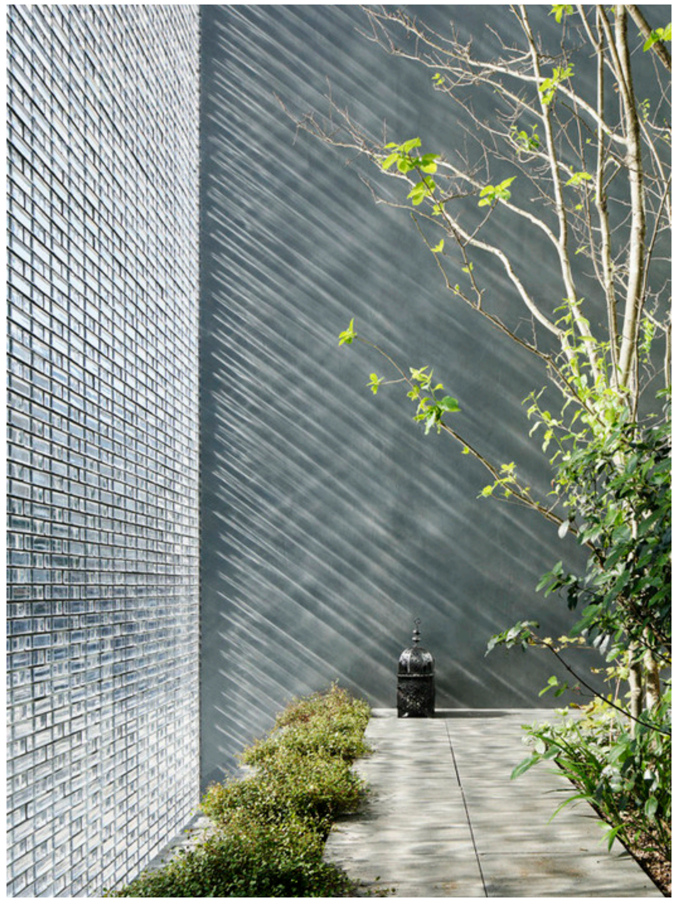


Figure 38: Optical Glass House. Source: Hiroshi Nakamura & NAP

Figure 39: Reclining Dress Impression with Drapery, 2009, Smithsonian American Art Museum, Source: Karen LaMonte

The annealing time is crucial aspect for glass casting and due its time length it makes it a design limitations. The annealing process in glass casting involves heating the glass until it is viscous enough to flow into the mold, followed by rapid cooling to prevent crystallization. The higher the viscosity the lower the probability for molecular rearrangement that leads to stress release (Watson, 1999). The glass is then slowly cooled to release any internal stresses and prevent the formation of residual stresses. Factors such as temperature differentials, shape, and mass distribution influence the magnitude of internal stresses, emphasizing the importance of uniform cooling and shape considerations (Oikonomopoulou, 2019). However, achieving optimal annealing conditions can be complex and influenced by various factors, challenging to accurately predict or simulate. Although it is challenging Koopman (2021) formulated in his MSc thesis an equation for time in cast glass:

$$T = 0.0156 \cdot t^2 + 0.139 \cdot t + 0.7266 \text{, h.}$$

T: Time in hours

t: Thickness in mm

It becomes evident that the annealing time increases exponentially as the glass thickness increases. For more complex shapes Hubert (2015) used a formula which considered also material properties:

$$h = \frac{\sigma}{\frac{E a_{ex} \rho c_p}{(1-\mu)\lambda} d^2 b} \text{, K/s}$$

σ: allowable permanent stress

d: characteristic dimension, radius in case of a sphere

b: shape factor

E: Young's modulus of the material (MPa)

α_{ex}: thermal expansion coefficient (K-1)

ρ: density (kg/m3)

cp: specific heat (J/(kg*K))

μ: Poisson's ratio

λ: thermal conductivity (W/(m*K))

The advantage of this equation is its ability to distinguish between different types of glass (Ioannidis, 2023).

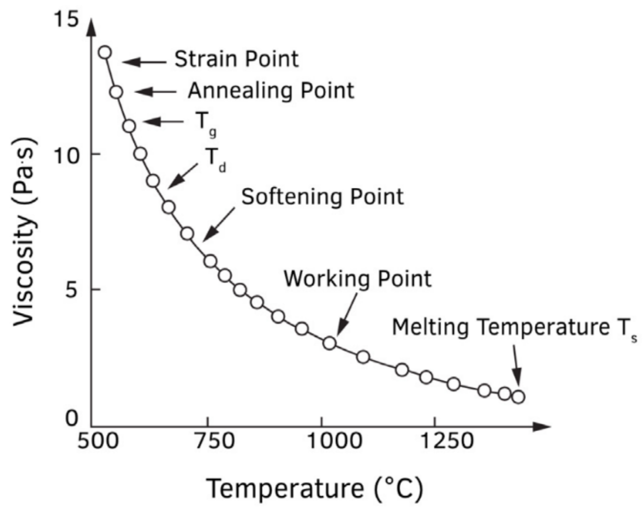


Figure 40: Viscosity curve as a function of temperature for soda-lime glass. Source: (Shelby, 2005)

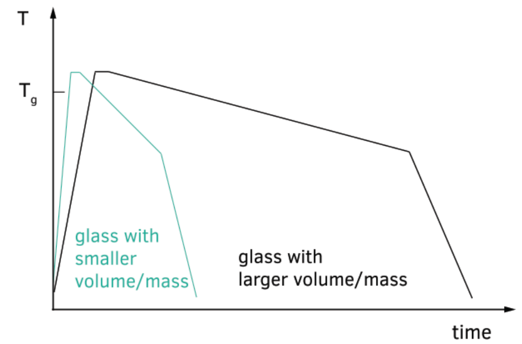


Figure 41: Annealing time for different volumes of glasses. Source: (Oikonomopoulou, 2019)

Another limitation of glass casting is the necessity of using a mould. Depending on the glass component casting, two types of moulds can be chosen. Permanent moulds, ideal for mass production, are constructed from durable materials like steel or graphite, capable of withstanding high temperatures exceeding 1600°C. These moulds, often employed in hot-pouring casting, offer high accuracy and precision, resulting in superior surface finish quality and minimal post-processing needs, but comes along high manufacturing costs (Oikonomopoulou, 2018). Permanent molds come in three varieties: open, pressed, and adjustable (Figure 42).

Disposable moulds are crafted from brittle materials and designed for single use due to their limited durability. Disposable moulds are preffered with kiln-casting due to their restricted temperature range. Despite being a cost-effective option favored for customized glass components, they offer lower accuracy, precision, and surface finish quality, requiring additional post-processing to refine the rough texture (Oikonomopoulou, 2019).
The choice of mould material significantly impacts accuracy and manufacturing costs. Silica-plaster moulds, the most economical option, are created using the lost wax technique but sacrifice precision and accuracy. Conversely, Alumina-silica moulds provide higher precision but come at a higher manufacturing cost, mainly due to CNC milling requirements (Schoenmaker, 2023).

Another disposable mould option is the 3D printed sand mold (3DPSM), known for its high quality and relatively low manufacturing cost. In this process, computer-aided designs are printed layer by layer with sand, and a liquid binder is applied to create precise negative molds (Giesecke & Dillenburger, 2022a). Despite its advantages, 3DPSM, like other disposable moulds, requires post-processing to address the rough finish of glass components (Oikonomopoulou, Bhatia, 2020). Due the rough surface, sand particules merges with the glass surface. Therefore coating is necessary (Figure 45) (Bhatia, 2019; Damen, 2019; Giesecke & Dillenburger, 2022; Oikonomopoulou, Singh Bhatia, et al., 2020).

Figure 42: Three types of permanent moulds. Source: (Oikonomopoulou, 2019)

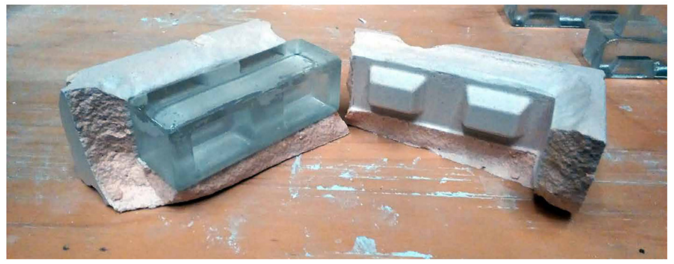


Figure 43: Disposable silica-plaster mould. Source: (Oikonomopoulou, 2019)

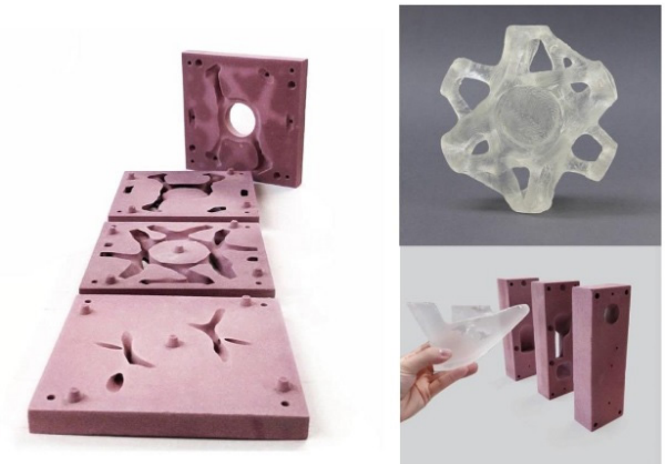


Figure 44: 3D printed sand moulds. Source: (Damen; Bhatia, 2019)

Figure 45: Different coatings for glass casting on 3DPSM. Source: (Ioannidis, 2023)

3.5.3 3D PRINTED GLASS

3D printing allows for casting without using moulds or fixtures. This manufacturing process offers customization of individualized units without the need for post-processing. However, challenges persist, limitations in suitable materials due to brittleness and decreased transparency, resulting in porous structures and high operational costs are associated with this type of casting (Zhang et al., 2020). As describe before both direct and indirect have potential and limitations.

Direct 3D printing methods offer precise control over the geometry and properties of glass objects, allowing for the fabrication of complex shapes with high resolution and surface quality. This approach provides flexibility in material selection and enables customization of glass compositions. However, direct printing processes like FDM and SLM may require high temperatures and post-processing steps, increasing energy consumption and production time (Xin et al., 2023). Additionally, scalability for large-scale production may be limited, and material wastage can occur during printing.

Indirect 3D printing methods, on the other hand, offer versatility in material selection for creating molds or patterns, allowing for customization and experimentation. These methods can achieve high resolution and intricate details in the final glass object while potentially being more cost-effective, especially for small-scale production (Yi et al.; Xin et al, 2023). However, the additional steps involved, such as mould creation and post-processing, can increase production time and complexity (Zhang et al., 2020) . The quality of the final object may also be influenced by the mould's design and fabrication. Despite these limitations, indirect printing methods provide a viable alternative for producing high-quality glass objects with intricate designs.

Figure 46: Glass microstructures developed by 3D printnig technology. Source: (Berkeley engineering)

Figure 47: Multiple glass prints. Source: (MIT)

Figure 48: Single multi-layer wall with free-standing print. Source: (Nobula3D)

3.5.4 CHOSEN MANUFACTURING METHOD

To choose a suitable manufacturing option for glass elements in hybrid panels, the three manufacturing methods under consideration are float glass production, kiln cast production, and 3D printed glass. The extrusion method of 3D printed glass is not considered further as it is not applicable for creating glass elements in this context.
As mentioned in section 2.7 of the overview, there are several design criteria important for creating a concrete-glass interface. Based on these criteria, the appropriate manufacturing method for glass is selected. The relevant criteria include interlocking, manufacturing, structural integrity, surface roughness, and recyclability. The criterion of thermal expansion is excluded from this evaluation, as it is discussed in section 3.3 concerning chemical composition.

INTERLOCKING

the criterion Interlocking primarily involves creating an interlocking form, with customization and design freedom being the most critical aspects.

- Float Glass: Due to production standardization, float glass has limited design freedom and comes in standardized thickness and size. Basic customization is possible through cutting and shaping, making it suitable for complex 2D shapes, but challenging for three-dimensional forms.
- Kiln Cast Glass: This method offers more flexibility in shaping and form, allowing for intricate designs, customization and realization of free-form elements. Any form of interlocking can be created with kiln casting.
- 3D Printed Glass: For creating complex geometries, 3D printed glass can be considered as the best option. It offers great creative freedom and customization potential with a high degree of geometric complexity. However, the limitations of the printer must be considered. Overhangs cannot be included in the interlocking design, and designs must account for nozzle thickness and layering.

MANUFACTURING

This section primarily examines the production processes and associated steps. It also considers wide availability, time and cost-effectiveness, and post-processing.

- Float glass production is the most widely used production method globally. This mass production ensures high-quality manufacturing that is safe and predictable. Its widespread application results in high cost-effectiveness.
- Cast glass production is an ancient technique that has become increasingly popular for structural glass elements in recent years. However, this method is labor-intensive. Production is time-consuming due to annealing and mould making. Additionally, the necessary post-processing steps to optimize the glass surface are time-consuming and costly, although this can be seen as a positive aspect, where the rough surface after demoulding can help with better concrete adhesion.
- 3D printing of glass is a new development (at laboratory scale), making this manufacturing method not as long-established as float and cast glass. Printing is limited to small-scale production and size constraints. The advantage is that no moulds or post-processing steps are required. However, the process can be complex and difficult, which is also time-consuming.

STRUCTURAL

Structural integrity is a crucial criterion when selecting a suitable glass manufacturing method because it directly impacts performance of the glass elements in their intended applications such as a hybrid panel.

- Float glass is renowned for its high structural integrity due to its uniform thickness and consistent composition. It is particularly strong and durable, making it a reliable choice for applications that require flat, stable glass surfaces.
- Kiln cast glass excels in applications that benefit from its ability to create thick, intricate shapes with high structural integrity. The process allows for forming complex geometries, which can significantly enhance its strength and durability. This labor-intensive process also introduces variability and inconsistencies in the final product. Larger pieces or those with very complex shapes might also have internal flaws that could affect their structural performance.
- As an emerging technology, 3D printed glass offers substantial design freedom. However, its structural integrity is currently less predictable and generally lower than that of float or kiln cast glass. Currently this method lacks in proven structural integrity of more established methods and is susceptible to weaknesses from the layered printing process.

SURFACE ROUGHNESS

When considering the surface roughness of glass elements and their adhesion properties after pouring concrete, the manufacturing method plays a crucial role.

- Float glass: typically has a very smooth and uniform surface due to its production process. This high-quality finish is beneficial for applications requiring optical clarity but may not be ideal for concrete adhesion.
- Kiln cast glass often has a naturally rougher surface compared to float glass. The surface texture can vary depending on the mould and casting process, providing a certain degree of inherent roughness. The rough surface of kiln cast glass is advantageous for concrete adhesion, as the texture provides better mechanical interlocking with the concrete
- 3D printed glass can have a varied surface roughness depending on the printing parameters, such as layer height and nozzle size. The layer-by-layer construction often results in a textured surface. The textured surface of 3D printed glass can enhance concrete adhesion without the need for additional surface treatments

RECYCLABILITY

This part is focussing on the sustainability including waste generation, recyclability potential.

- Float glass: minimal waste is generated during float glass production due to efficiency but more off-cuts arise after amending complex shapes. The float glass process requires high oven temperatures which results in a high energy requirement. The lamination process makes is hard to recycle.
- Kiln Cast glass: Kiln casting requires lower temperatures compared to float glass. This lower energy requirement can be more sustainable, although the process is slower and more labor-intensive. Almost no glass waste is generated due to trimming and shaping. Chosen a mouldtype varies in adding more waste in this production method. When recycling glass, kiln casting allows a wide range of glass compositions for re-melting (Bristogianni, 2020).
- 3D printing glass: Waste generation can be low if the process is optimized, as only the necessary amount of material is used in the printing process. However, failed prints and excess material may contribute to waste. Often this waste can be recycled but the technology is still emerging, so recycling processes are not as established.

An overview of the potential and limitations of the 3 main production methods are shown in the table at the next page (Figure 49).

	FLOAT GLASS	CAST GLASS	3D PRINTED GLASS
POTENTIAL	• Mass production • Precise manufacturing - high quality • Cost-effective • Wide availability • Versatility • Safety & predictable behaviour	• Versatility • Creativity • Customization • Low production temperature • Recyclable • Potential full transparency • No manufacturing waste	• Design freedom • Customization • No mould & post-processing • Zero waste • Recyclable
LIMITATIONS	• Limited design freedom - Thickness & size • Waste generation • Hard to recycle (interlayer) • Energy consumption - Oven temperature	• Labor intensive -> complex • Time consuming (production) - Annealing - Mould making • Size limitations • Costs • Post-processing	• Layered transparency • Small laboratory scale • Limited size • Process complexity • Time consuming

Figure 49: Comparitive table potential & limitations for glass production.

CONCLUSION

For creating a hybrid interface between glass and concrete different design aspects are considered.

As manufacturing method for this thesis Kiln casting is chosen as most suitable option because of the following:

- Ability to create complex geometries and detailed features for enhanced mechanical interlock with concrete.
- Inherently rough surface texture enhances mechanical adhesion with concrete.
- Ability to produce thicker, more structurally glass elements.
- Relatively straightforward method for producing custom free-form glass elements.
- few waste generation with full recyclability potential.

04 CONCRETE TECHNOLOGY

What key information about concrete properties and composition is essential for creating a hybrid facade panel with optimal adhesion to glass, while effectively managing thermal expansion at the glass-concrete interface?

4.1 BACKGROUND

Concrete, a versatile and durable building material, has been utilized for construction purposes for thousands of years. Initially used in ancient civilizations for structures such as aqueducts, temples, and fortifications, concrete evolved over time to become a fundamental component of modern architecture.
Since 1950 and early 1960s concrete has found new applications as a façade cladding material, transforming from its traditional role as a structural element (Brookes, 1998). Architects began utilizing concrete not just for its functionality but also for its raw industrial expression. Concrete holds a unique fascination unlike any other material due to its ability to be molded into virtually any shape while retaining exceptional pressure resistance and solidity once it solidifies (Knaack et al., 2015).

Todays use of concrete as a facade material includes a diverse range of compositions and materials, including steel, glass, and more. Architects employ innovative combinations to enhance structural integrity, introduce visual interest, and achieve desired aesthetic effects in modern building designs. This flexible approach to concrete application allows for the creation of dynamic and visually appealing facades.

Figure 50: Concrete facade of a small church in London called "The Famous Nostrils". Source: (John Peter Darvall)

4.2 PROPERTIES

COMPOSITION
Concrete is a composite material composed of three primary ingredients: cement, aggregates, and water. Cement serves as the binder, holding the mixture together and giving it strength and durability. Aggregates, such as sand, gravel, or crushed stone, provide bulk and volume to the concrete while enhancing its structural integrity. Water is added to the mixture to initiate the chemical reaction known as hydration, which causes the cement to harden and bind the aggregates together. Additionally, concrete may include supplementary materials such as admixtures or additives, which can modify its properties

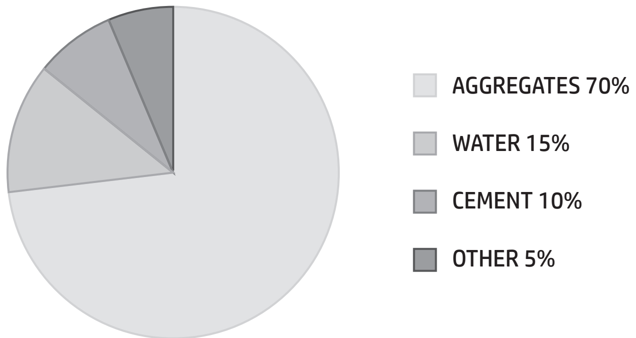


Figure 51 : Proportions of raw materials. Source: (Uffelen, 2021)

Figure 52: Concrete facade "Crushed Wall"simulating liquid forms. Source: (Walter Jack)

ALKALINE
Concrete has a naturally high pH level (>12) due to the presence of calcium hydroxide formed during the hydration process. This alkaline environment provides protection against corrosion for reinforcing steel embedded within the concrete. However, excessive alkalinity can lead to alkali-silica reaction (ASR) which is been discussed in chapter 4. The level of alkalinity in concrete is depending on the composition and mixture.

CURING
Curing is a critical process in concrete construction that involves maintaining adequate moisture and temperature conditions to promote proper hydration of cement and achieve optimal strength and durability. Proper curing helps prevent shrinkage, cracking, and surface defects in the hardened concrete by ensuring a uniform distribution of hydration products throughout the mixture. This process typically lasts for a specified duration, during which various curing methods such as water curing, steam curing, or curing compounds may be employed to maintain moisture levels and control temperature (Figure 53). Effective curing practices are essential for maximizing the long-term performance and durability of concrete structures.

POROUS
Concrete is inherently porous, meaning it contains microscopic voids and capillary pores within its structure (Figure 54). The porosity of concrete can affect its permeability, durability, and resistance to moisture ingress, chemical attack. Minimizing porosity through proper mix design and curing techniques can enhance the performance and longevity of concrete structures. Reduced porosity in concrete facade panels offers several advantages, such as weather resistance, thermal performance and surface finish.

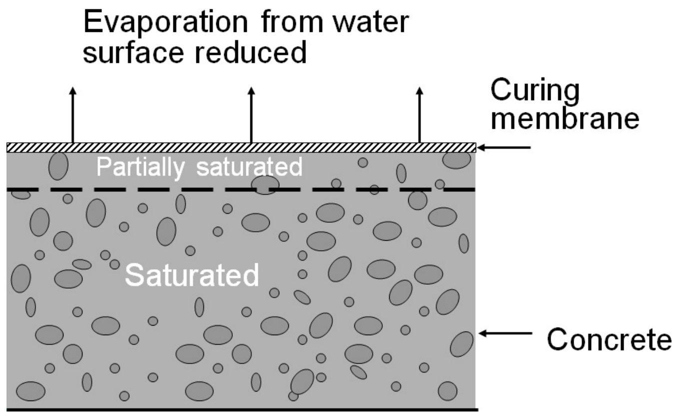


Figure 53: Water curing of concrete scheme. Source: (www.aboutcivil.org)

Figure 54: Non-porous concrete [left] versus porous concrete [right] . Source: (Florida association of country engineers & road superintendents)

4.3 TYPES & COMPOSITIONS

In the field of facade engineering, various concrete compositions are employed for different applications. Each of these compositions, with its unique mixture, comes with its own advantages and disadvantages. The following (and sometimes innovative) concrete compositions are commonly utilized in facade applications and show significant potential for use as facade panels (Knaack et al., 2015): normal strength concrete, high strength concrete, glassfiber-reinforced concrete, self-consolidating concrete, ultra-high performance concrete, and lightweight concrete.

NORMAL STRENGTH CONCRETE

Normal strength concrete (NSC) is the the most used type of construction applications worldwide. NSC is commonly used for structural elements such as foundations, columns, slabs, and beams in residential, commercial, and infrastructure projects because it contain balance of performance, cost-effectiveness, and versatility, making it suitable for a wide variety of applications.

HIGH STRENGTH CONCRETE (HSC)

By incorporating a higher amount of cement and coarse aggregates in comparison to Normal Strength Concrete (NSC), the concrete mixture becomes coarser, resulting in an enhancement of mechanical properties. This includes an impressive increase in compressive strength ranging from 40 MPa to 140 MPa. High Strength Concrete (HSC) is globally adopted due to not only its commendable mechanical attributes but also its durability and cost-effectiveness (Zhou et al., 2020). However, owing to a lower water-to-cement ratio than NSC, HSC exhibits reduced capillary porosity, which translates to lower fire resistance.

Despite the improved strength, as illustrated in Figure 55, it can be observed that the stress-strain curve for HSC is steeper. This phenomenon is attributed to its increased brittleness. Often, in response to this characteristic, additional fibers are introduced as reinforcement in the concrete matrix.

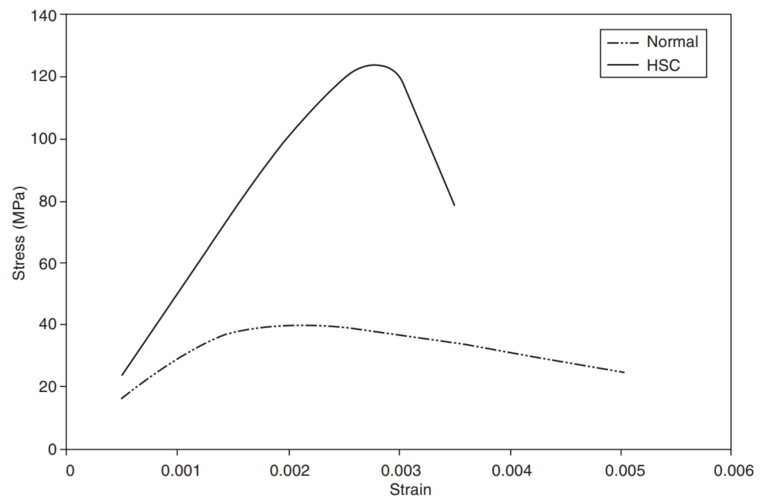


Figure 55: Comparisson of a stress-strain curve between NSC and HSC. Source: (ADD)

GLASSFIBRE REINFORCED CONCRETE (GRC)

GRC, also known as GFRC, is a composite where alkali-resistant glass fibers are added for reinforcement. Glass in the form of fibers exhibits exceptionally high tensile strength (>3GPa) compared to glass in a solid state (Bartos, 2017). The concrete matrix, combined with glass fibers, forms a perfect interaction that results in remarkable mechanical properties. The concrete matrix contributes to stiffness and compressive properties, while the glass fibers enhance ductility and improve tensile and flexural strength (Guzlēna & Šakale, 2021).

SELF-CONSOLIDATING (SCC)

This innovative fluid mixture, due its increased powder content and flux material, possesses the characteristic of being able to flow under its own weight, resulting in enhanced filling ability (Daczko, 2012). The mixture easily and compactly fills the formwork without the need for vibration. SCC also exhibits increased passing ability and stability, with passing ability referring to its resistance to aggregate blocking as it smoothly flows along obstacles, such as reinforcement. Stability pertains to the non-segregation property of the mixture (Xu & Jin, 2022). Once cured, it becomes a homogeneous and dense concrete with the same mechanical properties as regular (vibrated) concrete. However, this only occurs with a perfect composition. Self-Compacting Concrete (SCC) has a drawback in that it is highly sensitive to variations in consistency, particularly regarding water content (Knaack et al., 2015)

ULTRA-HIGH PERFORMANCE CONCRETE (UHPC)

UHPC represents the ultimate form of High Performance Concrete (HPC). While High Strength Concrete (HSC) excels in compressive strength, (Ultra) High Performance Concrete distinguishes itself in overall performance, encompassing durability, workability, and strength. The term “performance” here refers to a combination of these three factors. In the mixture of UHPC, coarse aggregate are eliminated to create a more densified matrix and replaced with fine-sand content. The well-graded fine particles fill the typically large voids that occur when using coarse aggregates. This is why some researchers argue that it doesn’t fit within conventional concrete, leading to its designation as ‘reactive powder concrete’ (RPC) (Akhnoukh & Buckhalter, 2021).
With a water-to-cementitious ratio of less than 0.25 and the aforementioned mix properties, UHPC creates a discontinuous pore structure that reduces liquid ingress and significantly enhances durability (Graybeal, 2014). Additionally, fiber filaments are often added for reinforcement in order to improve the ductility.

LIGHTWEIGHT CONCRETE (LWC)

The use of lightweight aggregates gives Lightweight Concrete (LWC) it’s name. LWC has a significantly lower density compared to other concrete compositions, and can be categorized into structural and non-structural LWC. Non-structural lightweight concrete (NSLWC) has higher air voids and a compressive strength of 17 MPa or lower (Krivenko, 2020). The porous aggregates in LWC have the advantageous properties of low density, low thermal conductance, and fire resistance (Knaack et al., 2015). These benefits are particularly favorable for applications in high-rise construction, considering factors such as transportation, labor, formwork, and dead load. However, structural LWC has drawbacks, including lower compressive, tensile, and shear strength compared to other concrete compositions. It also exhibits reduced stiffness and increased creep and shrinkage (Krivenko, 2020).

An overview of the different concrete types and compositions is shown in the table on next page (Figure 56)

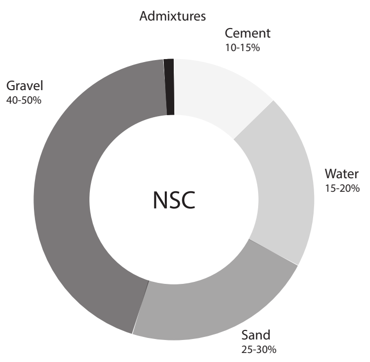
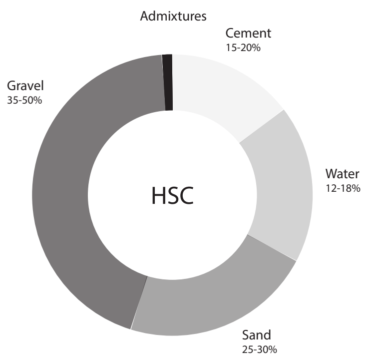
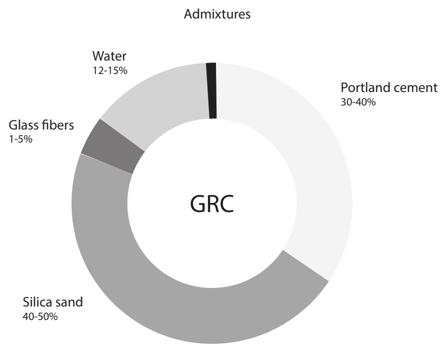
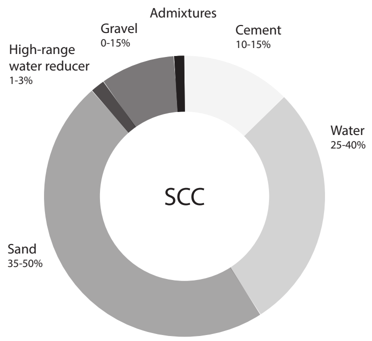
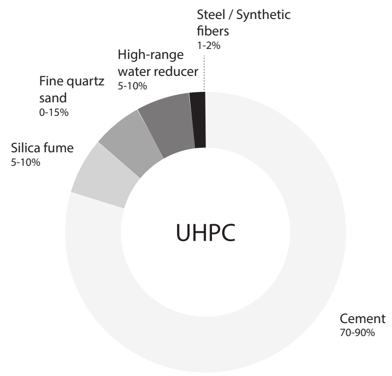
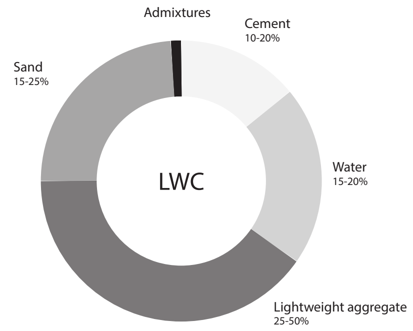
	NORMAL STRENGTH CONCRETE	HIGH STRENGTH CONCRETE	GLASSFIBRE REINFORCED CONCRETE	SELF-CONSOLIDATING CONCRETE	ULTRA-HIGH PERFORMANCE CONCRETE	LIGHTWEIGHT CONCRETE
MIXTURES						
PROPERTIES	Cost effective. Easy production. Raw materials widely avaiable. Versality in use. Lower strength. Limited durability. Cracking potential.	Increased compressive strength, but lower ductility. Better durability but more brittle than NSC. Costs economically viable.	High strength-to-weight ratio. Good durability and resistance to environmental factors. Enhanced tensile strength. Brittle. Color, texture and shape versatility. Cost-effective.	High fluidity concrete without vibration. Resistannce to segregation. Easy filling, Easy passage. High deformation ability. Significant shrinkage deformation.	High flowing ability. High early and final strength. Superior durability. Expensive.	Low weight. Improved thermal properties. Lower strength properties than normal weight concrete. Less stiff. More possibilities for creep and shrinkage.
C.	+	++	+++	+++	+++++	+++
DE.	2400 [kg/m3]	>3000 [kg/m3]	1800-2000 [kg/m3]	2400 [kg/m3]	2520 [kg/m3]	<2200 [kg/m3]
C.S	20-40 [MPa]	>60 [MPa]	>40 [MPa]	34 [MPa]	>150 [MPa]	17 [MPa]
T.S	2-5 [MPa]	4-7 [MPa]	11 [MPa]	4 [MPa]	>20 [MPa]	2 [MPa]
F.S	3-5 [MPa]	5-10 [MPa]	15 [MPa]	15 [MPa]	45 [MPa]	2 [MPa]
C.E	5.5 - 8.5 [10^-6/C]	5.5 - 8.5 [10^-6/C]	5-8 [10^-6/C]	5.5 - 8.5 [10^-6/C]	4 - 7 [10^-6/C]	5 - 8 [10^-6/C]

Figure 56: Overview table of different concrete composites and their properties. Source: Made by author

The design and development of hybrid façade panels necessitate a careful consideration of concrete compositions to ensure optimal performance. Among the various types of concrete, a mixture incorporating Glass Fiber Reinforced Concrete (GRC), Ultra-High Performance Concrete (UHPC), and Self-Compacting Concrete (SCC) stands out as particularly promising. Each of these materials contributes distinct advantages to the composite, making it highly suitable for façade applications.

- The incorporation of glass fibers within the concrete matrix can boost the adhesion strength of the hybrid interface. This enhancement occurs because the glass fibers act as micro-reinforcements, bridging cracks and reducing their propagation. The fibers also contribute to the toughness of the concrete, allowing it to absorb and distribute energy more efficiently under stress.

- The dense microstructure of UHPC, achieved through a combination of fine powders, superplasticizers, and a low water-to-cement ratio, results in minimal porosity and enhanced resistance to environmental degradation. This high strength and durability make UHPC ideal for façade panels, which benefit from the material's ability to maintain structural integrity even in relatively thin sections. Also the ultra-dense microstructure and very low porosity significantly reduce the ingress of water and alkalis, thereby minimizing the risk of ASR.

- Self-Compacting Concrete (SCC) is distinguished by its high flowability and ability to fill intricate molds without the need for mechanical compaction. This property is particularly advantageous when casting complex geometries around glass elements. However, one of the main disadvantages of SCC is its propensity for significant shrinkage. This shrinkage can pose challenges in maintaining a stable attachment to glass elements, potentially leading to stress concentrations and cracking.

In **conclusion**, the optimal composition for hybrid façade panels appears to be a strategic combination of GRC and UHPC. GRC's glass fibers enhance adhesion strength and toughness, while UHPC contributes exceptional compressive strength, durability, and adequate flowability and mimizises the risk of ASR. This hybrid approach promises to deliver façade panels that are not only structurally robust and aesthetically pleasing but also capable of withstanding the rigors of environmental exposure over extended periods. Further research and testing will be necessary to refine this composition and fully realize its potential in practical applications

In thesis a HSC mixture is used. The reason why HSC is used lays in the incorporation experimental MVRDV façade design. The same mixture is used in the continuation and advancement of previous experimental studies. These studies already have focused on optimizing concrete mixtures to achieve superior adhesion to glass. This time-saving approach allows me to concentrate more on other aspects of hybrid interface design.

4.4 SUPPLEMENTARY CEMENTITIOUS MATERIALS

Supplementary cementitious materials (SCMs) are materials used in concrete mixtures alongside Portland cement to enhance various properties and improve performance. The main reason for incorporating SCM's is the reducing the risk of ASR. For concrete cladding, the most commonly used SCMs are fly ash and silica fume. Both are briefly discussed in the text below

FLY ASH

Fly ash is a residue produced from coal combustion in power plants, comprising fine particles collected from flue gases through filtration methods. As a supplementary cementitious material, it is utilized in concrete compositions to enhance various properties. Fly ash acts as a partial replacement for Portland cement, contributing to the binding properties of concrete during hydration. This improves the strength, durability, and workability of concrete mixtures. Additionally, fly ash reduces the heat of hydration, mitigating thermal cracking and improving long-term performance (Thomas, 2013).

One of the key benefits of incorporating fly ash into concrete is its sustainability. Instead of using Portland cement, which has a high environmental footprint due to energy-intensive production processes, fly ash is eco-friendly. Furthermore, fly ash enhances concrete's resistance to alkali-silica reaction, sulfate attack, and chloride ingress, extending the service life of structures in aggressive environments.

Overall, fly ash offers a cost-effective and environmentally friendly solution for improving concrete properties.

SILICA FUME

Silica fume, also known as microsilica, is a fine powder made from silicon metal and ferrosilicon production. Both fly ash and silica fume are byproducts of other industrial processes. It's used in concrete to make it stronger and more durable. When mixed with concrete, silica fume reacts with calcium hydroxide to create more calcium silicate hydrate gel, also known as pozzolanic reaction. This makes the concrete denser and better at resisting damage from chemicals.

Silica fume also helps to prevent the concrete from separating and makes it easier to work with. It's especially useful in making high-performance concrete that needs to be really strong. Using microsilica in concrete can also reduce the need for other materials and make structures last longer. But because microsilica is so fine and reacts quickly, it needs to be handled carefully when mixing it into concrete. Overall, microsilica is a helpful and eco-friendly way to improve concrete (Thomas, 2013).

In this thesis, SCMs are not included in the concrete mixtures, as the time frame of the project does not allow for the long-term observation necessary to accurately assess the risk of ASR. However, should ASR become a concern in the future, the incorporation of SCMs could be a viable strategy to mitigate this risk. By reducing the permeability of the concrete and altering the chemical composition of the pore solution, SCMs can effectively limit the conditions conducive to ASR, thus enhancing the durability and longevity of the concrete.

4.5 SUSTAINIBILITY

Construction and Demolition Waste (CDW) is one of the largest solid waste streams in the world (Zhang et al., 2020). EU policies and regulations have significantly contributed to reduce this waste stream which is moslty landfilled (EC, 2018). Worldwide currently 64,02% of the concrete and other masonry materials is recycled or downcylced. Hiervan is maar 3% recycling voor in de concrete industry, 19% downcycling voor site evevation en de andere 78% word gedowncycled als road base material (Mulders, 2013). Zhang et al. (2018) showed that downcycling of concrete is still a reasonable method to deal with the CDW compared to a slightly better recycling.

This shows that recycling concrete is important and certainly possible. Moreover, the use of recycled concrete as new aggregates is increasingly happening (Zhang et al., 2020). Designing for disassembly in the design of a hybrid panel is therefore crucial for an environmentally friendly process.

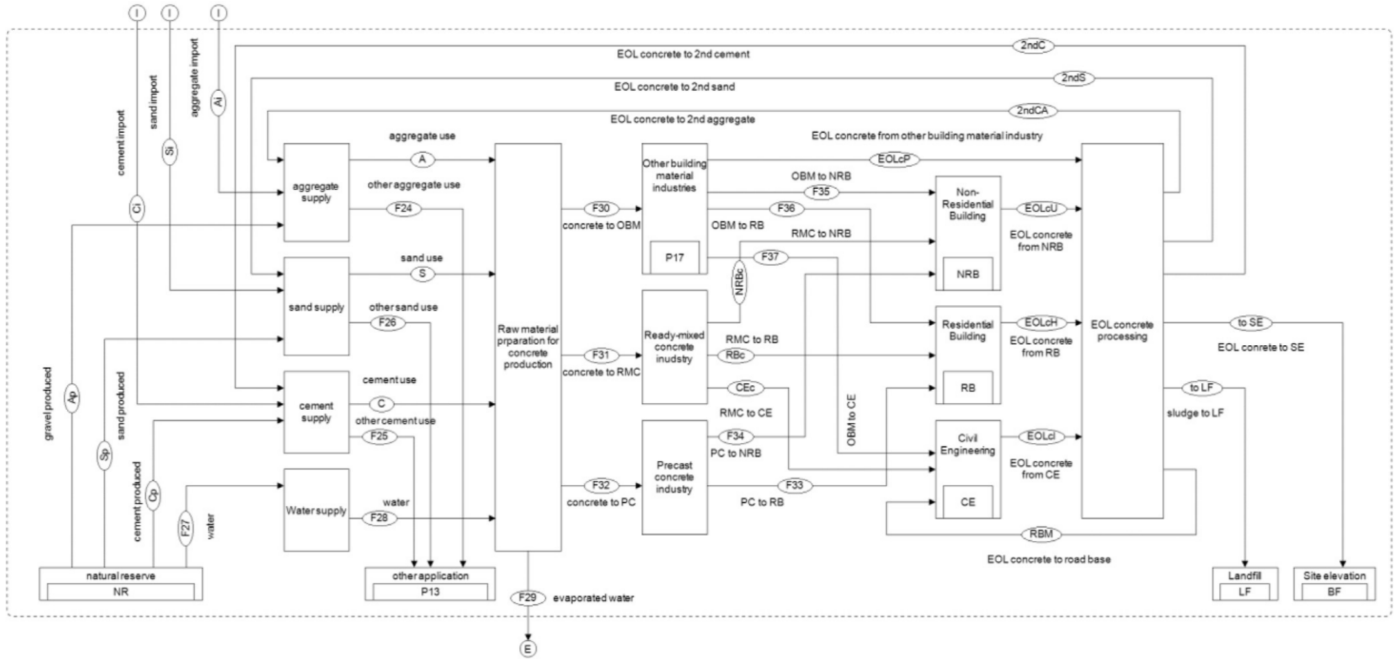


Figure 57: Concrete down and recycling map in the Netherlands. (Zhang et al., 2020)

4.5 TEST SET-UP

In order to test a concrete-glass interface, it is crucial to use a well-chosen concrete mix.

Different compositions are compared and evaluated based on various factors:

- Workability
- Adhesion to glass
- Sustainability
- Thermal expansion

The different compositions consist of:
cement + aggregates + water (+ additives)

CEMENT

There are five main types of cement:

CEM I = portland cement
CEM II = composite portland cement
CEM III = blast furnace slag
CEM IV = pozzolanic cement
CEM V = composite cement

The cement types available in the Stevin's lab for testing are CEM I & CEM III.

These two types of cement differ in their composition, leading to different properties. Below is the composition of CEM I and CEM III:

CEM I:	%
Portland cement clinker	95 - 100
Minor additional constituents	0 - 5
CEM III:	**%**
Portland cement clinker	35 - 64
Blast furnace slag	36 - 65
Minor additional constituents	0 - 5

Portland cement and blast furnace slag both serve as binders, but they have significant differences, especially in terms of sustainability.

Blast furnace slag, a byproduct of iron production, is utilized in multiple ways to enhance the sustainability and performance of concrete materials. As a successful replacement material for Portland cement, blast furnace slag improves durability, facilitates the production of high-strength and high-performance concrete, and offers environmental and economic benefits. By reducing the need for clinker production in Portland cement, blast furnace slag serves as a supplementary material, leading to decreased carbon emissions and energy consumption. This not only conserves resources but also provides a beneficial reuse for an industrial waste product that would otherwise require disposal (Ulubeyli, 2015; Zhang et al., 2020).

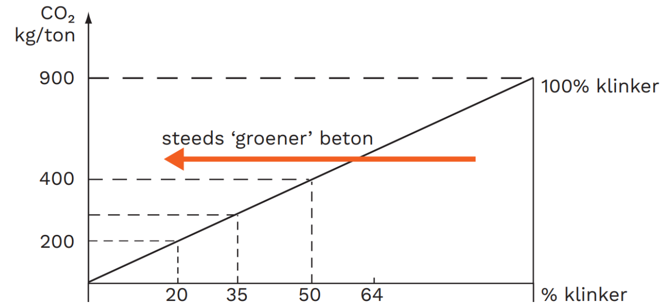


Figure 58: Table showing the less clinckers used in a concrete composition, the lower the carbon emissions thus 'greener' concrete (Betonhuis, 2020).

AGGREGATES

For the aggregates, the same material is used for each tested type of concrete. The aggregate material is 'Normand sand' (see Figure 59).

The characteristic of CEN Standard Sand is its specific grain size distribution. It ranges between 0.08 and 2.00 mm (EV, n.d.).

According to EN 196-1 mortar prisms for compressive strength testing are produced with a mixture of 450 (± 2) g cement, 225 (± 1) g water and one bag of 1,350 (± 5) g CEN Standard Sand (EV, n.d.).

ADMIXTURES

Glenium 51 is used to increase the workability of concrete.

Glenium is an aqueous solution combined with other chemicals which increases the strength a quality of Concrete Mix. Glenium is a high range water reducer and a low viscosity liquid which has been formulated by the manufacturer for use as received (Poornima, 2020). By adding Glenium 51 in the prodcution of concrete it will behave self consolidating (self compacting).

- Improves concrete's early and final compressive and flexural strengths (MasterGlenium 51, n.d.).
- Improves concrete's mechanic properties like carbonation, resistance to chlorine ion attack, resistance to aggressive chemicals, shrinkage, and creeping (MasterGlenium 51, n.d.).
- Enables the production of low water/cement ratio, low segregation and leaching risk Rheoplastic concrete (MasterGlenium 51, n.d.).

While plasticizers alone do not chemically prevent ASR, their use in concrete can contribute to mitigating ASR risk by enhancing workability, reducing the water-to-cement ratio, and improving the overall density and uniformity of the concrete matrix. These improvements help limit the ingress of water and alkalis, thereby reducing the conditions favorable for ASR development. Combining plasticizers with SCMs provides a more robust approach to ASR mitigation, leveraging both physical and chemical strategies to enhance the durability of concrete.

Four different composition zijn met dezelfde mengprocedure gemixt in een prisma mal. In het midden van een de prisma mal is een glasplaat gestopt met een dikte van 10 mm. De vier composition zijn hetvolgende:

(1)

Concrete mixture (per L):

CEM I 52.5 R	450	gr
Norman Sand	1350	gr
Water	225	gr

(2)

Concrete mixture (per L):

CEM III 52.5 R	450	gr
Norman Sand	1350	gr
Water	225	gr
Glenuim 51 (Plasticizer)	1	gr

(3)

Concrete mixture (per L):

CEM III/A 52.5 N	450	gr
Norman Sand	1350	gr
Water	225	gr

(4)

Concrete mixture (per L):

CEM III/A 52.5 N	450	gr
Norman Sand	1350	gr
Water	225	gr
Glenuim 51 (Plasticizer)	1	gr

(1)

(3)

(2)

(4)

Figure 60: The four different concrete workability after mixing the the composistion. In formulations incorporating Glenium as a plasticizer, the resulting mixtures exhibit significantly higher fluidity.

Figure 61: 4 different concrete compositions after 7 days of curing. It can be observed that with the addition of I+ (composition 2), the overall concrete has significantly shrunk due the plasticizer.

The use of Glenium 51 as a plasticizer significantly influences workability and fluidity. The amount of Glenium added typically ranges from 0.3% to 0.5% of the cement content. In the case of the composition 2 mix, it is likely that slightly more Glenium was added, leading to water separation from the cement and aggregates. As a result, the top layer of the cured mix remains soft and consists of dried water. Additionally, the considerable shrinkage is evident in the height compared to the other mixes.

Shrinkage is an important factor resulting in cracking of cementbased materials, thus being harmful to the mechanical behavior, impermeability and durability of concrete structures (Liu et al., 2021). Shrinkage kan bestaan uit twee soorten:

- Autogenous shrinkage is caused by a series of physical–chemical changes during the processes of cement hydration and hardening (Jensen & Hansen, 2001)
- Drying shrinkage is usually a long-term process due to moisture diffusion through pores under drying condition (Zhang et al., 2012).

Therefore, hydration kinetics of cement and pore structure of hardened cementitious matrix are two inherent parameters determining the shrinkage of cementitious materials.

The advantage of using a plasticizer to make it more self-compacting is that it reduces the occurrence of cracks at the glass interface. Due to its higher fluidity, the concrete dries more evenly against the glass (see figure), resulting in a smoother finish.

In mixtures 1 and 3 without a plasticizer, the substance is so thick that it cannot flow around complex shapes without compacting.

THERMAL EXPANSION

The initial idea was to test the four different concrete beams for thermal expansion coefficient in collaboration with G. Stamoulis. This involved measuring the autogenous bulk shrinkage of a cured concrete beam. By using a dilatometer, autogenous deformation can be measured and thus the coefficient of thermal expansion determined. The dilatometer consists of a frame for measuring and special moulds to enclose the cement paste (see figure 63). It's placed in a glycol bath that's controlled at a steady temperature during tests (Jensen & Hansen, 1995).

However, due to the time and complexity constraints of this thesis, a simpler thermal cycling test was chosen instead.

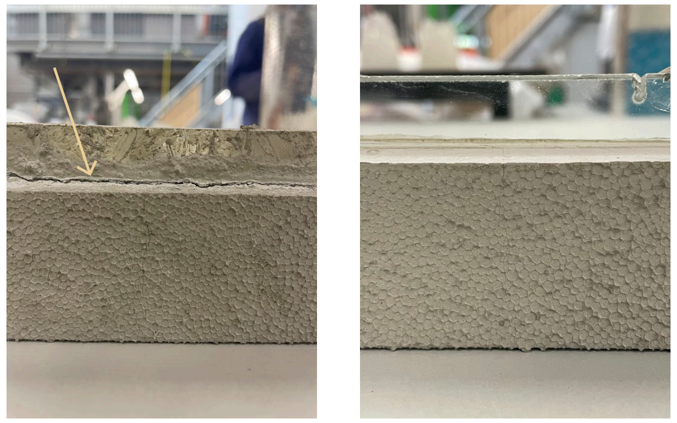


Figure 62: Cracks along the glass edge due to the drying of concrete mixes with lower workability.

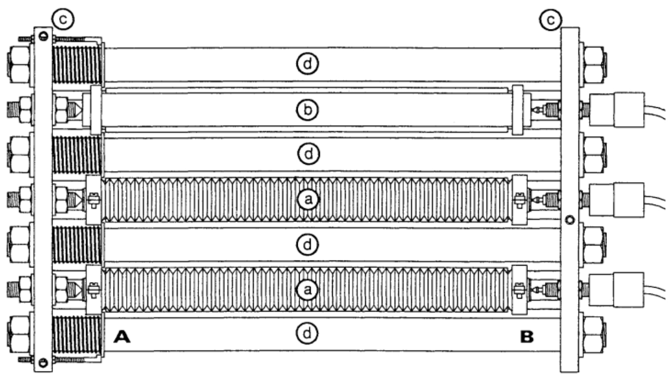


Figure 63: A dilatometer frame with specimens of 300 mm.

The specimens were placed in an oven at a constant temperature (80 degrees Celsius) for a duration of 4 hours to observe changes in the concrete and its adhesion to the glass (figure 65). This test was repeated three times for all specimens. While this test does not allow for the calculation of the thermal expansion coefficient, it does reveal the behavior of the concrete under constant temperature changes.

The various concrete compositions exhibited a few cracks, all of which were not found at the interface with the glass but within the bulk of the concrete itself (likely drying shrinkage cracks). Most cracks were observed in the compositions where no plasticizer was used. Furthermore, little difference was observed between the compositions.

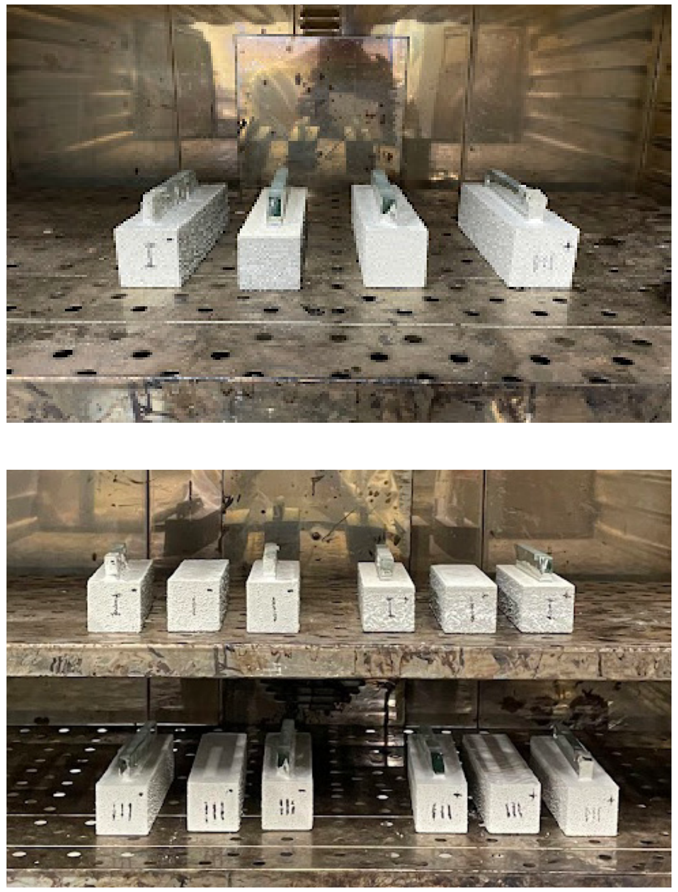


Figure 64: Specimens are placed in oven at 80 ^{0}C degree for 4 hours.

4.6 CONCLUSIONS

Various mixes were tested with different compositions and admixtures. Since the thermal expansion could not be accurately determined, a composition was chosen primarily based on the design criteria of workability and sustainability.

- The concrete mix with CEM III 52.5, supplemented with a small amount of plasticizer (Glenium 51), shows the most potential. CEM III is significantly more durable compared to CEM I and has a lower pH (alkali) value.
- By adding a plasticizer, the workability is greatly increased, and fewer drying shrinkage cracks occur against a glass surface. Plasticizers indirectly can contribute to mitigating ASR risk by enhancing workability, reducing the water-to-cement ratio, and improving the overall density and uniformity of the concrete matrix. To fully tackle ASR a combination of plasticizers with SCMs can provide a better approach to ASR mitigation, leveraging both physical and chemical strategies to enhance the durability of concrete.
- Since there is no exact value for the thermal expansion coefficient, it is also uncertain whether limestone fillers or silica fumes need to be added. These materials, which normally reduce the Coefficient of Thermal Expansion (CTE), can always be added in later testing phases.

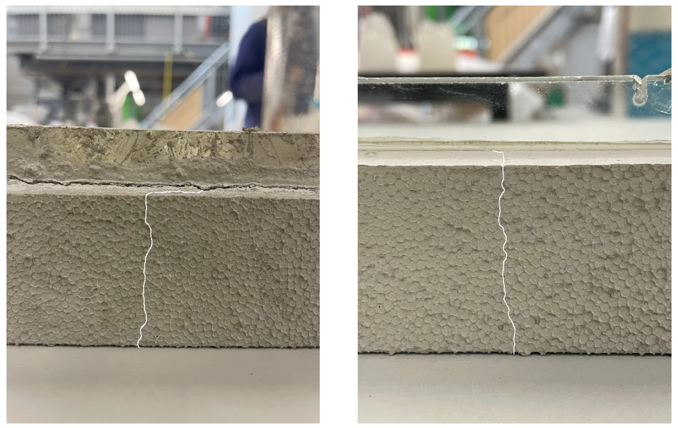


Figure 65: Cracks found in the bulk of the concrete bij concrete compoistion #1 (left) and #3 (right).

05

INTERLOCKING FORM

Incorporation interlocking forms and shapes, can it enhance adhesion strength and structural integrity in hybrid interfaces? In what we can we achieve the perfect interlocking form for a hybrid interface?

5. 1 INTRODUCTION

An interlocking system can contribute the improve the lateral stability of structure.Components whose geometrical shape and mutual arrangement provide kinematic constraint, thereby ensuring stability of the structure in one or two directions, typically perpendicular to the assembly plane and its transverse direction, are referred to as interlocking (Oikonomopoulou, 2019).

Another way of making a stronger interfacial bonding, when looking at mechanical interlocking, is the use of interlocking geomteries and forms for the purpose of structural interlocking. Due the assemblage so that no connectors or interlayer is needed interlocking forms can be needed to hold the different elements in place. When pouring concrete besides the individual glass element the assemblages is furnished by the kinematic constraints provided by the concrete by virtue of the element geometry and the mutual arrangements of the elements within the hybrid panel. This design principle is called topoligical interlocking (Estrin et al., 2021). The whole assembly is stabilized by compressive forces due self-weight of the construction (Oikonomopoulou et al., 2018)

Oikonomopoulou (2018) also showed a significantly effect of interlocking geometry in resistance of localized stress in cast glass blocks with complex shapes compared to the rectangular Crystal House blocks. The intricate design of the contact surface is more inclined to produce peak tensile stresses (see figure 67).

The cross-sections of the interface between the concrete and glass does not change along the directions normal to the faces. Since the hybrid panel works as one the aim is to minimize the thickness, thus a limited cross-sectional design options. Therefore the hybrid assembly always needs a two-dimensional design approach.

A more recent paradigm is the inclusion of the inner architecture of the material as an additional 'degree of freedom' in materials design (Ashby, 2003). The geometry ofthe constituent elements ofsuch an architectured material (or archimat), along with their mutual arrangement, become the defining factors controlling the properties of the material (Estrin et al., 2021).

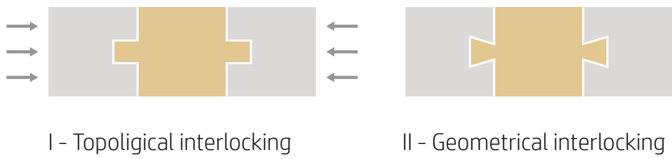


Figure 66: Visualisation of topological and geometrical interlocking

Figure 67: Top: interlocking cast glass blocks. Bottom: rectangular cast glass block.

5.2 FORM FINDING

Topological interlocking works due the employement of geometry to stabilize the whole assembly by compressive forces (Oikonomopoulou, 2019). A hybrid interface between concrete and glass is not a dry stacked interlocking mechanism but still can take structural benefits of using interlocking geometries. Therefore six different mechanical interlocking systems are investigated. The interlocking forms are based on already excisting geometries explored in different testing set-ups. To assess the best option for an interlocking system differenet criteria are formed.

The six different forms will be assessed by five design criteria:

- Level of interlocking
- Manufacturing
- Movement constraints
- Integrity
- Contact surface

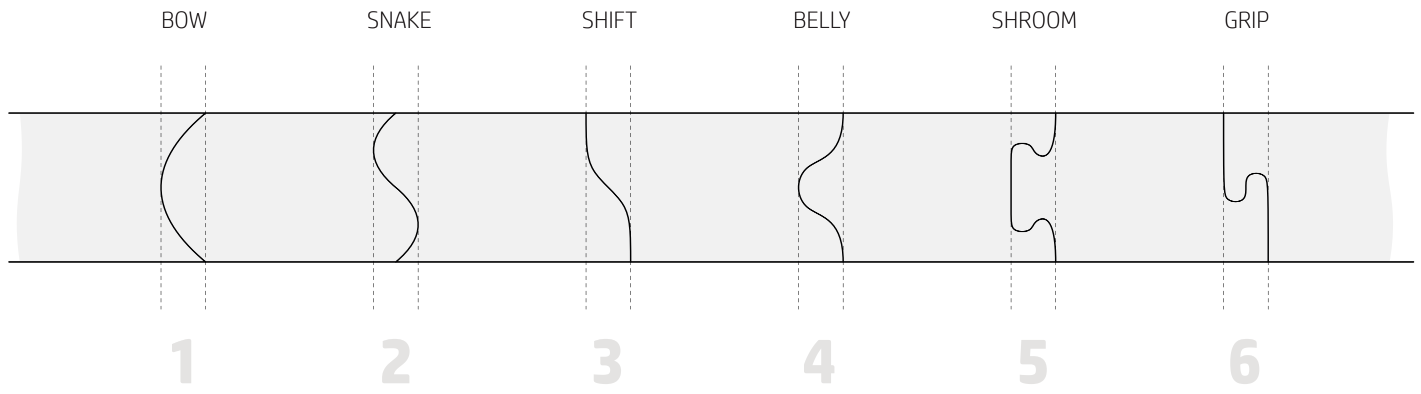


Figure 68: Six different interlocking forms to be investigated.

Interface shapes numbers 1, 2 and 4 are known due its investigation in a dry interlocking glass bridge at the Greenvillage TUDelft (Aurik et al., 2018). The interface configurations numbered 3, 5, and 6 are based on Bouwmeester's (2023) design for a demountable glass connection. These forms originate from Japanese interlocking connections types; Sashimono. The original interface shapes feature angular corners and rectangular profiles. When translating this design from wooden joints to glass, the rectangular profiles are transformed into smoother, curved forms (see Fig. 69). This adaptation is necessary because cast glass cannot accommodate sharp edges. Achieving a consistent and thin section thickness throughout the object is crucial to ensure uniform cooling rates during casting. This uniform cooling minimizes internal stresses within the cast element (Oikonomopoulou et al., 2018a).

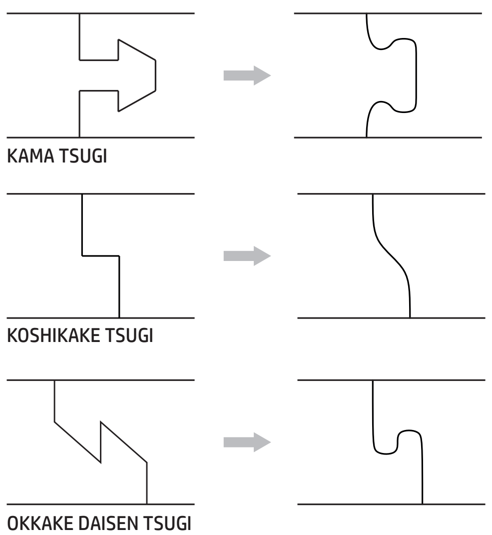


Figure 69: interlocking forms retrieved from old Japanese timber connections.

MANUFACTURING

One of the advantage of cast glass lies in the possibility of design freedom. This design freedom also translates into the freedom to create interlocking forms. However, there are a few design restrictions that must be considered during the casting of freeform geometries.

To prevent residual stress concentrations, fitting the characteristics and peculiarities of cast glass, sharp edges and 90° corners needs to avoided. Organic shapes with curved geometries are preffered (see Figure 70) (Oikonomopoulou, 2018a).

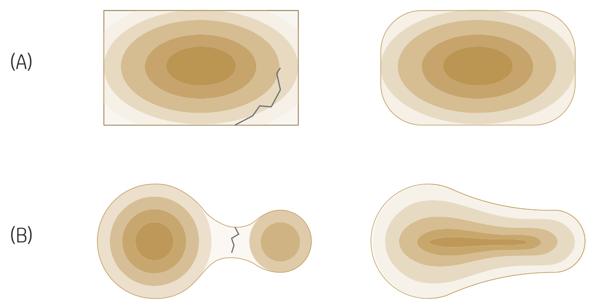


Figure 70: Shape limitations for cast glass elements. Edited from (Damen, 2019). (A): Sharp edges will increase residual stress, thus premature failure. (B): A connector/key with a considerably smaller cross-sectional area also leads to increased stress and high risk of premature failure.

Variations in the thickness or uneven volume distribution of a glass element result in different temperatures within the glass which leads to inhomogeneous shrinkage rates. This causes strain and internal residual stress (Oikonomopoulou, 2018a; Koniari, 2022).

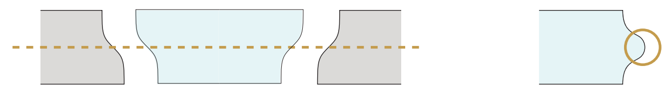
Due to the properties of glass as a brittle material, traditional connectors or keys with a significantly smaller cross-sectional area compared to the overall cross-sectional area should be avoided, as they result in concentrated stresses that can lead to premature failure (see figure 70 (B)) (Oikonomopoulou, 2019).

So to conclude the manufacturing limitations:

- no sharp edges
- smooth (convex surfaces)
- equally distributed mass

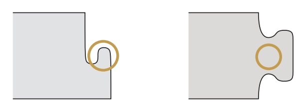
When looking at the 6 geomteries designed for possible interlocking forms, it can be observed that not all shapes adhere to the design limitations of the manufacturing process of cast glass elements. Shapes 1 and 2 (Bow & Snake) both have angles <90 ° degrees, resulting in sharp edges. Especially in glass production with a small cross-section, this can lead to premature breakage.

For shape 3, an asymmetric form (in relation to the axis of the cross-section) may pose a problem due to inhomogeneous shrinkage caused by unequally distributed mass.



For the Belly shape (4) increased internal residual stress can occur in the 'belly' if the shape becomes too wide.

The last two shape (5&6) both have a more complex form. Due to the small workable cross-sectional area of the hybrid panel, the connector and key parts of the two shapes will have a much higher chance of premature failure due to excessive stress factors. Therefore, these two shapes will not be examined further.



MOVEMENT CONSTRAINTS

The way different shapes interlock with each other creates a specific movement constraint. This is crucial for the overall stability and dictate how the components of the structure interact under various loads. When designing with interlocking forms, it's essential to ensure that the elements remain securely connected and aligned to maintain structural integrity. Movement constraints help prevent unintended displacement or separation of the interlocking components, which could compromise the stability and functionality of the structure.

Below is a visualization showing the various shapes and the direction in which the interlocking form is held by the geometry. Here, the 'snake' and 'belly' demonstrate being held in two directions by the form, whereas with the 'shift', it's only in one direction. The 'bow' has no constraints at all and essentially rolls out of its shape.

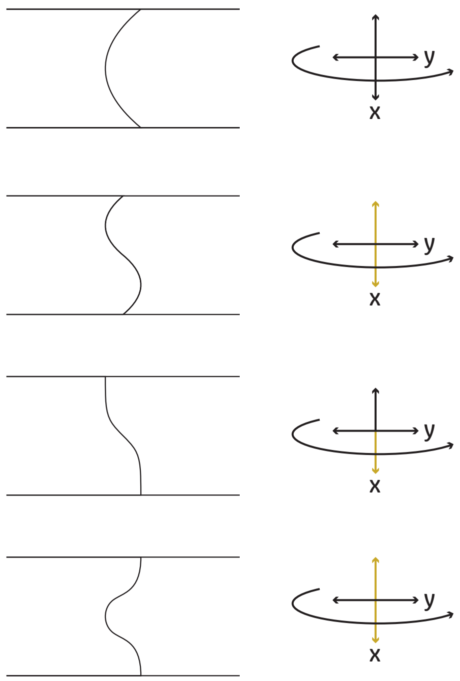


Figure 71: interlocking forms retrieved from old Japanese timber connections.

CONTACT SURFACE

The greater the contact surface area between the concrete and the glass, the better the adhesion strength. The test models have a very small contact surface, but they are compared to determine the percentage relative to a flat planar surface as the contact surface (100%).

- Bow = 105,71%
- Snake = 120,43 %
- Belly = 114,44 %
- Switch = 109,02 %

The contact surface is highly dependent on the design of the shape. Each shape can have many different variants. For now, only the shape used in the test setup has been considered.

FORM	AREA (mm²)
1) Bow	1268.53911
2) Snake	1445.21651
3) Belly	1333.73635
4) Switch	1308.24916

Figure 72: overview of the areas of the different interlocking forms

Integrity (an experimental approach)

A scaled reconstruction of a panel has been created to investigate which of the different interlocking forms can withstand the most force without collapsing. Since a facade panel need to withstand wind force perpendicular to the panel and its own weight, it was chosen to rotate the test model 90 degrees to facilitate the perpendicular force (see figure 73).

To replicate the interlocking form between the concrete and cast glass interface, experiments have been conducted using 3D prints, gypsum and sugar glass.

When sugarglass is heated between 100 and 150 degrees Celsius it becomes in a similar viscosity phase as molten glass (Figure 74). After the right viscosity sugar glass can be cooled down and becomes brittle (Micciche, 2007). This allows for quick exploration of different forms to cast glass.

Snijder et al. (2016) utilized sugar glass as a medium to explore the glass flow within the mould, aiding in the observation of sharp corner details. However, when using sugar glass as a medium against which other materials are cast, it may not be the most suitable testing medium. Instead of the incomplete hardness and stickiness potentially aiding in adhesion, it is gradually absorbed by other materials, leading to detachment and making it challenging to remove from the mould (See figure 75).

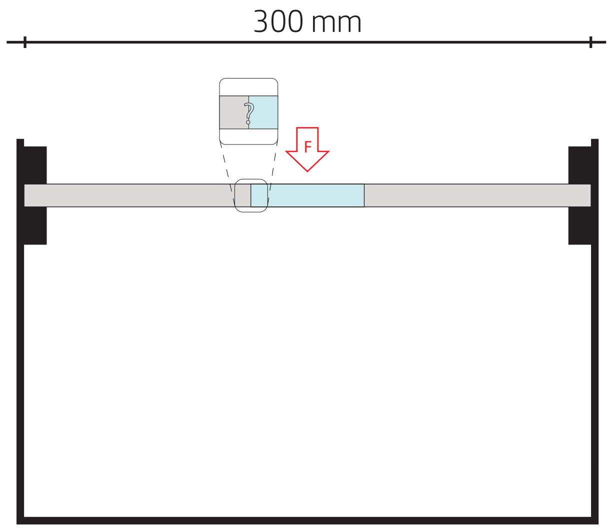


Figure 73: Test set up for testing different interlocking forms.

Figure 74: Making sugar glass, shows similar behaviour as cast glass.

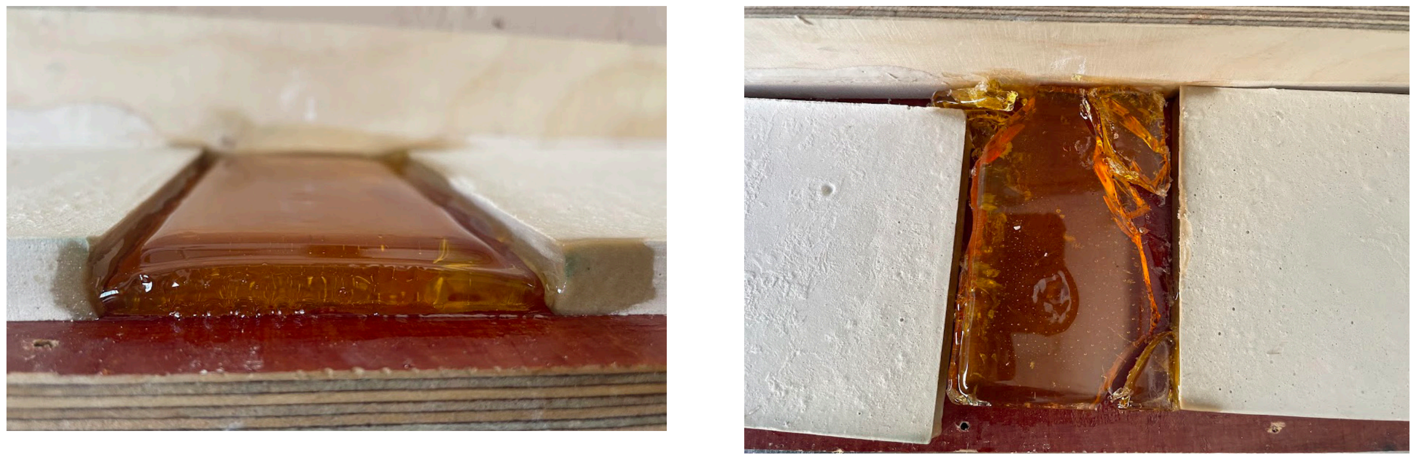


Figure 75: Left: Instead of the plaster sticking to the edge of the sugar glass, it is gradually absorbed. Right: Because sugar glass adheres too firmly to the mold, detaching is not possible, resulting in the sugar glass breaking.

For the search for the best interlocking form, a different design setup has been devised where the various shapes are inserted as a setup piece into a wooden panel to subject them to different forces.

As the initial setup piece, an FDM 3D printed model was first created. The issue with the 3D printed setup pieces was the layering of the printing, resulting in a less smooth surface. Additionally, warping was often encountered during printing.

We transitioned to a setup piece printed with SLA. This technique ensures high accuracy and a smooth surface, promoting the geometry of an interlocking connection so that the two parts fit perfectly together (see figure75).

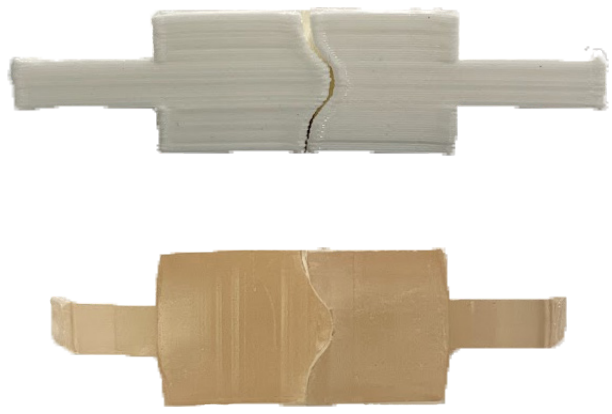


Figure 75: Top: layered FDM printed interlocking form. Bottom: Higher accuracy SLA printed interlocking form.

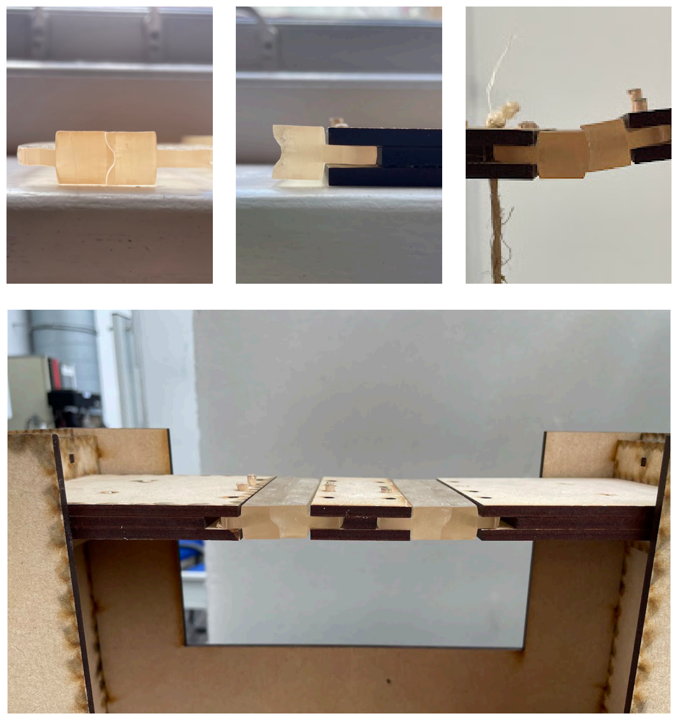


Figure 76: Test set up for testing different interlocking forms.

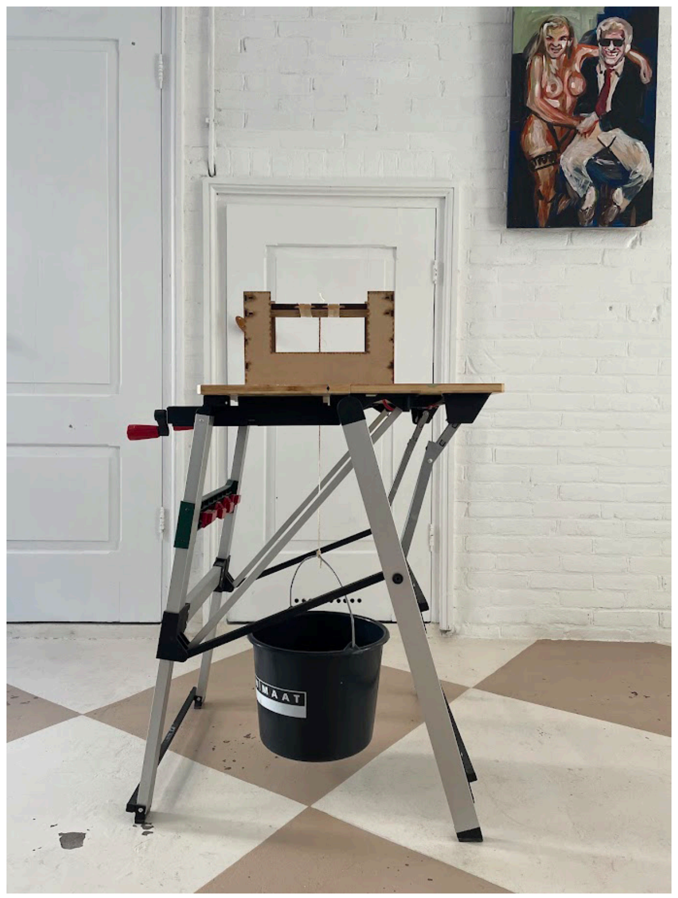


Figure 77: Left: test set-up for testing the interlocking strength with a bucket filling up with water. The interlocking strength was higher than the water capacity of the bucket.

The 'bow' shape shows significantly less interlocking strength and consequently the least deformation capacity.

All specimens exhibit a linear relationship, indicating that as the applied force increases, deformation proportionally increases until the maximum deflection is reached, causing the central wooden element to be pushed out of the interlocking shape.

Specimen 1 shows a less linear curve with a drop in force, which can be attributed to the frame in which the specimens are clamped. The wooden frame is secured with pin-and-hole joints, but if the force becomes too high, these joints may loosen. It is also possible that the specimen partially slipped out of the clamp, resulting in a sudden increase in deflection. Despite this setback, it remains the strongest connection. Specimens 3 and 4 demonstrate comparable strength, with the belly shape allowing for greater displacement and thus absorbing more force.

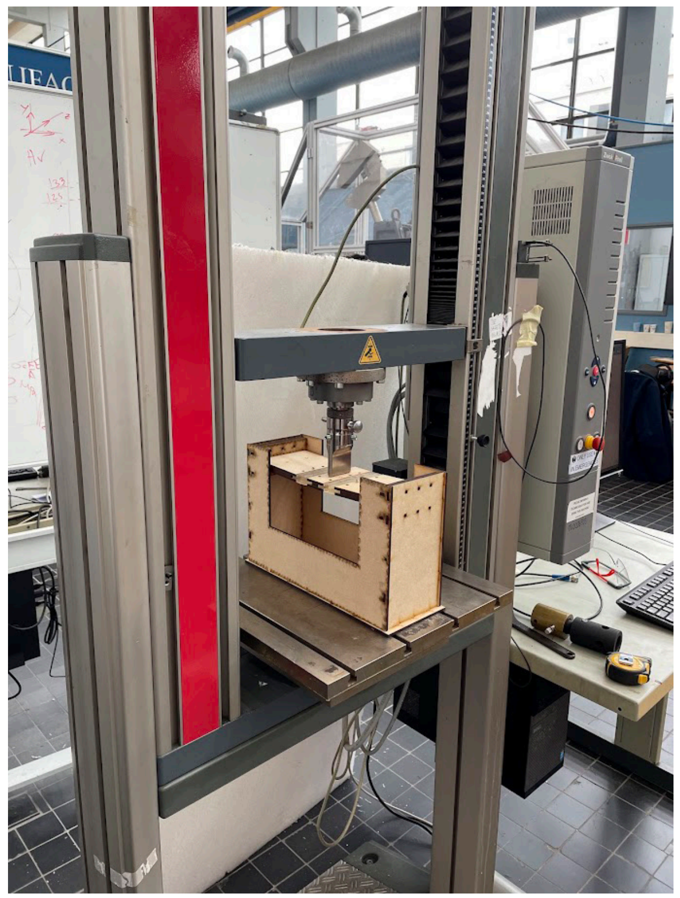


Figure78: point load test with a clamped specimen is conducted at ME with Fred Veer.

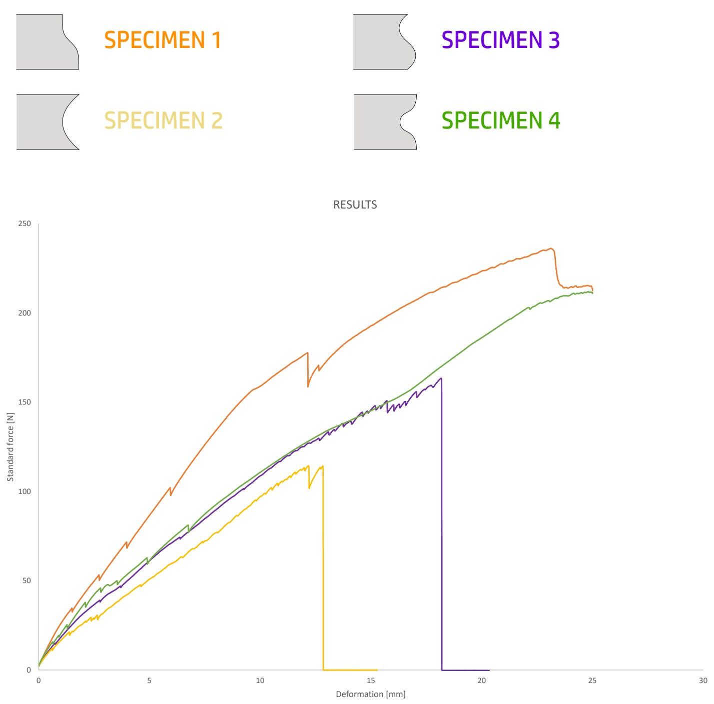


Figure 79: Test results of 3-point bending test of the interlocking specimens.

5.3 CONCLUSION

The final shape chosen for creating an interlocking form for a glass-concrete interface is the belly shape. Despite the 'shift' having higher interlocking strength, this shape lacks the geometry for constraints on both sides. As for the 'snake', the sharp angles pose a design limitation for the cast glass element.

Further research into the precise form is necessary to design the most optimal belly shape for a hybrid interface application (Figure 80).

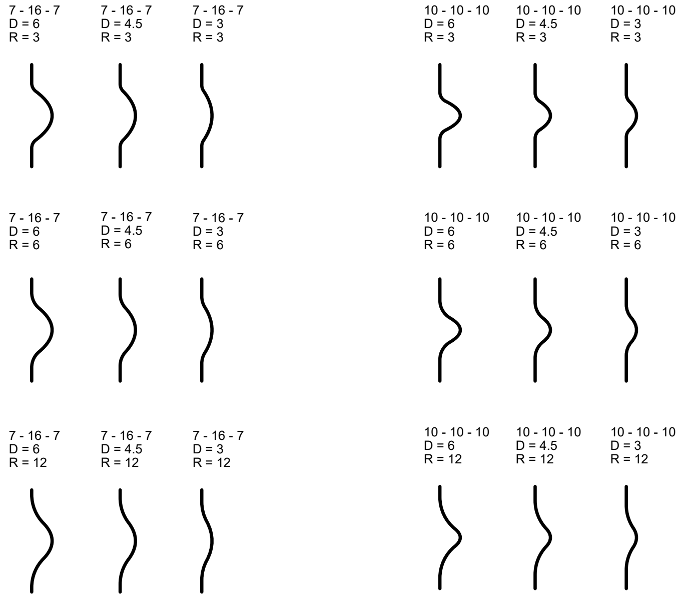


Figure 80: Variations of the belly shape interlocking form.

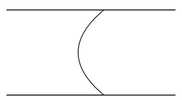
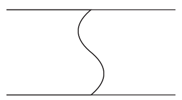
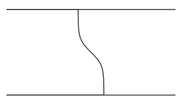
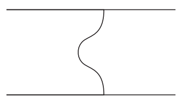
	INTERLOCKING FORM	INTERLOCKING	MOVEMENTS	MANUFACTURING	STRUCTURAL	CONTACT SURFACE
1		+	+	+++	+	+
2		+++	+++	+	++	+++
3		+	++	+	+++	++
4		+++	+++	+++	++	++

Figure 81: Coprehensive overview of the different interlocking forms assessed by different design criteria.

06

SURFACE ROUGHNESS

What is the influence of surface roughness on adhesion strength of hybrid interface? Is an unpolished cast glass surface beneficial in terms of adhesion?

6.1 INTRODUCTION

When establishing a concrete-glass interface, surface quality and roughness of materials are crucial considerations. Recent research on glass aggregates within concrete mixtures revealed a positive correlation between aggregate surface roughness and interfacial bond strength (Hong et al., 2014; Freytag, 2004). Concrete with rougher coarse aggregate surfaces exhibited enhanced mechanical properties, including tensile strength and compressive strength. Optimizing surface characteristics can bolster interface performance and durability. Moreover, adhesive bonding between concrete and glass plays a pivotal role in ensuring structural integrity. Adhesive selection, surface preparation, and curing conditions are vital for robust connections. By addressing these factors we can enhance the reliability and longevity of concrete-glass interfaces in architectural applications.

In Figure 82 a surface profile figure is shown, where *X* shows the ideal surface position. R_a represents the value of the different surfaces. When looking at the high borosilicate glass aggregates (HBG) (Figure 83), the three different surfaces (polished, sandblasted and notched) all have a different R_a value. So the bigger the R_a value the rougher the surface which lead to better mechanical properties and stronger interfacial bond strength (Hong et al., 2014).

When having a concrete-glass interface where float glass is used as web in a load-bearing composite (Figure 84) both Freytag (2014) and Martens et al. (2015) pre-treated the glass by roughening its contact surfaces which resulted in a stronger and improved adhesive bonding.

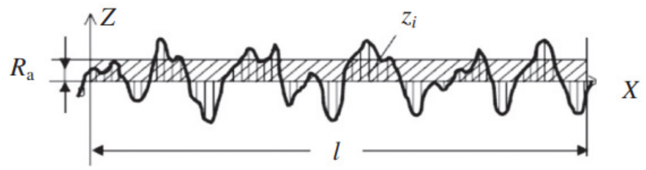


Figure 82: Surface profile and R_a. Source: (Hong et al., 2014)

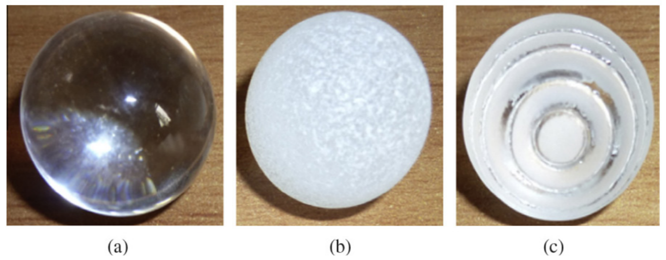


Figure 83: Different surface roughness of HBG aggregates;
(a) polished surface with R_a = 24.0 um
(b) sandblasted surface with R_a = 48.3 um
(c) notched surface with R_a = 259.6 um
Source: (Hong et al., 2014)

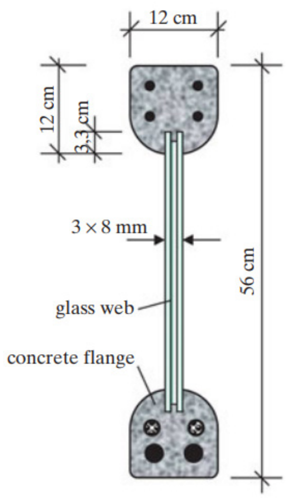


Figure 84: Pre-treated glass web in glass-concrete composite for improved structural performance. Source (Freytag, 2014).

CUTTING

Instead of treatening the glass surface, Dudutis (2020) observed the surface roughness after processing glass with different cutting technologies. Normally, achieving the lowest possible surface roughness is desired when cutting glass to reduce stress levels in the glass and minimize surface flaws. Dudutis's work (2020) clearly illustrates the influence of cutting techniques on roughness (Figure 85). The drawback of using cutting techniques to create roughness is the axis along which the cut is made. This only makes sense when a 2D planar surface is desired. As discussed in Chapter ..., an interlocking form is desired for better integrity of a glass-concrete interface. Creating roughness on a 3D interlocking form is not possible when working with glass cutting, as it operates in the y-axis (figure 86).

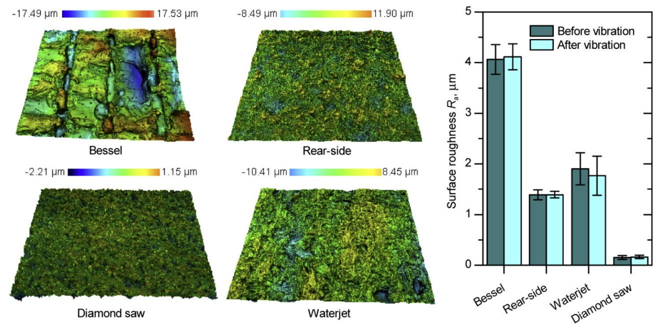


Figure 85: surface topographies and average roughness of different glass cutting technologies (Dudutis, 2020)

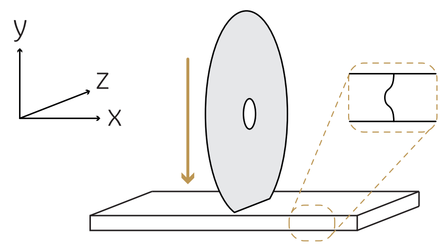


Figure 86: Illustration of the drawback of cutting cutting technologies (diamond saw) when using 3D cross-sectional forms.

BLASTING

As mentioned pre-treaten glass urfaces van increase its roughness. Blasting is one of those treating options. The most common used blasting method for increasing surface roughness is sandblasting. Sandblasting uses abrasive particles propelled at high speed to roughen the surface of the glass, creating a coarse texture. Bousbaa (1998) showed in her work the effects of the sand blasting duration and impact angle on soda-lime window glass, that the roughness increases. With a 90° degree angle. The mechanical strength tends to stabilize after 30 minutes of sandblasting with a decrease in strength of 22%. Shooting sand particles, the surface roughness increases significantly over time (see Figure 87). Also Roumili et al. (2015) and Adjouadi. et al (2007) observed an increased roughness of a glass surface, in a range of 1,15 < R_a < 2,27 μm.

In the scope of this thesis and the scale at which research is conducted, the use of sandblasting for achieving different surface roughness levels on cast glass elements will not be pursued. However, the possibilities do show potential.

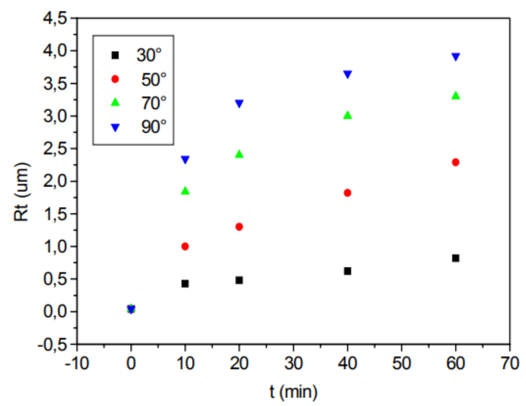


Figure 87: Bousbaa (1998) observed an increased surface roughness over time

POLISHING

Opposite to the notion that a rougher surface leads to improved adhesive bonding, stands the fact that a much higher strength of kiln cast specimens is possible with fine polishing (Bristogianni, 2022). As mentioned earlier in Chapter..., imperfections and flaws in the glass surface can lead to lower strength.

Not only did Bristogianni (2022) investigate this, but Veer and Zuidema (2003) also tested annealed float glass specimens of 400x40mm dimensions, with thicknesses of 3, 6, and 8mm in 3-point bending, with varying edge qualities, from manually cut to machine cut and polished. This research shows that the design strength of manually cut pieces (38MPa) is almost twice as low as the strength of machine cut and fully polished specimens (70 MPa).

Similarly, Vandebroek et al. (2012) conducted structural tests on annealed float glass specimens with either cut or polished edge finishing. It was observed that during loading, the tensile strength was higher in specimens with polished edges (68-127MPa) compared to those with cut edges (28-48MPa).

In her work, Bristogianni (2022) presents more examples from other studies on the intensification of surface flaws and different surface finishes of cast glass elements.

So overall the Post-processing of the surface/edges of the cast elements can greatly minimize the effect of such flaws, which greatly influence the introduction of peak stresses (Oikonomopoulou, 2019)

DESIGN CONSIDERATIONS

The aforementioned studies on the correlation between surface flaws and the strength of glass have primarily been conducted for situations where glass is used as a structural element (structural glass). In a hybrid panel form where there is a direct connection between glass and concrete, it is plausible that the interface will fail before the glass itself fails to imperfections on the glass surface. The adhesive strength of the interface will be lower than the strength of the glass, even with surface and edge flaws.

$$\sigma_{interface} < \sigma_{glass} \quad \text{(MPa)}$$

Since the glass in a hybrid panel serves as transparency from outside to inside, and thus possesses an aesthetic value, a finely polished outer surface of the glass is still desirable. Therefore, the glass element ideally possesses two different surface roughnesses. The surface where the glass adheres to the concrete requires a certain roughness, while the glass with a surface from inside to outside requires a finely polished surface (see figure 88).

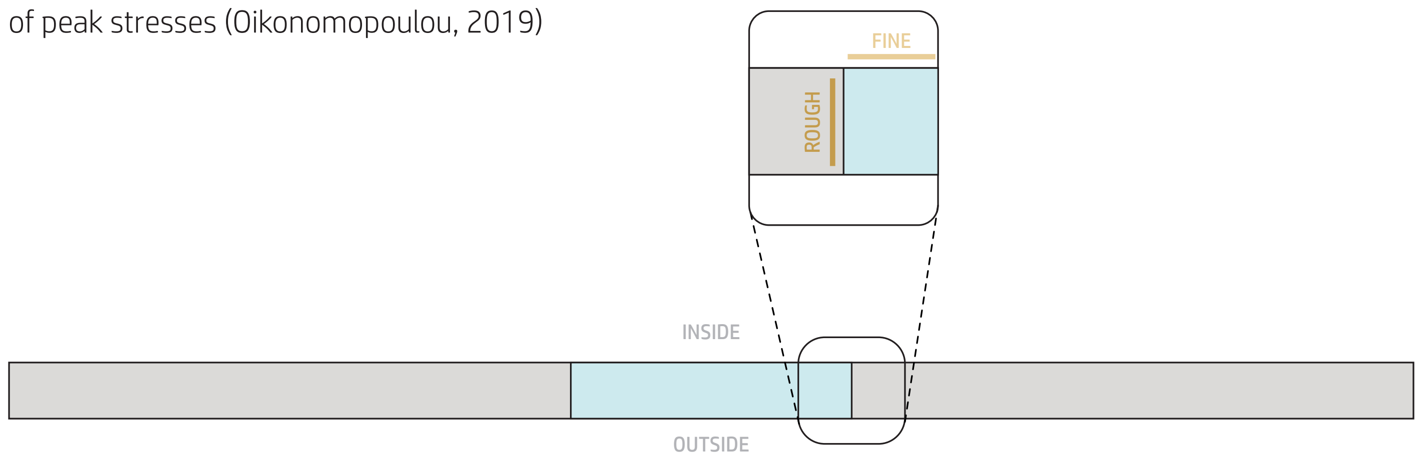


Figure 88: A cross-section of a hybrid panel consisting of concrete and glass, where the interface between the materials requires a rough surface, while the exterior demands smoothness.

After demoulding a cast glass element the glass surface will acquire a translucent, rough skin that needs post-processing for a transparent result (Oikonomopoulou, 2019). This post-processing steps requires multiple polishing steps to achieve a high-quality surface without flaws and imperfections. Kiln-cast glass elements made at TU Delft can be polished with a Provetro flat grinder and diamond abrasive discs in sequences of 60, 120, 200, 400 and 600 grit sizes.

In order to understand to the correlation between the different grit sizes for polsihing and the corresponding surface roughness, table (89) shows a range in roughness between 0,2-1,8 x 10^{-6} m for the different grit sizes.

Reducing the amount of polishing thus post-processing, decreases not only the manufacturing costst and production time but also in increases the roughness of the kiln cast glass surface which will have a positive impact of the adhesive bonding strength of the glass-concrete interface.
Although the post-processing steps for grinding / polishing the glass surface with a 60 grit sizes is a signifacant less time consuming process compared to a 600 grit, you still need post-processing steps.

The most efficient way of treating the glass surface in terms of post-processing, time consumption, and manufacturing costs is by not treating the surface. Adding surface roughness increases the manufacturing process and therefore costs. As mentioned earlier, the glass surface in contact with the mold develops a rough texture. In theory, this roughness should also contribute positively to the adhesive strength of a glass-concrete interface.

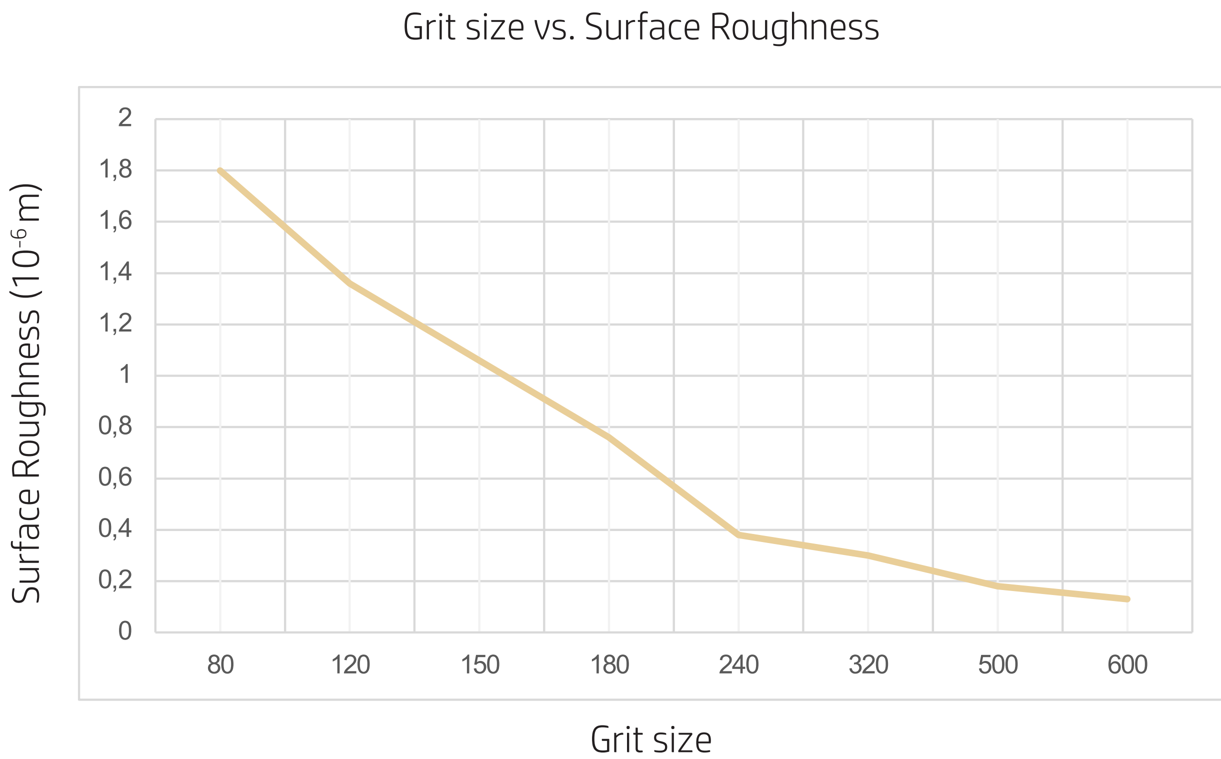


Figure 89: A table displaying the correlation between surface roughness corresponding to various grit sizes used for polishing cast glass.

SURFACE ROUGHNESS MOULD

The roughness of an unpolished cast glass element is een directe weerspiegeling van de (negatieve) binnenkant van de mal. Waarbij de binnenkant van de negatieve mal weer in een directe verbinding staat met het positieve 3D model waar de mal omheen wordt gegoten.

As mentioned earlier in Chapter 3, there are several methods for creating molds for kiln-cast glass elements. The degree of accuracy and precision of the positive 3D (wax) model translates into the accuracy of the negative mold, ultimately determining the surface roughness of the glass skin.

For making complex 3D shapes research have shown great potential in 3D printing the positive models for investment casting. Ioannidis (2023) shows the most potential is within printing using the FDM (fused deposition modelling) and SLA (stereo-lithography appartus) techniques.

Fused deposition modeling (FDM) operates by continuously feeding filament through a computer-controlled heated nozzle. This nozzle moves within the printable volume, depositing material layer by layer onto the printer's bed (Ioannidis, 2023).

The utilization of the Stereo-lithography Apparatus (SLA) method for printing the positive of the mould can result in enhanced precision and superior surface detailing in the final product. (Glass group TU Delft). SLA employs a reservoir containing liquid photo-polymer resin, which is selectively cured by a computer-controlled laser system. When exposed to the laser, the resin solidifies, transforming into solid parts. (American Society of Testing and Materials, n.d.).

To understand the difference between teh surface quality after different printing methods effecting on the mould, 3D models are printed (Koriari, 2022). Figure 88 shows the difference in printing a postive 3D model with FDM and SLA.

To increase the surface roughness of a complex cast glass element, a 3D positive FDM printed (wax) model is preferred due it's less accuracy compared to SLA printed 3D models.

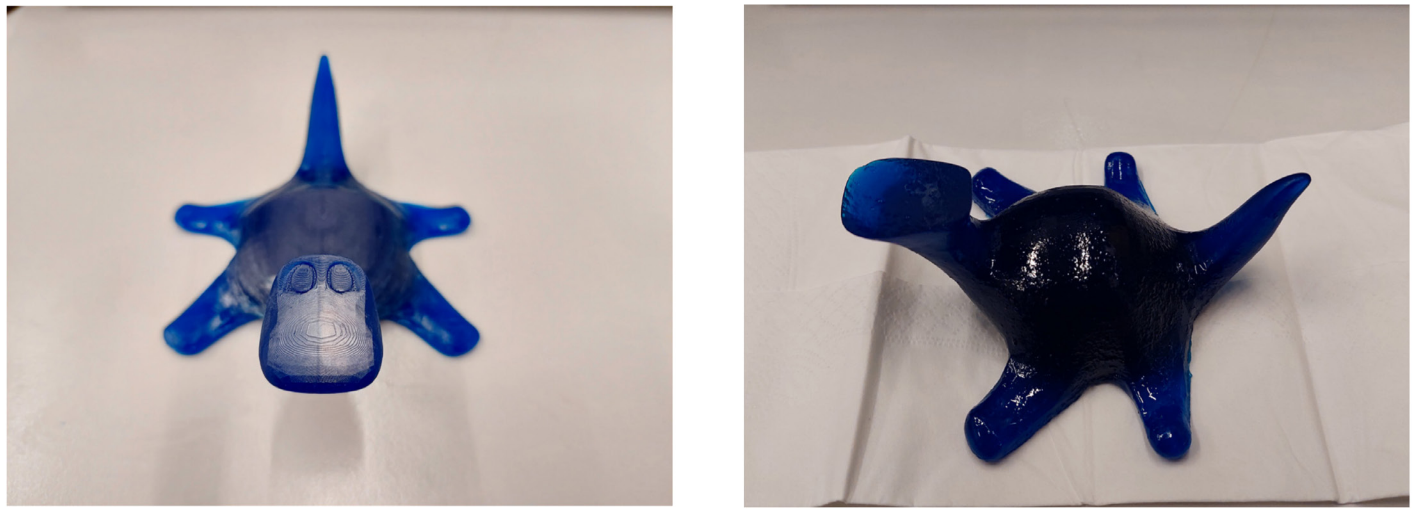


Figure 90: A layered FDM printed wax model (left) and a smooth SLA printed wax-based photosensitive raisin model (rigth). Photo by: Anna Maria Koriari (2022)

6.2 EXPERIMENTAL VALIDATION

GLASS

To compare the adhesive strength between an unpolished cast glass element and a 60 grit element the mechanical properties are tested, including tensile strength and compressive strength to see the potential of the different surface roughhnessess.

Figure 91: Example of a specimen (30x30x240mm) with a 60 grit surface.

In the test there will be three different surface roughness tested on the cast glass surface in a hybrid beam 30x30x240 mm (see figure 91). For each surface roughness, three different beams will be tested. The hybrid beams can be described as the following specimens:

3 x polished cast glass surfaces with 600 grit size
3 x polished cast glass surfaces with 60 grit size
3 x unpolished cast glass surfaces

All cast glass specimens are made from Fully tempered float glass.

The dimensions of the hybrid beams are chosen because of the previous PhD work of Bristogianni (2022). In her work Bristogianni tested the flexural strength and stiffness of kiln-cast beams (30x30x240mm) with different types of non-recyclable silicate glasses. The beams are casted at relatively low temperatures between 820°C - 1120°C. This particular beam size is selected as it provides a substantial thickness of cast material so that the influence of the defects in the bulk can be evaluated, while keeping the mass below 1kg, and therefore reducing the annealing time. For each different glass surface, 3 samples are produced for statistical purposes.

The beams with a 60 and 600 polished surface derived from Bristogianni (2022) her PhD work. The unpolished glass specimen are newly made. In order to make sure the beams have similar properties, the same technical production steps are followed:
All specimens are subjected to a thorough annealing process: they are initially held at peak temperature for 10 hours and 22 minutes, then rapidly cooled to their annealing point at a rate of -160°C per hour. After a 10-hour heat-soak, they are gradually cooled to their strain point at a rate of -4°C per hour, followed by controlled cooling to room temperature. This annealing regimen effectively eliminates residual stress in the specimens.(Bristogianni, 2022).

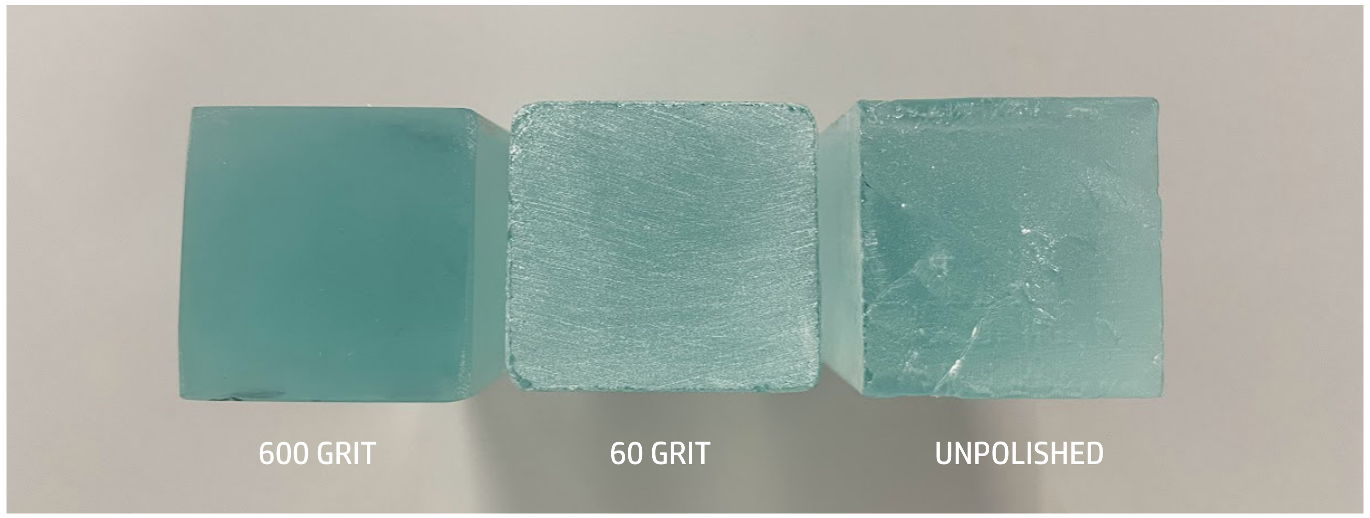


Figure 92: Three different glass surface roughnessess.

CONCRETE

For the concrete to be poured, the composition chosen is the one selected in Chapter ...

Concrete mixing is not only about designing a mix design but also a field of experience. The way mortars and concrete are mixed can have a notable effect on their eventual properties. The effectiveness of the mixing process is frequently determined by the homogeneity of the resulting concrete (Jézéquel, 2007). This can also be observed in the various pours in Figure ... In pours 1 and 2, it's evident that the concrete is not homogeneous. Officially, this is not qualitatively sufficient for further research. The top layer of the concrete consists of a foam-like layer made up of air with water. The pour has disintegrated, causing the cement and aggregate materials to detach from the water (with air).

As mentioned earlier, the mixing of concrete depends on many factors. The mix design remained the same for all three pours (Figure 93). However, the mixing procedures were altered per pour to ultimately achieve a homogeneous result.

The different mixing procedures are as follows:

I)
Mixing of cement (1 minute)
Mixing additive with water.
Adding water to cement (1 minute of mixing)
Slowly adding aggregate materials until desired workability is achieved. (after all is added, mix faster for 2 more minutes)

II)
Mixing of aggregate materials (1 minute of mixing)
Adding cement (1 minute of mixing)
Half of the water (1 minute of mixing)
Mix the additive with the remaining water.
Then add this mixture to the concrete until the desired workability is achieved. (after all is added, mix faster for 2 more minutes)

The first mixing procedure applied is taken from the Kintsugi Facade research by Restruct Group of TU Delft. The second mixing procedure is recommended by concrete technologist Maiko van Leeuwen (Department: Materials, Mechanics, Management & Design at TU Delft).

(A) (B) (C)

Figure 93: Different types of pouring against the glass, where the concrete composition remains the same but various mixing and compaction procedures are employed. (A): Test pour 1, (B): Test pour 2, and (C): Test pour 3.

The second mixing procedure ensures that the cement, along with the aggregate materials, are well mixed and distributed within the mixture. By adding water last, you have more control over the workability of the mixture. It's possible that not all the water and additive are needed per mixing procedure. This is because the amount of water is an assumption based on the maximum particle size distribution. However, fluctuations in factors such as moisture content and particle distribution can already have an impact.

Concrete mixture (per L):

CEM III 52.5	450	gr
Norman Sand	1350	gr
Water	225	gr
Glenuim 51 (Plasticizer)	1	gr

(A) (B)

Figure 94: Concrete mixture of pour #1. The workability was too fluid. The disintegrated upper layer, consisting of numerous air bubbles and water from the cured concrete (B), is evident in the mix (A).

TEST SPECIMENS

#1
After the first pour, the concrete mixture was non-homogeneous and disintegrated, it was decided not to conduct mechanical tests for the three specimens that were the only ones adhered to the concrete. The result of the pour was not qualitatively sufficient for research.

- 3/9 bonded interfaces (3x 60 grit)

#2
After the second pour, the concrete disintegrated again and was officially not qualitatively sufficient for research. After the pour, the concrete was compacted. Compacting on the vibrating table caused the concrete to flow around the glass element. This resulted not only in adhesion at the interface area (contact surface) but also around it (see figure 95).

- 3/9 bondend interfaces (2x 60 grit; 1x unpolished)

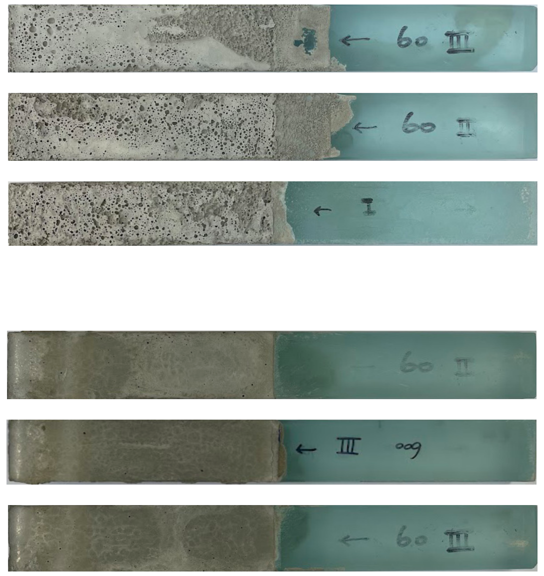
#3
The third pour yielded a homogeneous result (see figure 96). The number of bonded interfaces doubled. To achieve adhesion solely at the interface area, hand compaction was chosen.

- 6/9 bonded interfaces (2x 600 grit; 3x60 grit; 1x unpolished)

The percentage of successful adhesions with different surface roughnesses after three pours is as follows:

- 600 grit: **22,2%**
- 60 grit: **88,9%**
- unpolished: **22,2%**

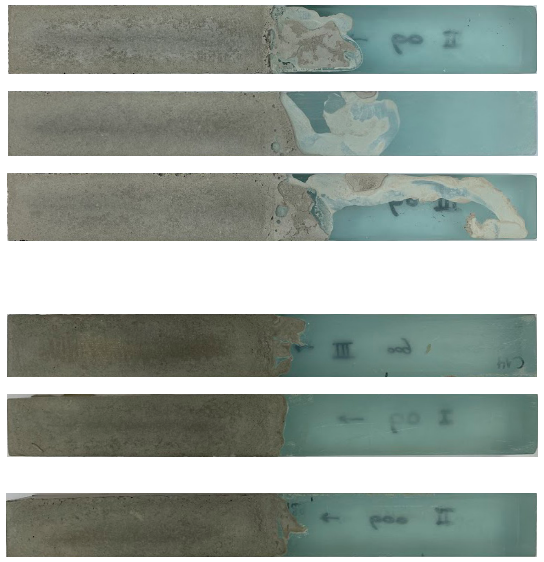
All bonded specimens can be seen in the next page.



(I)

(II)

Figure 95: In the second pour, it is evident how the concrete has disintegrated, creating a brittle top layer of concrete (I) compared to well-mixed homogeneous concrete (II).



(A)

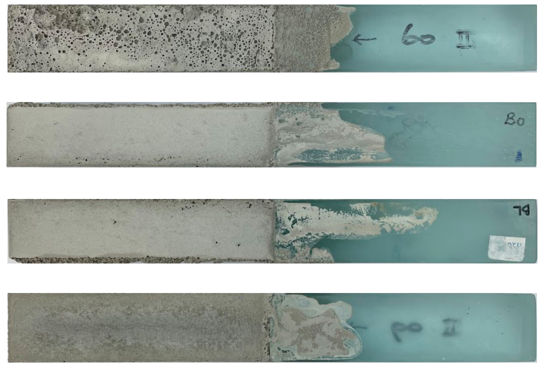
(B)

Figure 96: Compacting on the vibrating table causes the concrete to come beneath the glass (A). With a more self-compacting type of concrete, less vibration is necessary, allowing the concrete to stay in place better (B).

POURING #2

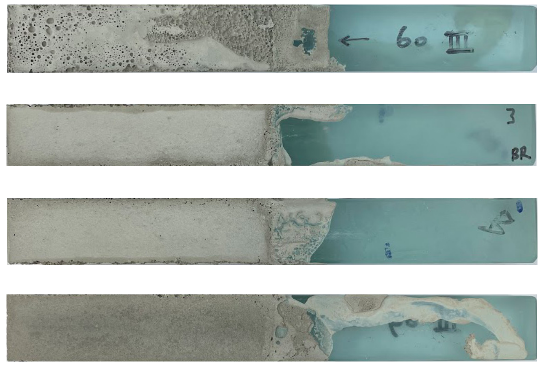
SPECIMEN 5 (60 grit II)

FRONT
LEFT
RIGHT
BACK



SPECIMEN 6 (60 grit III)

FRONT
LEFT
RIGHT
BACK



SPECIMEN 7 (unpolished I)

FRONT
LEFT
RIGHT
BACK

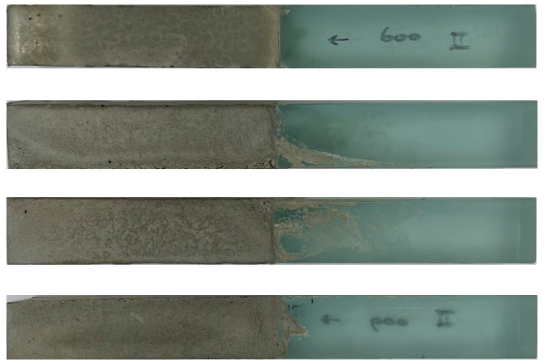
RESULTS POUR #2

RESULTS POUR #3

POURING #3

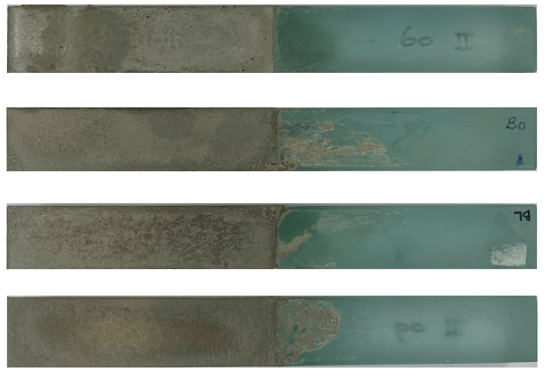
SPECIMEN 2 (600 grit II)

FRONT
LEFT
RIGHT
BACK



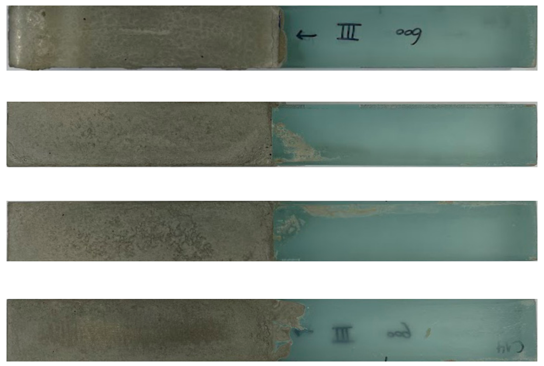
SPECIMEN 5 (60 grit II)

FRONT
LEFT
RIGHT
BACK



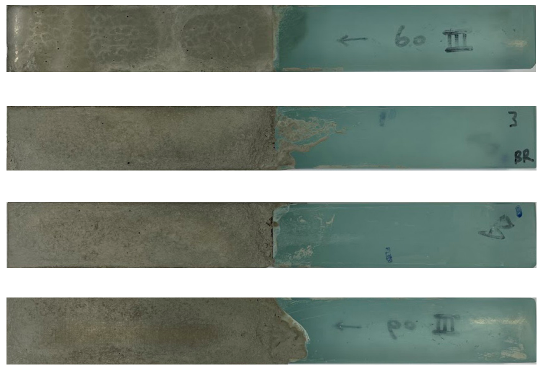
SPECIMEN 3 (600 grit III)

FRONT
LEFT
RIGHT
BACK



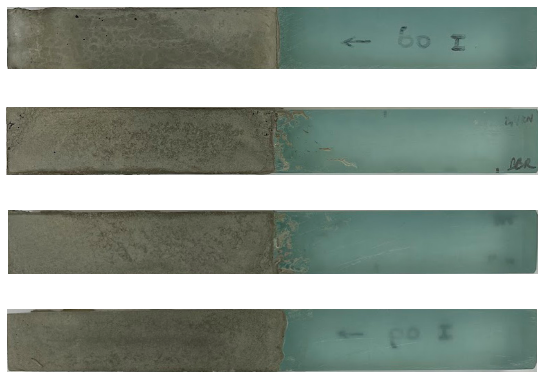
SPECIMEN 6 (60 grit III)

FRONT
LEFT
RIGHT
BACK



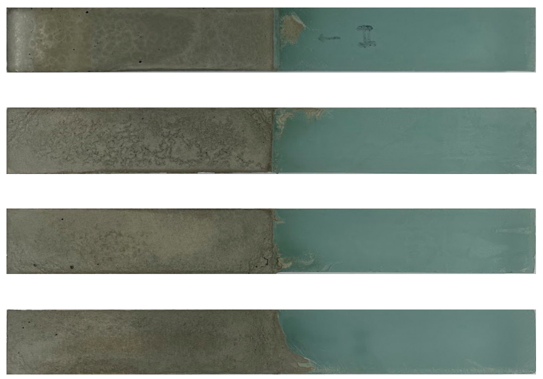
SPECIMEN 4 (60 grit I)

FRONT
LEFT
RIGHT
BACK



SPECIMEN 8 (unpolished II)

FRONT
LEFT
RIGHT
BACK



TEST SET-UP

To compare the adhesive strength of different surface roughnesses, a four-point bending test is conducted at the Mechanical Engineering Faculty.

Below is a visualization of how the test will be conducted and its corresponding parameters.

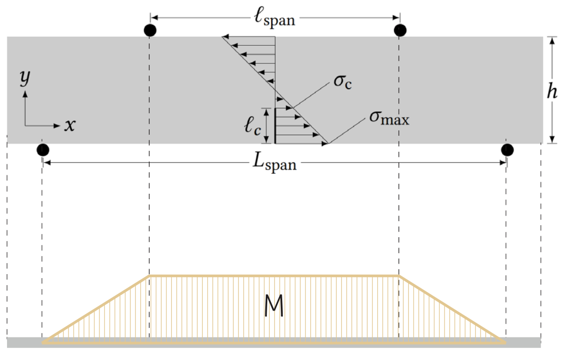


Figure 97: Visualisation of the parameters for the formula of maxiumum bending stress in a 4-point bending set-up and the corresponding bending moment diagram (Doitrand et al., 2021).

The objective is to assess the extent of adhesive failure and analyze the impact of varying surface roughness on bond strength. The four-point bending test offers advantages over other methods by evenly distributing stress across the specimen (maintaining a constant 'M' between 'l_{span}'), thus providing more precise and dependable results (refer to figure 97).

The flexural strength of each specimen is determined by measuring the maximum force it can withstand. For flexural strength (σ) calculation, the following formula is applied:

$$\sigma_{max} = \frac{3}{2}\frac{F_c(L_{span} - \ell_{span})}{th^2}$$

As mentioned earlier, four specimens were tested after the second pour, and six after the third pour. All tests were conducted following a concrete curing period of at least 7 days.

The specimen beams measure 30x30x240mm and are supported during the test with a 50/100 mm support (ratio 1/2), as shown in Figure 98

Figure 98: Test set-up of 4-point bending after the second pouring at Materials lab (ME). Testing a concrete-glass interface of a 30x30x240 mm beam with 50/100 support.

RESULTS

RESULTS POUR #2

As expected, all tested beams failed at the concrete-glass interface, confirming that the connection acts as the weakest link.

The initial test results are presented in the force-deformation figure 99
The tested beams with a glass interface polished with 60 grit exhibit significantly better adhesion than those with an unpolished interface. Although only one specimen with an unpolished interface was tested, it suggests a weaker adhesive bond to the concrete mixture.

The displacement of the specimens is nearly identical, indicating the maximum capacity of the interface regardless of surface roughness.

An overview of the data and the calculated flexural strength is provided in in the appendix.

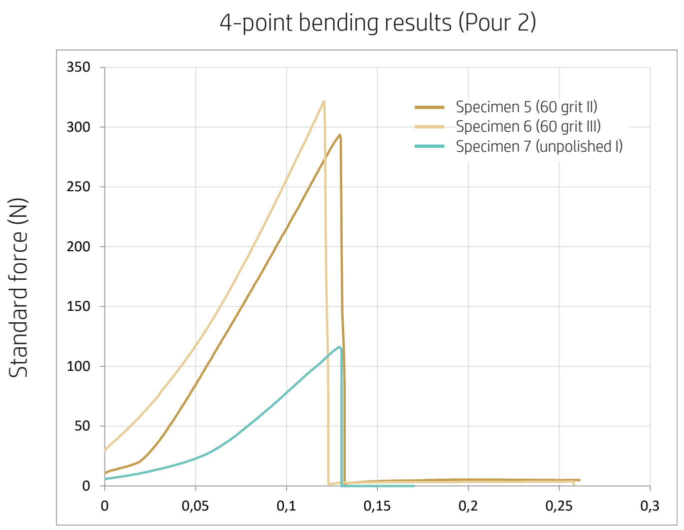


Figure 99: Force-Deformation diagram of the 3 specimens (Pour #2)

RESULTS POUR #3

Compared to the results of the 2nd pour, a stronger bonding strength is observed. Both the maximum normal force and the deformation capacity have increased. This underscores the importance of a proper concrete mix. Even the mixing procedure alone can make a difference in the bonding strength of a glass-concrete interface.

The flexural strength and deformation capacity of the various specimens are closely aligned. While different polishing methods may influence adhesion, they have less significant impact on adhesion strength.

Similar to the previous test, all specimens failed at the interface. The glass and concrete parts remained intact in all beams.

The results after the 4-point bending are presented in Figure 101 and 102.

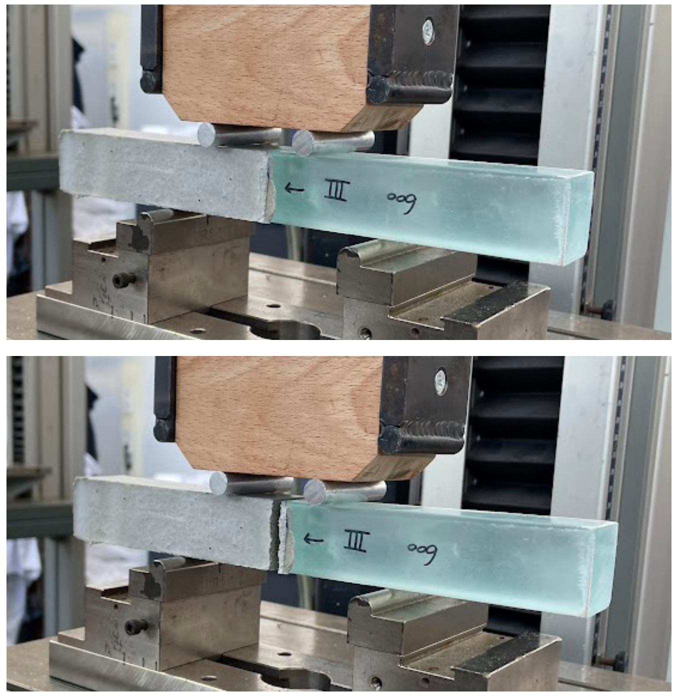


Figure 100: All specimens broke in the interface with a clear breakline just like Specimen 3 shown above.

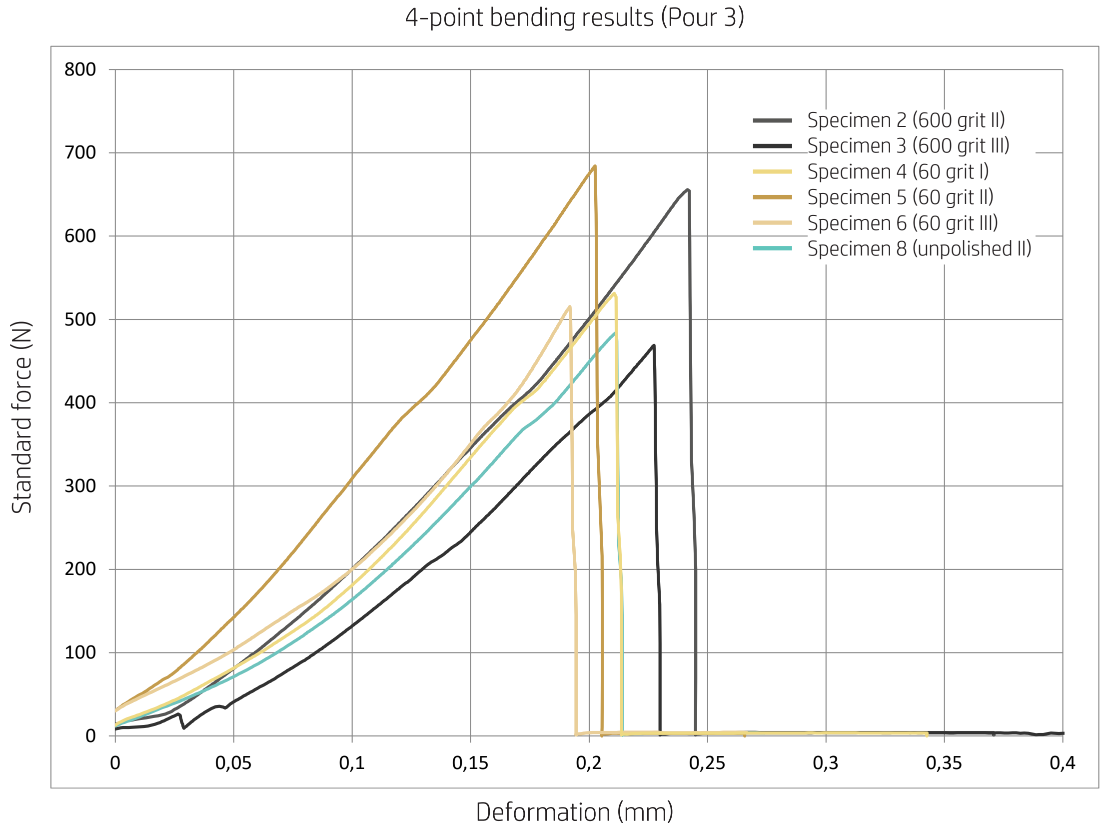


Figure 101: Force-Deformation diagram of the 6 specimens (Pour #3)

Grit size		Contact Area	F_{max}	Dl at F_{max}	Flexural strength	
#		mm²	N	mm	MPa	$MPa_{average}$
600 grit	Specimen 2	872,25	655,86	0,246	1,82	1,56
	Specimen 3	822,67	468,88	0,227	1,30	
60 grit	Specimen 4	849,42	531,27	0,211	1,48	1,603
	Specimen 5	924,71	515,25	0,192	1,43	
	Specimen 6	922,18	684,36	0,203	1,90	
Unpolished	Specimen 8	905,08	484,56	0,212	1,35	1,35

Figure 102: Force-Deformation diagram of the 6 specimens (Pour #3)

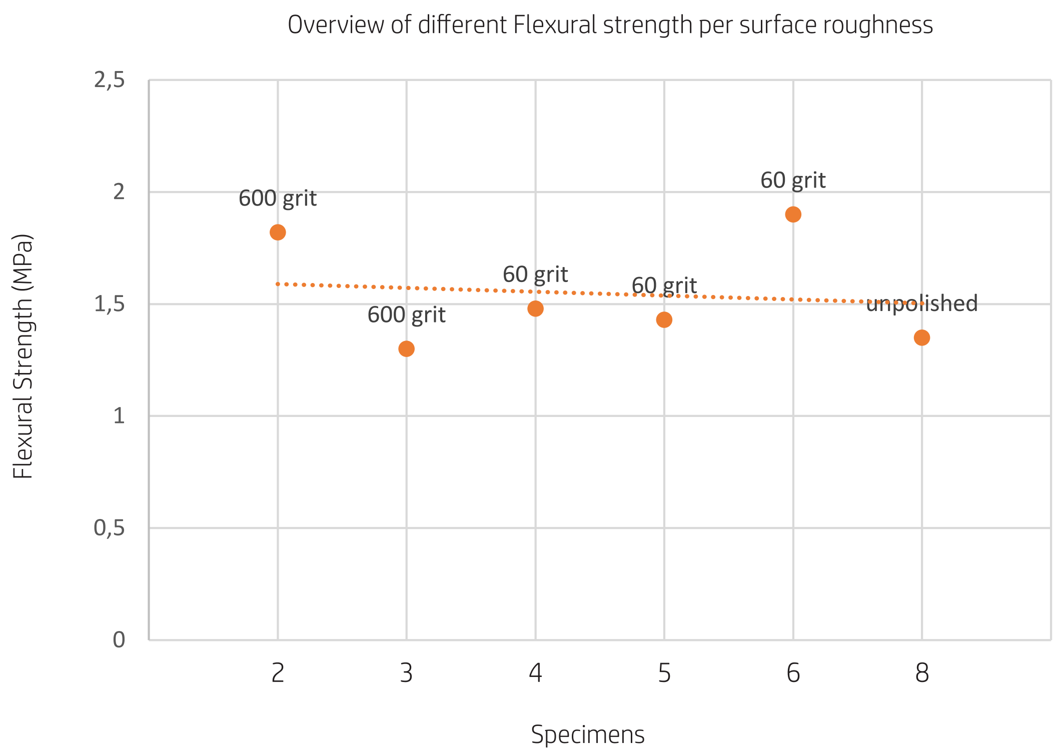


Figure 103: Overview of different Flexural strength per surface roughness

CONCLUSION

- What can be observed is despite varying surface roughness, the flexural strength remains almost constant. This suggests that the interfacial bond strength between the glass and concrete is not significantly influenced by surface roughness within the range tested.
- The failure mode of all the specimens is at the interface. The interface strength might be primarily governed by factors other than roughness, such as chemical bonding.
- In figure 102 a clear break can be observed for all specimens suggesting that the failure occurred suddenly and without significant deformation. Brittle failure often suggests that the failure occurred at or near the maximum shear strength of the interface.
- Brittle fractures at the interface can also indicate that stress concentrations might have been present at the interface, possibly due to imperfections of the concrete mixture.
- While surface roughness did not affect flexural strength, it still influenced the percentages of adhesion successes of the concrete glass interface. Where 8 out of the 9 specimens remained intact, compared to a 3/9 score for the 600 grit and unpolished ones.

6.3 AFM & PROFILOMETER

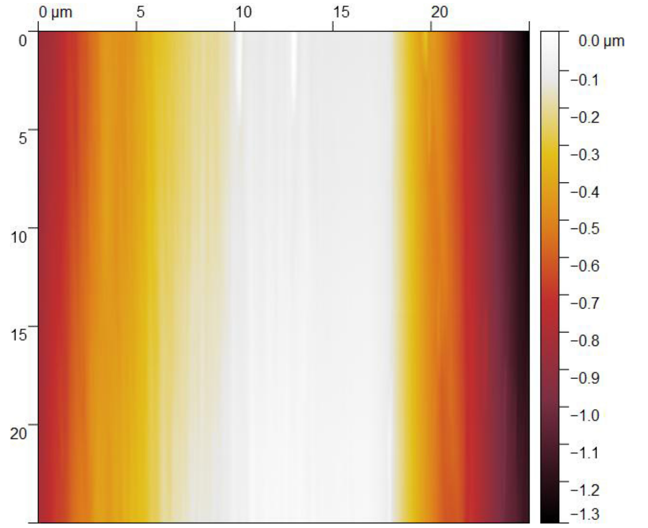
The surface roughness of a cast glass element has not been investigated to date. The results show that a 60 grit polishing yields a better adhesion score than leaving the glass unpolished. To better understand the surface roughness of an unpolished cast glass element and its impact on adhesion, microscopic examination was conducted.

In order to achieve accurate visualization and determine surface roughness more precisely, the decision was made to utilize an instrument for physical examination.

6.3.1 ATOMIC FORCE MICROSCOPE

The Atomic Force Microscope (AFM) was chosen for this purpose, as it allows for probing surfaces of materials and imaging with resolution at the atomic scale. Given that the roughness range of polishing falls between 0.2 - 1.8 micrometers, it was assumed that unpolished cast glass surfaces would also fall within this range.

The AFM operates by physical interaction of a cantilever tip with the molecules on the cell surface. Adhesion forces between the tip and cell surface molecules are detected as cantilever deflection (see figure 105.



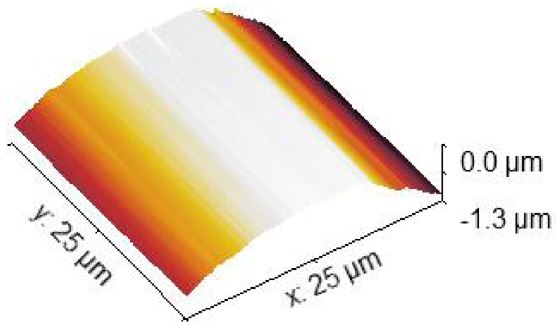


Figure 103: Top: surface profile of an unpolished cast glass element measured on a 25x25 µm area. Bottom: 3D visualisation of the surface profile.

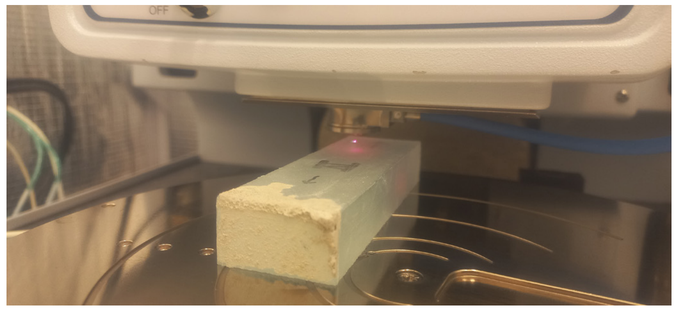


Figure 104: Probing an unpolished cast glass sample with an AFM

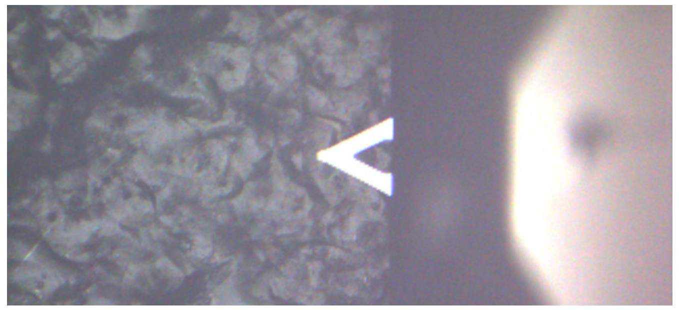


Figure 105: Selfmade image of the probe of an AFM.

Nine measurements were conducted using the AFM, each measuring progressively smaller areas. The measurements range from an area of 25x25 µm to 1x0.3 µm. The AFM probe tip radius is 2,12 nm (R_{tip}). The measured surface profile is obtained by tracing the actual surface using a probe, with the measured values filtered by the stylus tip radius R_{tip} (DIN, 1998).

The average surface roughness measured at an area of 25x25 µm is filtered with the R_{tip} and gives a roughness average of **Ra = 4.322 nm** (see figure 105 below).

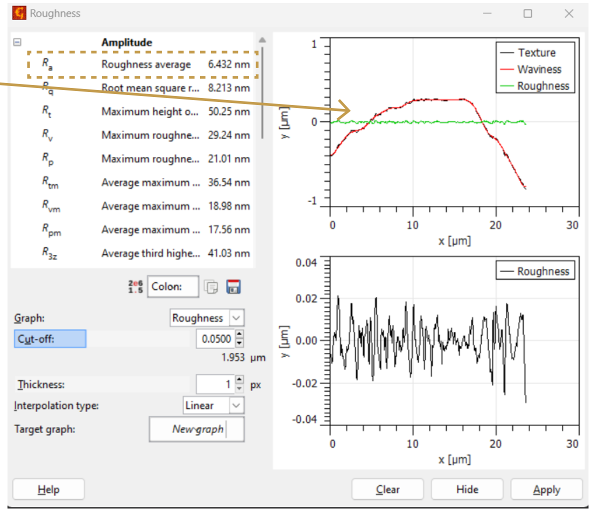


Figure 105: Measurement of the average surface roughness of a 25x25 µm area.

The measurement result indicates an average roughness nearly 1000 times smaller than that of the polished surfaces.

This can be explained by the fact that this scale of surface measurement is too precise and too small. The extent of the surface being measured is so small that it only represents a fraction of the total surface area of an unpolished glass surface.

The smaller measurements taken (1.0x0.3 µm) yield an even smaller average result, namely Ra = 710.7 pm (see appendix).

Officially surface imperfections such as cracks, scratches, and dents are not considered in roughness measurements and should not be included (see figure 106) (DIN, 1998).

In this research the idea that mould particles could contribute to the surface roughness of an unpolished surface is not really applicable. The particles are so small and occur so irregularly that this cannot be considered a real advantage compared to a polished surface (with grit 60). The particles have a height of around only 20 µm. The measurement below is, of course, just a single measurement of a particle, but it does give an indication of the approximate order of magnitude.

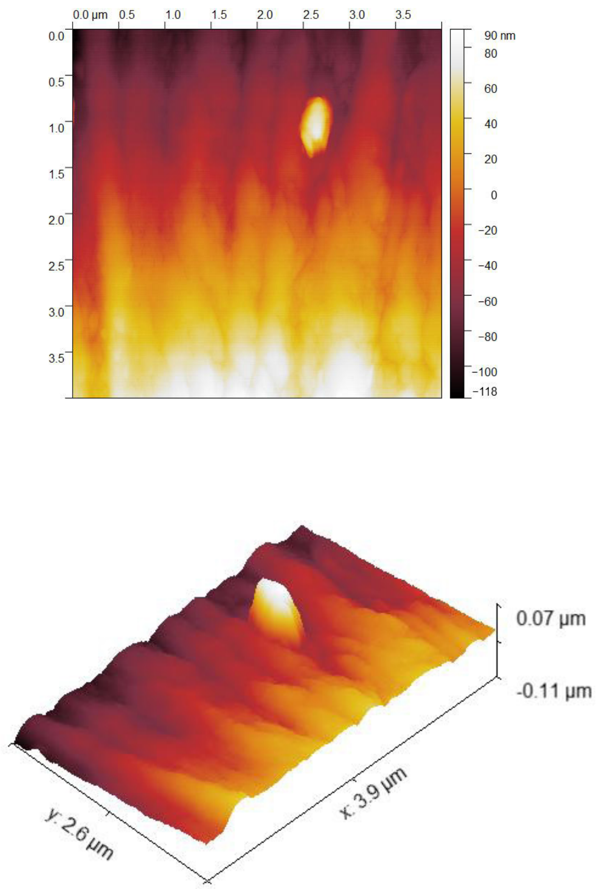


Figure 106: Roughness profile measured on 3.5 x3.5 µm surface with a surface imperfection. Likely a gypsum particle that remained stuck to the glass surface from the Crystalcast mould.

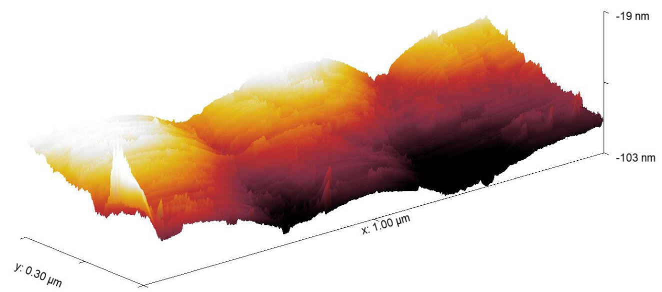


Figure 107: 3D visualisation surface profile of a 1x0,3 µm area with AFM, showing the different roughness in nano scale in which the extreme peaks have a difference of only 84 nm.

6.3.2 PROFILOMETER

Due to the AFM providing roughness at too small a scale, we switched to another microscope: the Dektak XT. The Dektak is a profilometer primarily designed to measure step height and contact surface roughness. During a profilometer measurement, a fine stylus moves across the surface to capture its topography. The vertical movement of the stylus is recorded to create a surface profile.

The main distinction is that while an AFM measures at the nanoscale, a profilometer operates at the microscale, offering lower resolution. Consequently, the output from a Dektak measurement is not visually displayed like an AFM but rather depicted as a surface profile in a graph.

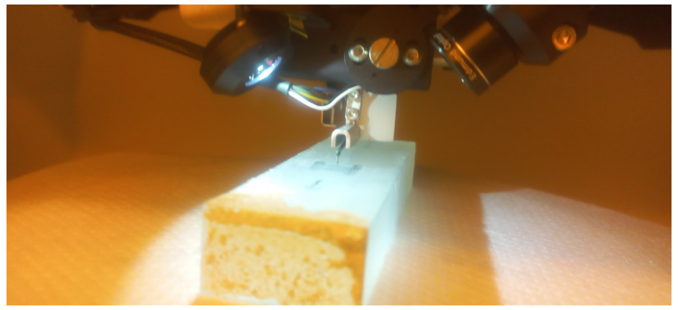


Figure 108: Probing an unpolished cast glass sample with a Dektak profilometer.

Measurements of the surface profile with the profilometer were conducted over a distance of 8 mm, with increasing magnification until the distance was reduced to 0.5 mm. A total of 6 measurements were taken (as shown in Appendix. The profiler stylus has a tip radius of 0.7 µm (R_{tip}).

The graph over a distance of 8 mm shows a repetition of peaks. Due to the repetitive nature of these peaks, it can be concluded that there is a consistent surface profile. An average surface roughness was calculated, filtered by the stylus tip radius (R_{tip}), resulting in **R_a = 6.225 µm**.

Examining a single peak, the distance is 1.35 mm with an average R_a = 5.656 µm. It is likely that the peaks in the graph reflect the layered structure of the 3D printed model, which left an imprint in the mould, and this is observed in the surface profile of the cast glass element.

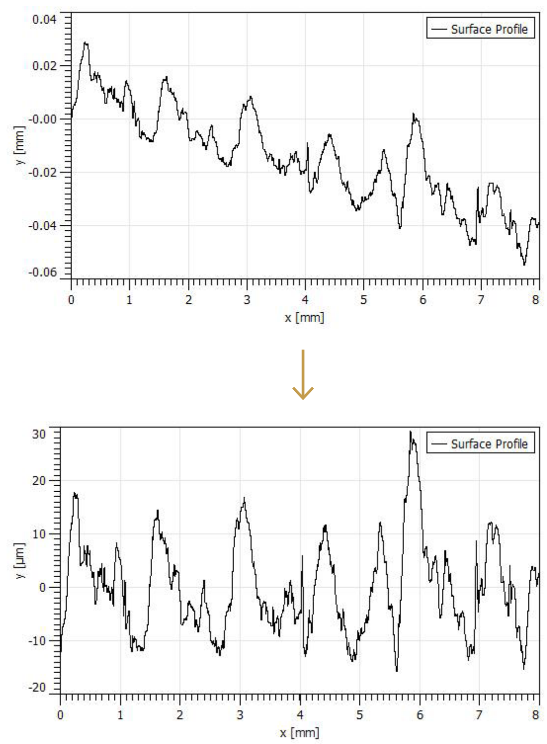


Figure 109: Correct data by leveling for a more accurate average surface roughness calculation after measuring with Dektak.

6.5.3 RESULTS

This study shows that the average surface roughness of R_a = 6,225 µm, which is more than three times higher than that of the polished 60-grit surface (R_a = 1,8 µm). However, the polished surface exhibited a better adhesion percentage.

This could possibly be explained by the fact that a polished surface with 60-grit has a more consistent roughness over a shorter length which results in more more contact surface. Although the peak heights might be lower (resulting in a decrease in average surface roughness), the totale surface length can be higher, leading to better adhesion.

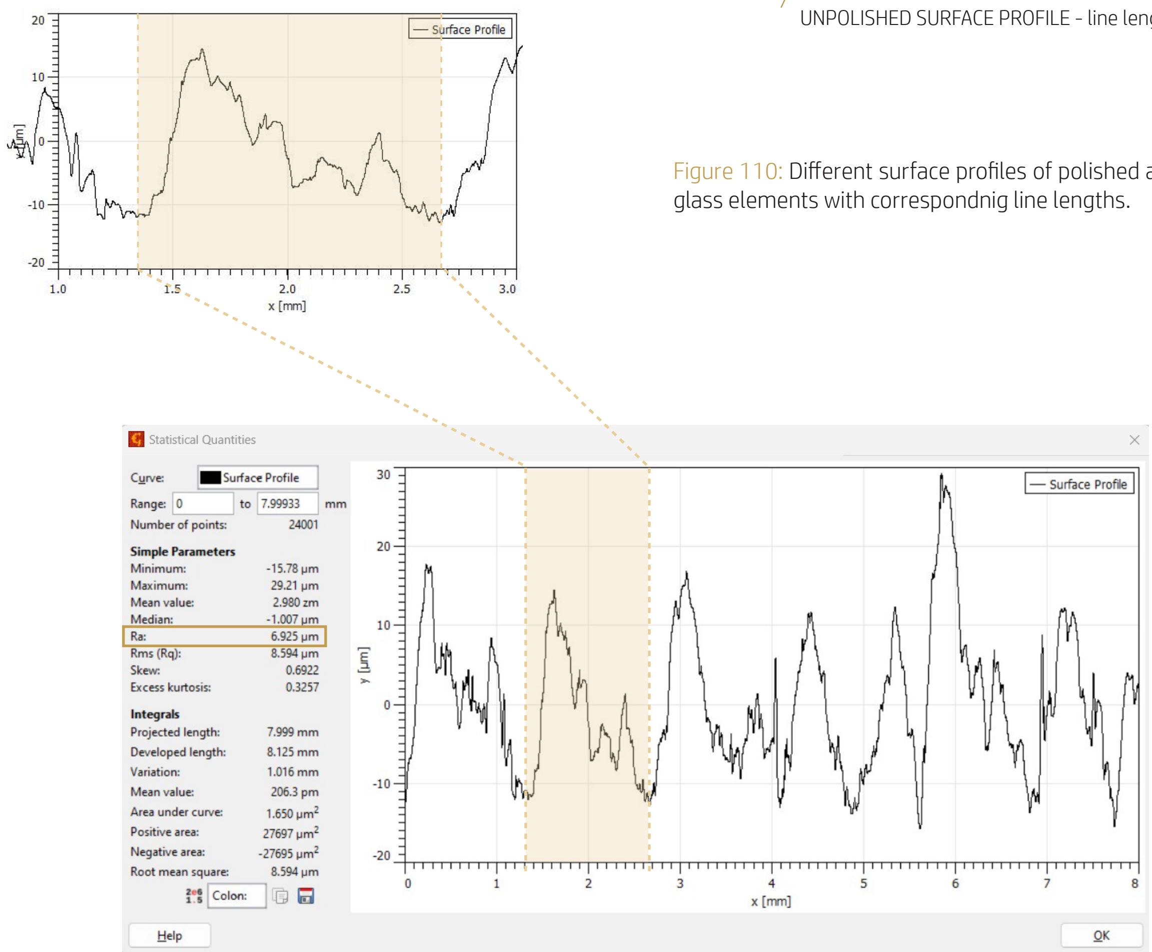


Figure 111: Top: surface roughness calculation of one peak over a distance of 1,35 mm (Ra = 6,356 µm). Bottom: Average surface profile over a length of 8 mm with an average surface roughness of (Ra = 6,935 µm).

Below is a visualization of the difference in the surface profiles of polished and unpolished glass surfaces (Figure 110).

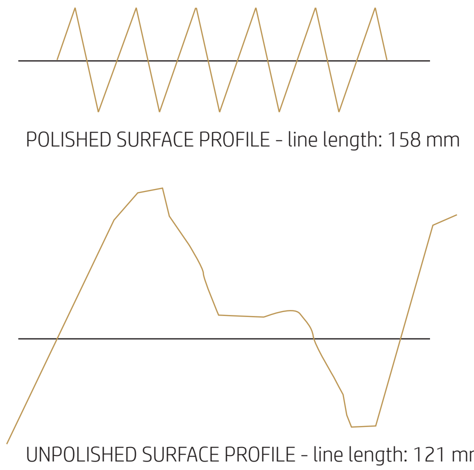


Figure 110: Different surface profiles of polished and unpolished cast glass elements with correspondnig line lengths.

6.4 CONCLUSION

In the creation of a hybrid panel, the interface between the concrete and glass is the weakest point in terms of structural integrity. To achieve stronger adhesion, a rougher surface is necessary. A greater surface roughness provides more adhesion area, resulting in better adhesion. Ideally, a surface that is unpolished and comes directly from the mould would be most favorable in terms of manufacturing time and costs.

- while creating surface roughness aids in enhancing initial adhesion, it does not significantly improve the strength of the interface.
- The brittle and clear break observed during testing suggests a weak adherence bond to the non-porous surface of glass.
- findings highlight the critical influence of the concrete mixture on the bond strength at the interface. A properly formulated concrete mixture can substantially enhance the strength of the bond between glass and concrete. This underscores the importance of selecting and optimizing concrete compositions.
- unpolished cast glass with a rough surface does not necessarily promote improved adhesion to concrete. The presence of mould particles further does not contribute positively to bond strength. It is evident that an increase in average surface roughness does not directly correlate with enhanced adhesion.
- the design and consistency of surface roughness features play a more crucial role in adhesion strength. The configuration and uniformity of grooves and other roughness elements are pivotal in creating effective mechanical interlocking with concrete (see discussion).

6.5 DISCUSSION & RECOMMENDATIONS

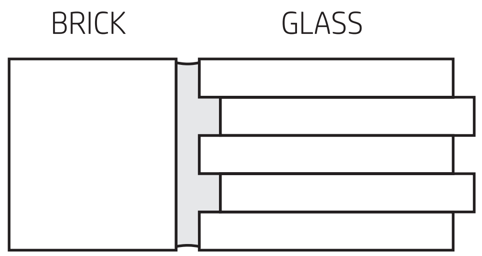
DISCUSSION

During the mechanical tests, only bending was considered, not shear, although shear testing might be more suitable for comparing different surface profiles. Shear tests could provide additional insights into how different textures affect the interface strength, which is crucial for applications where shear forces are prevalent.

Since the 3D printed model reflects the surface profile of the cast glass element, it is worth exploring the effects of varying the print settings, such as layer thickness. Printing with thicker layers might result in an improved interface when casting concrete against an unpolished glass surface. This could potentially enhance adhesion due to a more pronounced texture.

Given that the changes we are considering are on a microscale, it might be more beneficial to examine surface roughness variations on a larger scale. The interface strength is relatively low, so minor flaws on the glass surface are unlikely to significantly impact the overall performance. However, more pronounced textures or patterns could make a notable difference.

In this line: In her 2023 study, Barou conducted a comparative analysis of the adhesion properties between glass and mortar or adhesives. Her research revealed that, similar to the findings of the present thesis, the interface of glass adhesion to mortar exhibited brittle failure characteristics. Barou (2023) demonstrated that incorporating a saw-tooth geometry enhanced both the load-bearing capacity and maximum displacement.



Furthermore, the orientation of stacked glass elements was identified as a critical factor influencing the shear strength and ductility of joints involving brittle materials. To optimize performance, a combination of interlocking geometric forms and surface roughness was proposed. Specifically, employing an interlocking shape with a more layered configuration was recommended.

Barou's findings underscored the preference for macroscale roughness over microscale roughness in achieving robust interfacial adhesion between glass and mortar or adhesives. This approach aims to enhance overall structural integrity and durability in applications involving brittle materials.

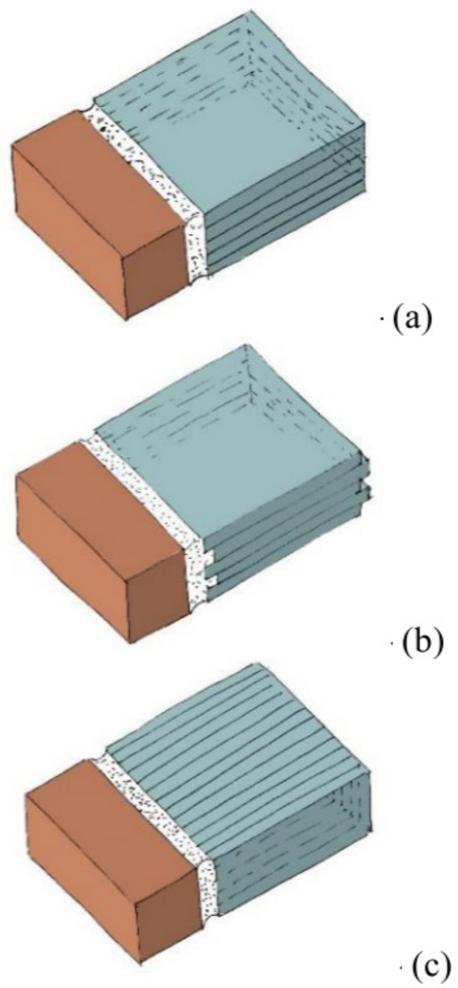


Figure 112: Barou (2023) showing a stacked glas orientation improves shear strength and displacement capacity in a glass-mortar interface.

RECOMMENDATIONS

- Conduct shear tests in addition to bending tests to better understand how different surface profiles influence interface strength.
- Experiment with different 3D printing settings to produce models with thicker layers. Assess how these changes affect the surface profile and the resulting concrete interface.
- Investigate the impact of larger-scale surface roughness on interface strength. This could involve testing surfaces with significantly different roughness profiles to identify the optimal texture for adhesion. Examples of testing with a larger0scale surfaces are given below:

Ribbed Surfaces: Explore the creation of ribbed (or waved) surfaces with varying wave heights. This could be achieved by adjusting the 3D printing design or by manually creating these features.

Surface Indentations: Test the effectiveness of surface indentations made with tools like a diamond saw or Dremel. These features could later be incorporated into the design to enhance mechanical interlocking and improve adhesion, so that no additional post-processing steps are required, saving manufacturing time and cost.

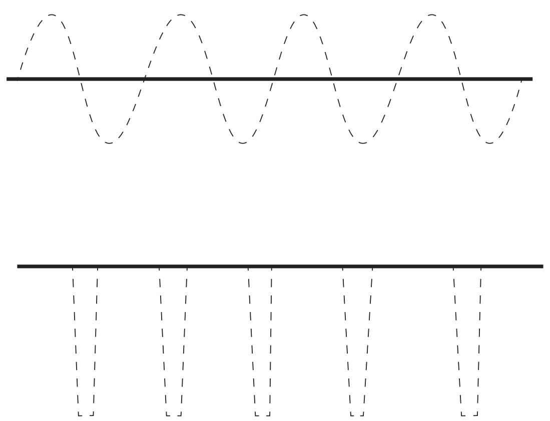


Figure 112: Top: A consistent ribbed surfacae profile. Bottom: By making incisions, also a consistent surface profile is created. Both can be benefical in terms of adhesion.

07

DESIGN

In what way can the determination of the design area of a glass-concrete interface and industrialise the production of a hybrid panel?

7.1 INTRODUCTION

In a hybrid panel consisting of concrete and glass, the interface is the weakest link. Research has been conducted to enhance adhesion through surface roughness, interlocking form, and materials composition. Now, all these aspects need to be integrated to design a hybrid panel.

The design focuses on a facade panel with the height of a floor and the width of a standard dimension for curtain wall systems. The dimensions are illustrated in Figure 114.

These dimensions are chosen to facilitate transportation of multiple panels to the site simultaneously.

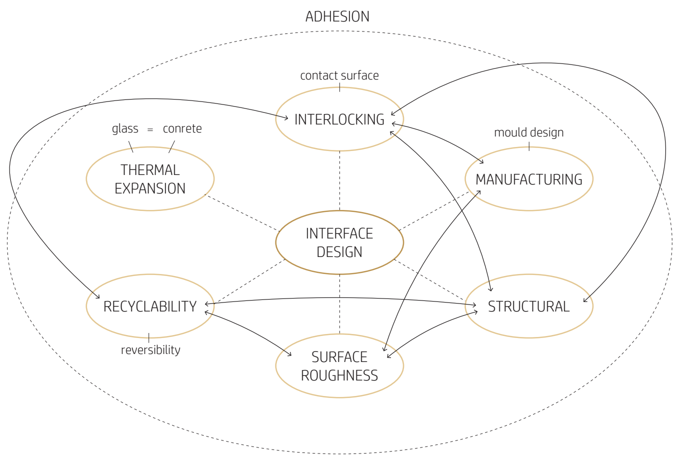


Figure 113: Overview of the different interface design parameters.

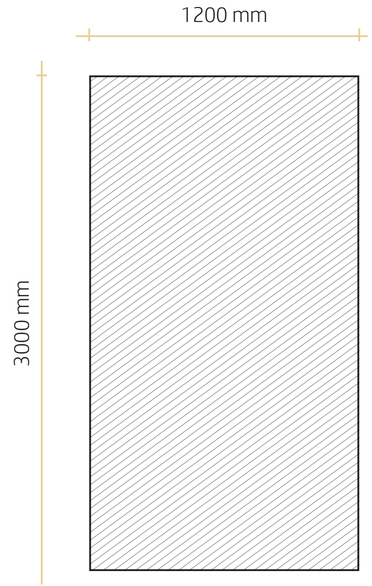


Figure 114: Dimensions of a facade panel with a floor to floor height.

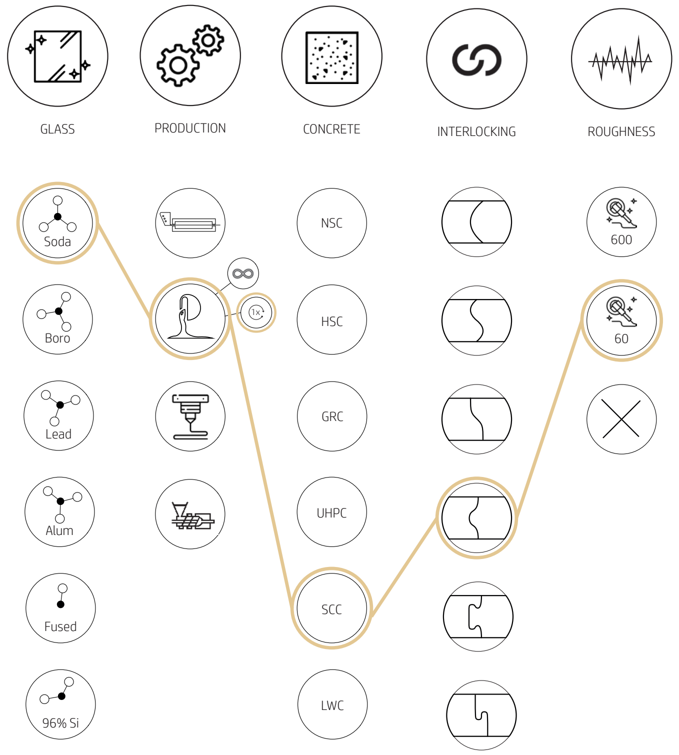


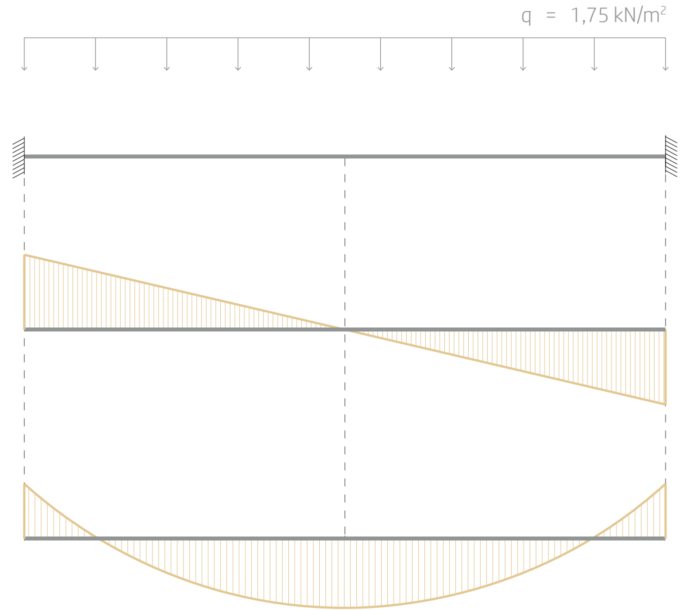
Figure 115: Overview of the literature and experimental research results.

7.2 SUPPORT SYSTEM

Three main principles to support the facade panel are considered. The three options differ from bending moment force and shear force. To simplify the understanding of these forces, the panels are visualised in supported beams.

Some rudimentary calculations show the maximum bending and shear forces. For all three design options a live load (windload) of 1,0 kN/m² and a deadload of 25*0,03 = 0,75 kN/m² with a span of 3 m have been assumed. The width of the panel used for the calculations is 1,2 m. All calculations are done over the long side of the panel.

No safety factors are considered since this is a comparitive calculation.



The support system with both fixed ends shows the most favourable condisation. The panel allows 'moment free' places in the panel. The maximum bending is at the ends of the panel. Considering that it is preferable to have the interface in the middle of a panel rather than entirely on the outer edge, this is a favorable situation. In general, this support experiences the least bending.

In terms of shear it is similar to the simply supported beam, therefore bending is de decisive factor for the support system.

(A) Fixed Both Ends

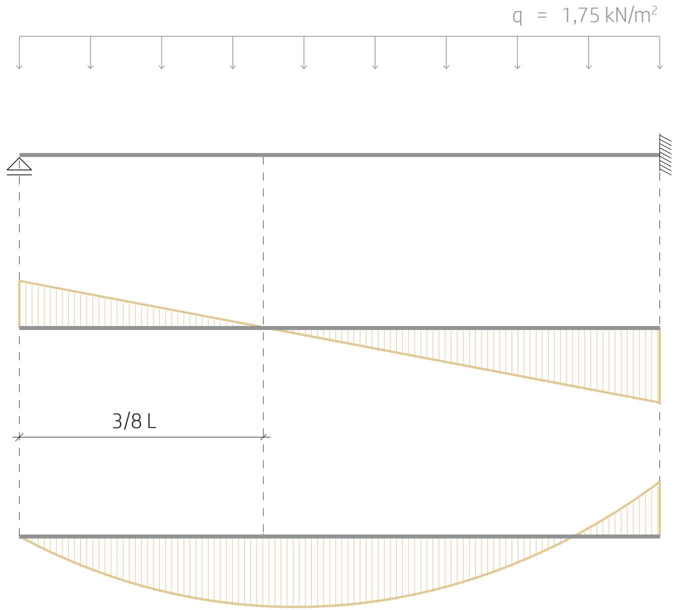
Max bending moment (end):
$M = q L^2 / 12 = (1750 \text{ N/m} * 3^2) / 12$ **= 1312,5 Nm**

Bending moment (middle):
$M = qL^2 / 24 = (1750 * 3^2) / 24$ **= 656,25 Nm**

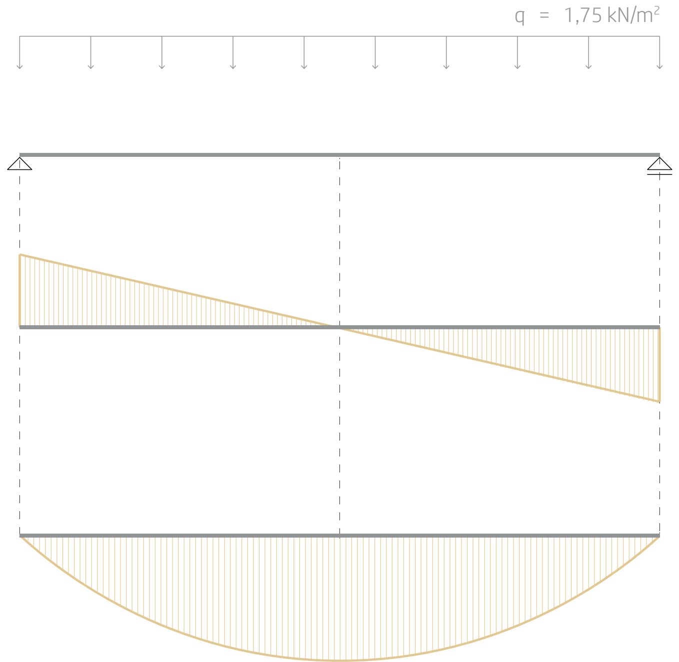
Bending Stress (end)
$\sigma_m = m*z / I = (1312500 * 15) / (1/12 * 1200*30^3)$
= 7,29 N/mm²
Bending Stress (middle) **= 3,64 N/mm²**

Max Shear force:
$V_x = q (L/2 - x) = 1,75 * (1,5 - 0)$ **= 2625 N**

Shear stress
$V/A = 2,625 / (0,03*1,2)$ **= 0,0729 MPa**



(B) Fixed End



(C) Simply Supported

Max bending moment (end):
$M = q L^2 / 8 = (1750 \text{ N/m} * 3^2) / 8 =$ **1969 Nm**

Bending moment (3/8L):
$M = 9qL^2 / 128 = (9 * 1750 * 3^3) / 128 =$ **1107,4 Nm**

Bending Stress (end)
$\sigma_m = m*z / I = (1969000 * 15) / (1/12 * 1200*30^2)$
= **10,94 N/mm²**

Bending stress (3/8L): = **6,152 N/mm²**

Max bending moment:
$M = 1/8\, q L^2 = 1/8 * 1750 \text{ N/m} * 3^2 =$ **1969 Nm**

Bending Stress
$\sigma_m = m*z / I = (1969000 *15) / (1/12 * 1200*30^3)$
= **10,94 N/mm²**

Max Shear force:
$V_x = 5qL / 8 = (5 * 1,75 * 3) / 8$ = **3281 N**

Shear stress
V/A = 3,281 / (0,03*1,2) = **0,0911 MPa**

Max Shear force:
$V_x = q\,(L/2 - x) = 1,75 * (3/2)$ = **2625 N**

Shear stress
V/A = 2,625 / (0,03*1,2) = **0,0729 MPa**

WINDLOAD

In addition to supporting its own weight, the panel must also withstand wind loads. The kinetic energy of wind hitting a building converts into pressure. This can be expressed as follows:

$$F_w = P_d A = 1/2\, \rho\, v^2 A$$

Wind velocity (v) increases with height (Figure...), meaning wind forces increase quadratically per elevation.

For a weak concrete-glass connection in the panel, higher placement means this connection will fail more quickly in design terms.

As a design strategy, the amount of concrete-glass bonding should decrease with height on the building. The design boundaries illustrated in Chapter ... thus become smaller at greater heights, limiting the design freedom of a hybrid concrete-glass panel.

The size of the concrete or glass area in the hybrid panel is irrelevant here. It's the quantity of concrete-glass interfaces that receive more load per meter of height. In terms of transparency, this indirectly leads to a design that is more open at the bottom and more closed at the top of a building facade (see figure).

Interestingly, this contradicts consumer preference, as taller buildings typically demand increased transparency for better views.

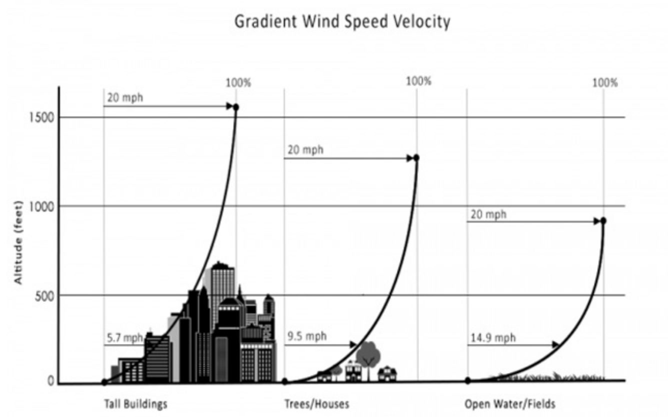


Figure 116: Wind velocity increase in height.

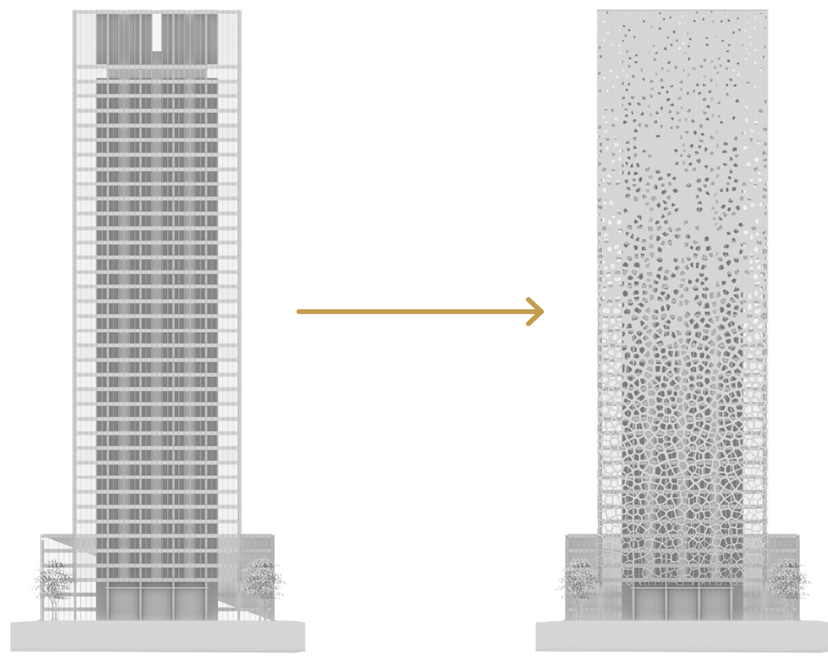


Figure 116: Design consideration of a more open facade at a lower height and. Reducing the interfaces in the top area of the building. Downside is a view obstruction.

7.3 INTERFACE DESIGN

In the design of a clamped panel, there is no shear stress at the center, and there are also regions where bending stress is absent (see figure 115). For a panel made of glass and concrete, it is desirable to have the glass-concrete interface at these locations, as this interface is the weakest part of the panel. By placing the interface in these areas, it will be subjected to minimal shear and bending stresses.

To identify the design zones for shear and bending stresses, tests are performed to determine the stress limit of the interface. This stress limit can then be translated into the shape of a facade panel, indicating the stress capacities and thus the design capacity.

The tests conducted include a 4-point bending test to determine the bending stress capacity and a direct shear test to calculate the shear stress capacity. The procedure involves placing a cast glass element in the center of a mold and pouring concrete beside it. The resulting beam has dimensions of 30x30x240 mm, consistent with the previous tests.

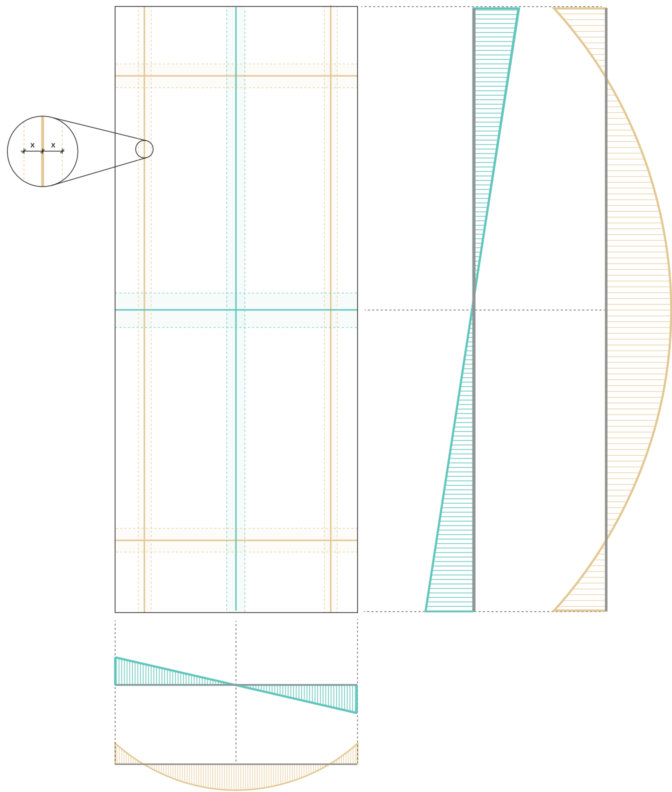


Figure 115: European standard truck dimensions for transport.

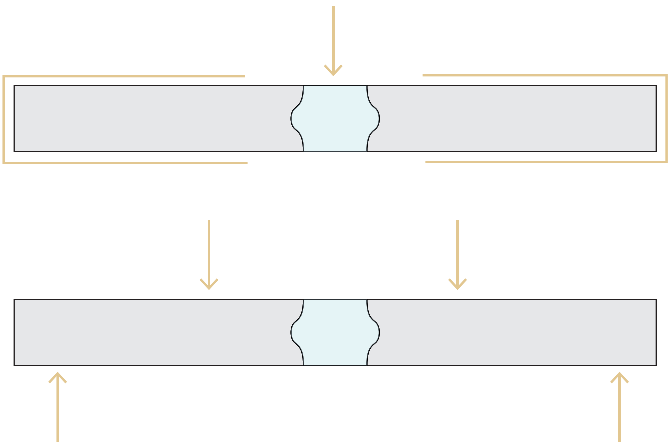


Figure 116: Visualisatio of a direct shear test (top) and a 4-point bending test.

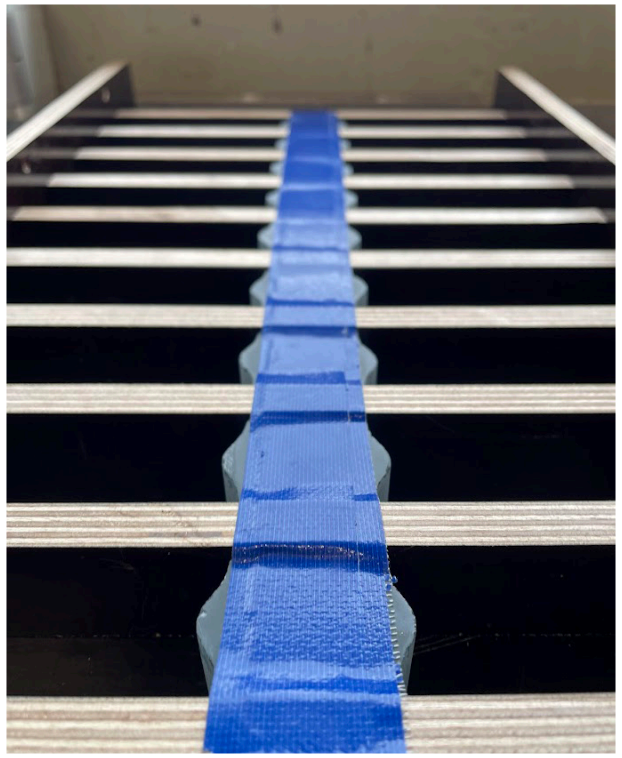


Figure 117: European standard truck dimensions for transport.

MATERIAL

For the cast glass element again float glass cullets are used and put in the oven at a temperature of 1120 C°.

For the concrete the same mixture is used as for the previous testing:

CEM III	- 450 gr
Norman sand	- 1350 gr
water	- 225 gr
Glenium 51	- 1 gr

INTERLOCKING

For the interlocking form, the belly shape has been favored as the application in a hybrid panel. In Chapter 5, only one type of belly shape was tested for interlocking strength. This shape has a significant impact on the behavior of the interlocking and adhesion strength.

The location of the belly, its width, length, and rounding radius are all variables that can be adjusted. Figure ... shows several possible belly shapes that can be applied. In Sombroek's (2016) thesis, a belly shape was also chosen as the optimal form for an interlocking cast glass bridge. Through structural validation, a belly width-to-length ratio of 1:2 with a radius of 12mm was selected as the best form.

In the design choice for an interlocking belly shape, a variant that closely aligns with these findings was selected.

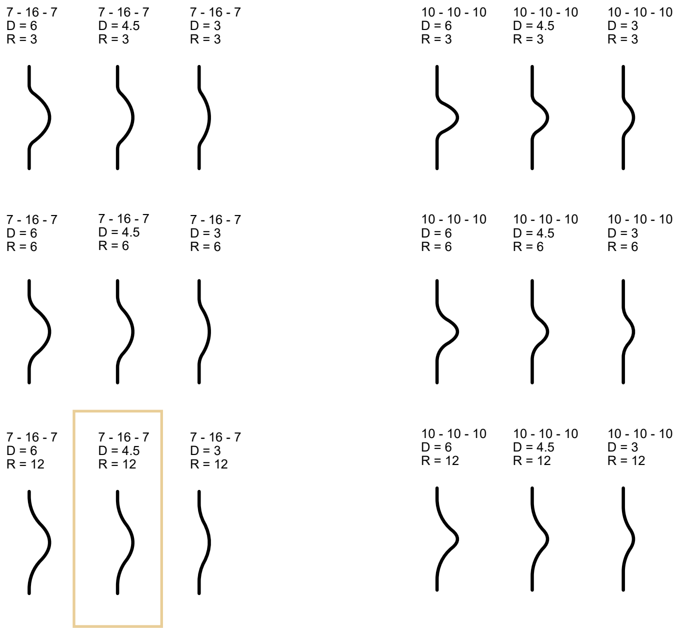


Figure 118: only a small part of various belly shape forms with different height, width and rounding radious.

Figure 119: Casted interlocking belly shaped glass elements.

To assess whether the belly shape accumulates excessive internal stress after melting due to unequally distributed mass, a polarized picture was taken to visualize the stress distribution within the glass element. The results indicate that the 90-degree angles exhibit the highest concentration of accumulated stress, while the stress within the belly shape is relatively minor.

The stress within the glass is unlikely to affect its strength or lead to failure, as the interface strength will always be lower. However, it is important to consider this as a point of attention for potential future design forms.

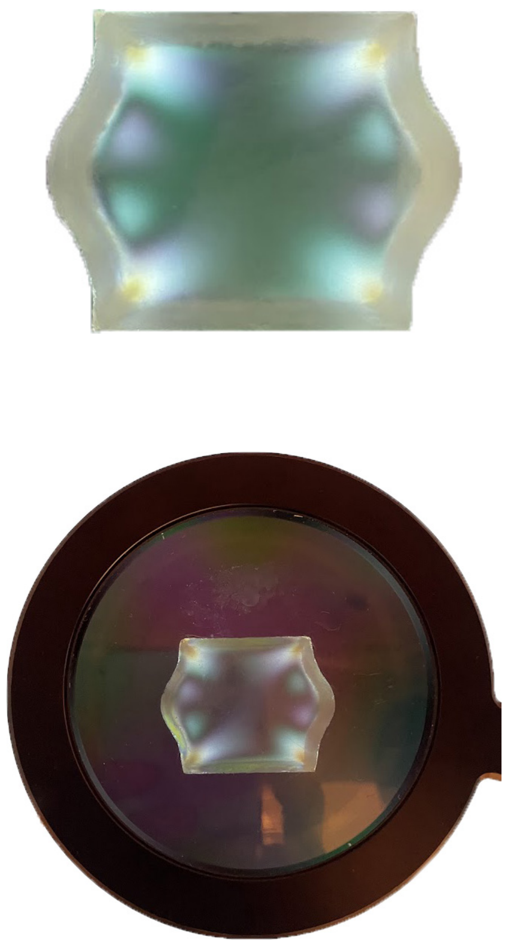


Figure 120: Polarised pictures of the belly shape cast glass element, introducing the highest internal stress in the90 degree angles and not in the belly.

SURFACE ROUGHNESS

Chapter 8 revealed that a grinded surface with grit 60 achieved the best adhesion percentage. Therefore, this was chosen to be applied to the interface surface of the belly-shaped glass elements.

The more complex shape, compared to a flat surface, immediately demonstrates that polishing is significantly more challenging. These more difficult post-processing steps indicate that the implementation phase for a hybrid panel will require additional manufacturing time thus costs.

Since polishing was performed with a rotating polishing machine, roughness was introduced in only one direction. This could potentially affect the adhesion of the concrete (see figure 121).

Figure 121: Polished interface surface with grit 60.

TESTING

After the concrete has cured against the interlocking glass element, one side of all specimens has detached. The detachment occurred at irregular locations.

One possible explanation for this is that the shrinkage of the concrete during curing did not occur towards the glass but rather away from it. Although the mould was oiled beforehand to prevent this, it remains a plausible explanation for the detached areas. Another possibility is that the polished surface, being polished in only one direction, resulted in poor adhesion. Since both interface surfaces underwent the same treatment, the first explanation is the most logical.

Due to the detachment and time constraints, the bending test could not be performed, so only a direct shear test was conducted on the nine specimens.

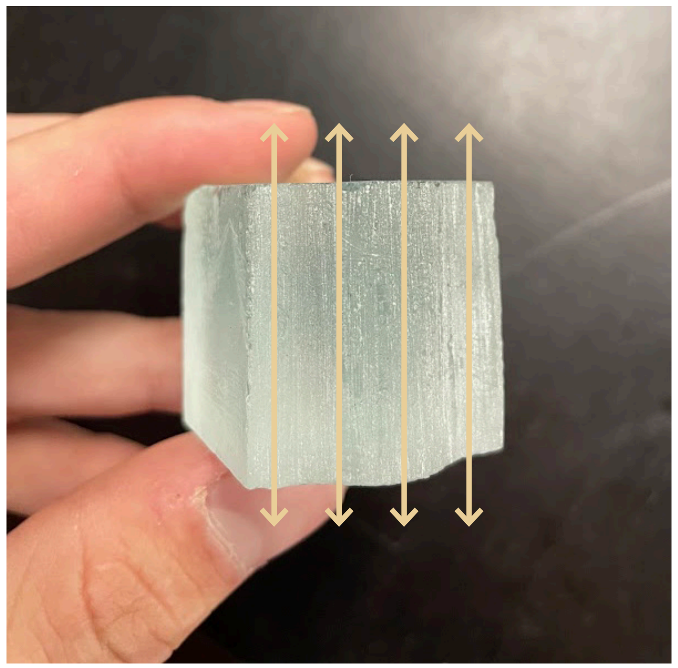


Figure 123: Horizontal polishing lines are visible due to one-way polishing.

Concrete shrinkage can cause stresses that pull the glass on one side, resulting in better adhesion on that side. Uneven shrinkage of the concrete during curing can create stresses and deformations that spread across the surface of the glass. These stress differences can lead to stronger adhesion on one side of the glass if the glass yields slightly under these forces.

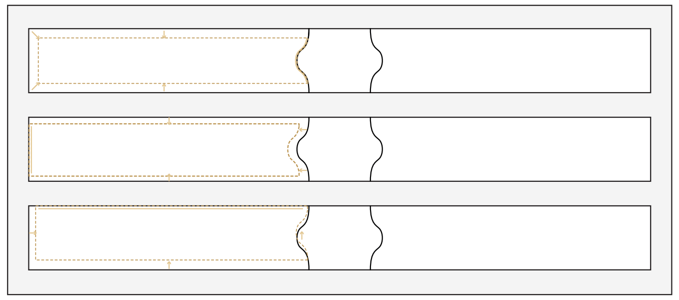


Figure 124: Drying shrinkage causing detachment of the conrete to the glass interface.

Figure 122: Deattachement of the concrete parts after demoulding the specimens.

OBSERVATIONS

De maximum shear stress of the facade panel is:

$$\tau = \frac{2625\ N}{38448{,}12\ mm2} = 0.0683\text{N/mm2}$$

The results from the tests show that this maximum shear stress can all be sustained (see table). With an average shear stress capacity of:

τ = 0,567 N/mm².

It is also observed that there is strong interface adhesion, causing the fracture not only at the interface but also in the concrete. Four out of the nine specimens exhibited a serrated interfacial failure (see figure 126). This could be attributed to the short 7-day curing period of the concrete, which might not have reached its full strength yet. a serrated failure mode after a direct shear test can suggest strong adhesion between concrete and glass, with effective adhesion strength, interlocking, and consistent performance across loading levels:

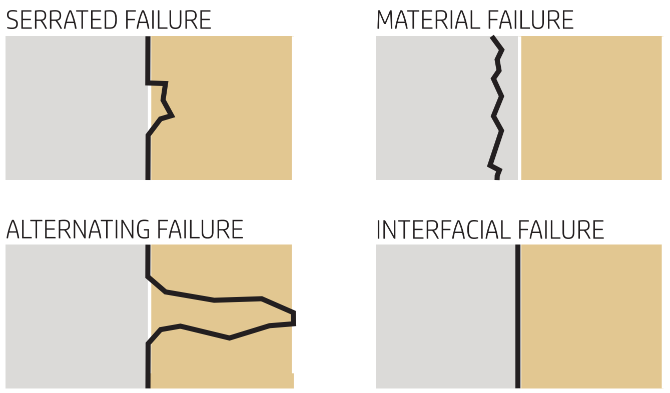


Figure 126: Schematic illustration of different failure modes possible after direct shear test.

- Interfacial interaction: The occurrence of a serrated failure suggests a significant degree of interaction between the concrete and glass at the interface thus an effective bonding between the materials. The adhesive forces between concrete and cast glass effectively absorb energy before seperation, allowing the interface to deform gradually beofre failure
- Interlocking: The alternating periods of stress build-up and serrated failure may indicate that the interlocking form contributes to the interface strength between the two materials. This implies the formation of physical anchorages at the interface.
- Consistent performance: A serrated failure mode can also indicate consistent adhesion between concrete and glass across different loading conditions. This gives confidence in the durability and reliability of the interface.

The challenge with the test results is that while some specimens exhibit good adhesion and shear strength, others show very low adhesion strength. When examining the photos of the various specimens (see appendix), there is little to no visible difference on the exterior of the different specimens.

The bonding strength remains uncertain until it is tested, making it difficult to design with due to the high uncertainty and associated risk factor.

For the design area, all results were considered, including the specimens with low adhesion strength, to obtain a more comprehensive understanding of the average strength.

What was noticeable during the tests is that specimen nine broke quickly at the interface with a low shear force. However, due to the interlocking form, the glass remained embedded in the concrete (see figure 129). Therefore, the interlocking shape not only contributes to structural improvement but also adds constraints.

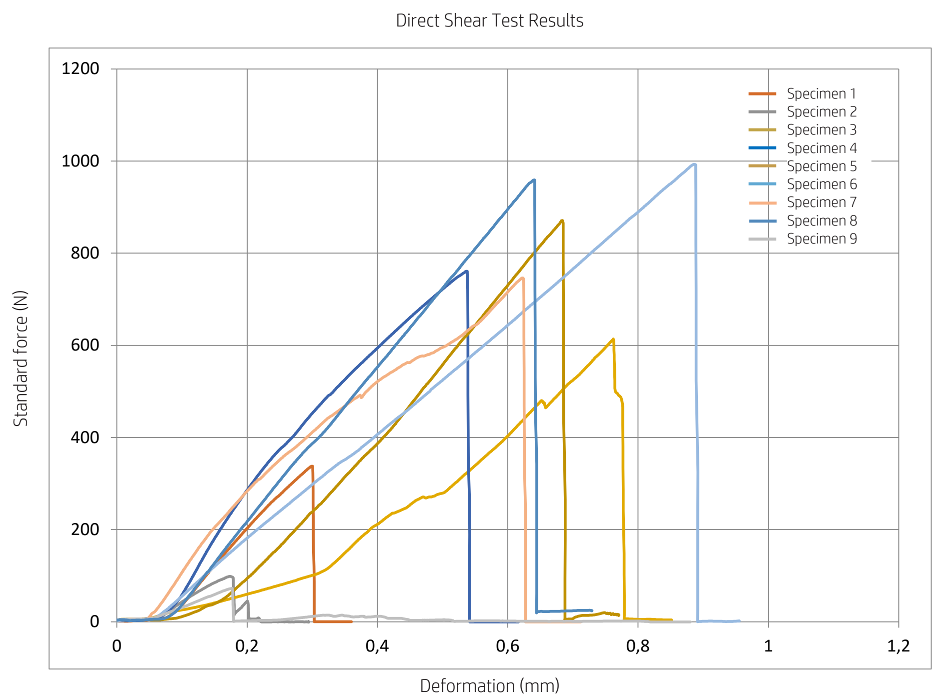


Figure 130: Table of test results of the nine specimens after direct shear test.

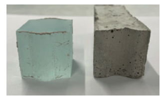
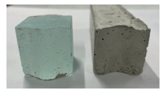
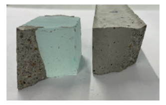
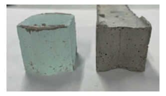
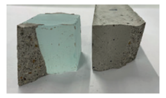
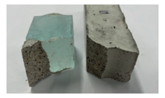
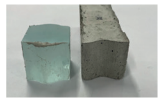
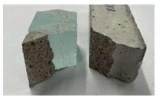
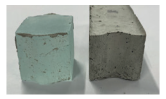
	Failure mode		F_{max} N	Dl at F_{max} mm	Shear stress MPa
Specimen 1	INTERFACIAL		337,83	0,30	0,3515
Specimen 2	INTERFACIAL		98, 61	0,174	0,1026
Specimen 3	SERRATED		613,65	0,762	0,6384
Specimen 4	INTERFACIAL		760,66	0,536	0,7914
Specimen 5	SERRATED		870,73	0,684	0,9059
Specimen 6	SERRATED		992,98	0,885	1,033
Specimen 7	INTERFACIAL		746,16	0,623	0,7763
Specimen 8	SERRATED		958,85	0,641	0,9976
Specimen 9	INTERFACIAL		72,56	0,177	0,0755

Figure 128: Overview of the test result and failure mode after a direct shear test for the nine specimens

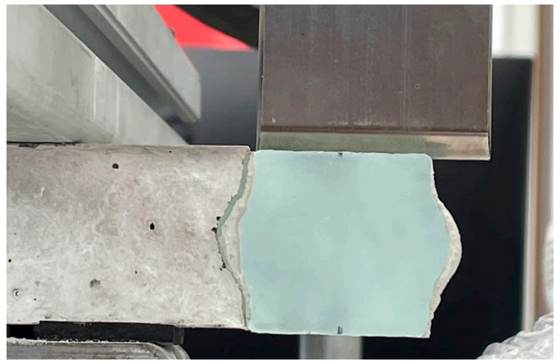


Figure 129: Interlocking shape contributes to movement constraints.

CONCLUSIONS

While the specimens tested in the direct shear test do not provide enough data for statistical evaluation and are not conclusive for determining mechanical properties, they offer an initial insight into performance. The result of the test conclude the following which need to be taken into account for durther design implementation and research:

- successful interface adhesion was achieved on only one side of all specimens. This issue is likely due to concrete shrinkage. Since the mold is oiled to prevent concrete from sticking, it is probable that the problem lies with the glass components. If the glass is not securely fixed within the wooden mold, concrete shrinkage can cause the glass on one side to move, resulting in better adhesion on that side due to reduced stress. Therefore, ensuring the glass components are firmly fixed in further testing is crucial.

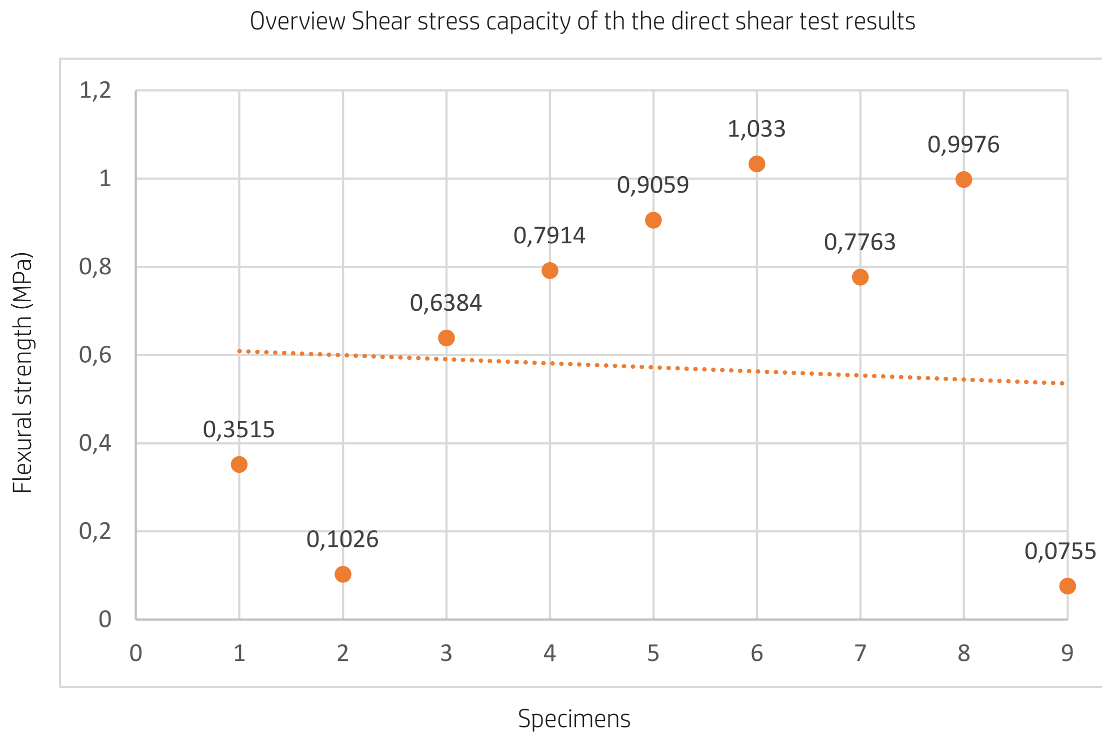


Figure 128: Overview of the test result and failure mode after a direct shear test for the nine specimens

- The serrated failure mode of the interface indicates a failure in the concrete, which should not be the weak link. Properly mixed and cured concrete should reach a strength of 52 MPa after 28 days. However, the concrete in this study achieved an average strength of only 1 MPa, likely due to the interlocking form creating thin sections prone to breakage and the concrete being cured for only 7 days. To enhance bond strength, a stronger concrete mixture is necessary.

- Despite the weak concrete, the serrated failure mode also suggests stronger adhesion strength and more successful interfacial bonding compared to initial experiments. These are the first steps for a hybrid interface and shows potential.

- Additionally, Specimen 9 exhibited non-brittle behavior, indicating that the interlocking form helps prevent sudden brittle failure. This design ensures that the glass is well-embedded in the concrete, contributing to better constraint and overall structural integrity.

- Microstructural variations within the concrete or at the interface with the glass, such as microcracks or differences in the distribution of aggregates, can lead to differences in mechanical performance. This can explain the different flexural strength of the specimens since the concrete mixture, glass compositions, surface roughness and production is the same.

RECOMMENDATIONS

In a direct shear test, deformation primarily involves shear deformation, whereas in a four-point bending test, both bending and shear deformations occur.

Furthermore, attention must be paid to the maximum deformation capacity. For this purpose, the Young's modulus of a hybrid specimen (comprising concrete and glass) is required. This will enable the calculation of the maximum deformation of a facade panel:

$$\Delta_x = \frac{wx^2}{24EI}(L-x)^2$$

The Young's Modulus can be determined using a DIC analysis by correlating the force data with the maximum displacement at the bottom middle of the beam. The formula associated with this is:

$$E = \frac{\Delta F}{\Delta l_{max}} \cdot \frac{\left(\frac{L_s - L_l}{2}\right)\left(3L_s^2 - 4\left(\frac{L_s - L_l}{2}\right)^2\right)}{4 \cdot w \cdot h^3}$$

Due time limitations is a DIC analysis not possible for this research, but would a recommendations for optimizing the interface design boundaries.

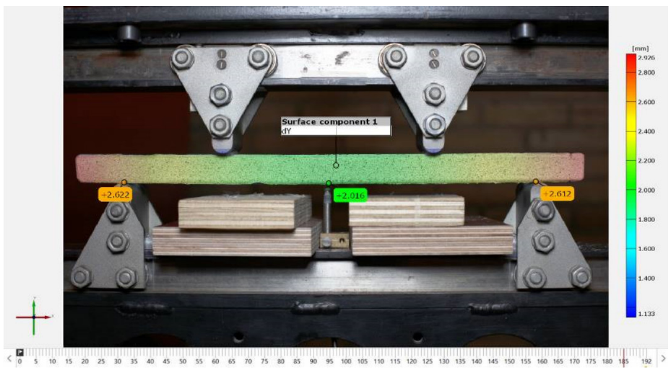


Figure 127: Bristogianni (2022) showed how to measure the displacement in the Y direction, by analyzing the images using the ***GOM Correlate*** software.

SHEAR + BENDING MECHANICAL TESTING

In the final experiment, an interlocking hybrid interface will be tested again. The interlocking shape remains the same as before, but the surface roughness differs. The roughness was manually created using a Dremel to make grooves, providing a rougher surface compared to polishing with 60 grit. In theory, this should result in better adhesion and bond strength. Eight specimens were made and will be tested using a four-point bending test and a direct shear test, with four specimens allocated for each test.

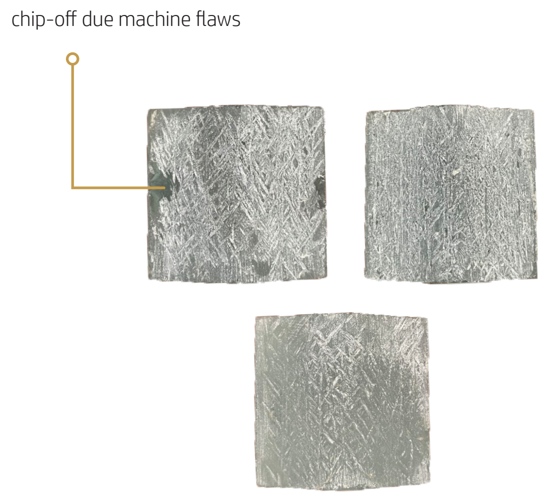


Figure 127: Increasing the roughness manually with a dremmel on the glass surface of an interlocking glass element.

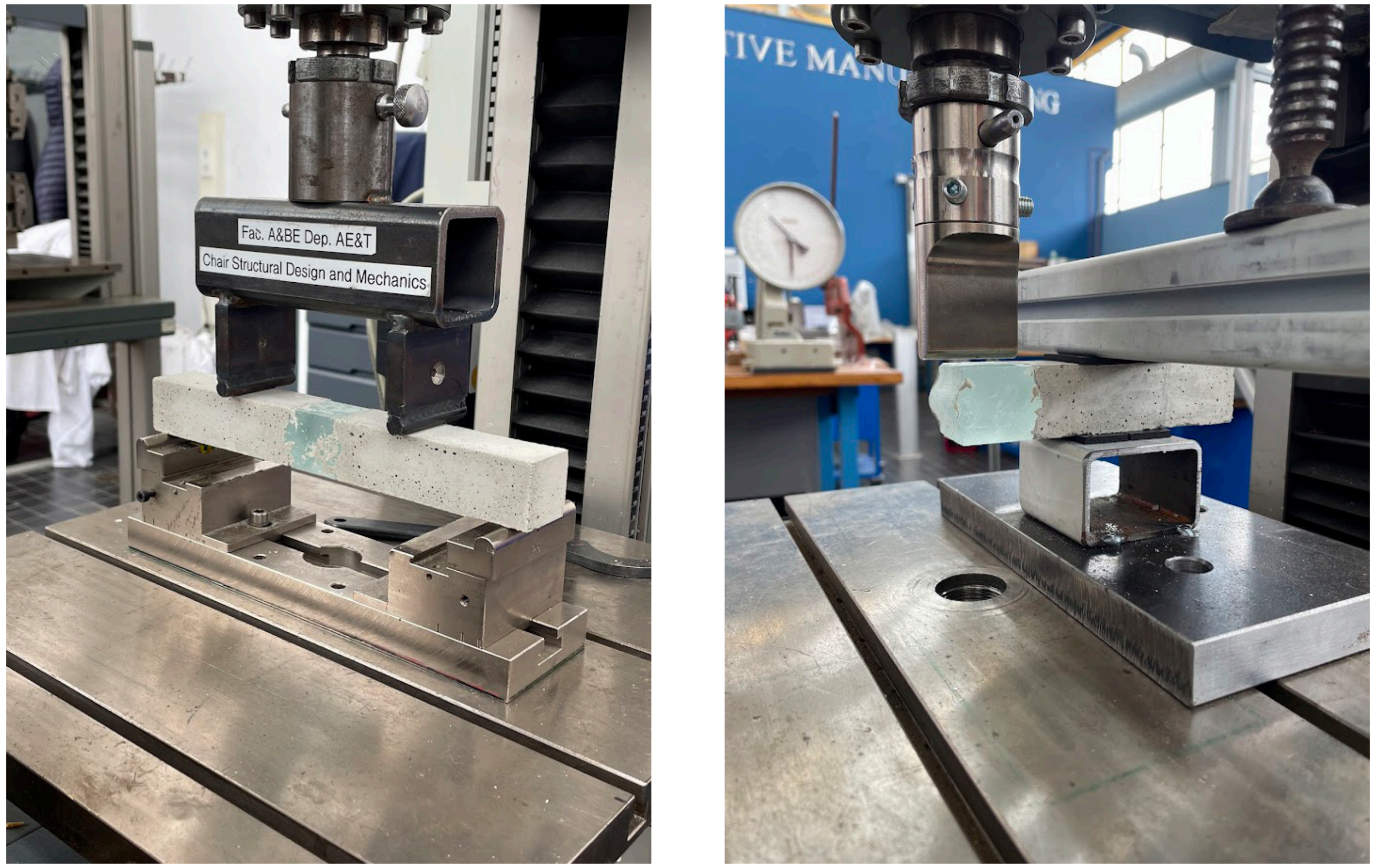
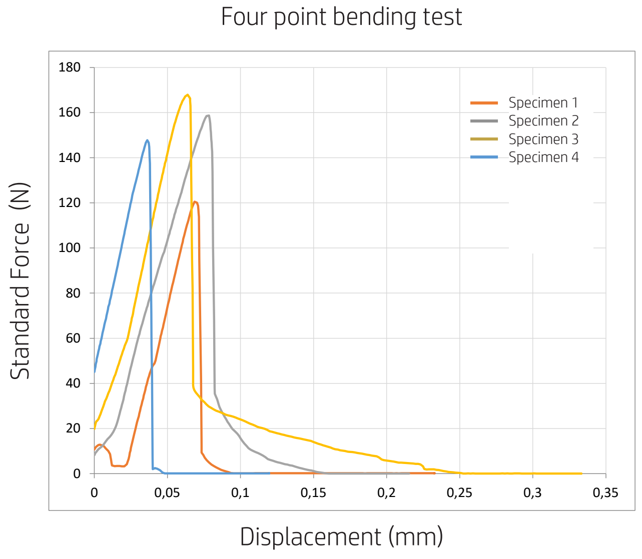
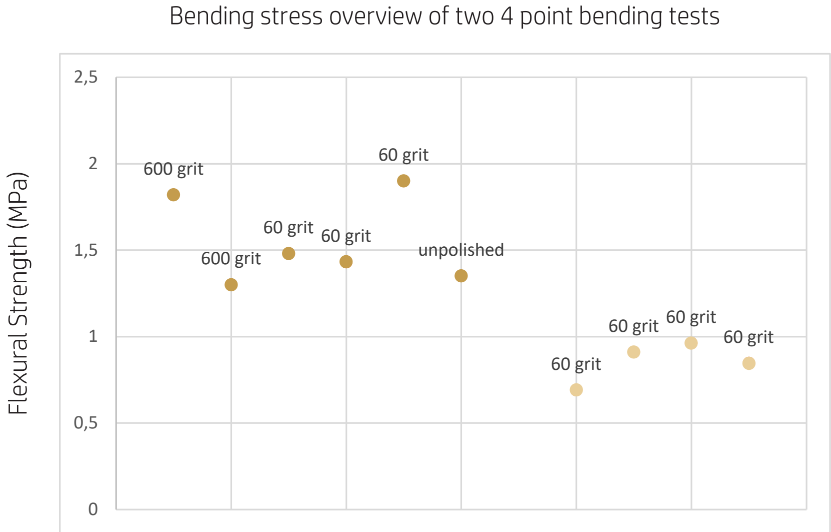


Figure 127: Left: 4 point bending test with an interlocking glass pieces surrounded by concrete.Right: A direct shear test by clamping the concrete part and applying pressure on the glass part.

CONCLUSIONS BENDING:

- the consistent breaking of only one side of the glass-concrete interface in all specimens indicates localized weakness or stress concentration at that particular interface side.
- Test 2 showed a lower bending stress capacity primarily due to the presence of two interfaces.
- The concrete shrinkage during curing is likely to be responsible for the stress in one side. Increasing the glass cross-section helped mitigate this pulling effect caused by shrinkage forces.
- the bending stress capacity remains insufficient for implementing a full-scale facade panel. Increasing the panel thickness is crucial for enhancing its strength.
- all specimens exhibited non-brittle failure, indicating that the interlocking form contributed to preventing sudden brittle failures





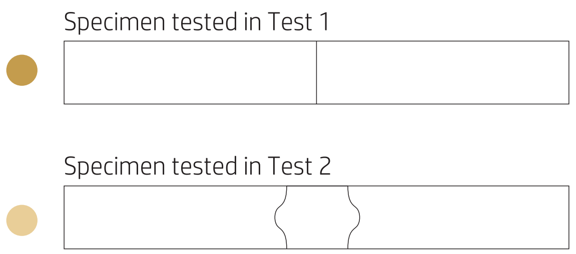
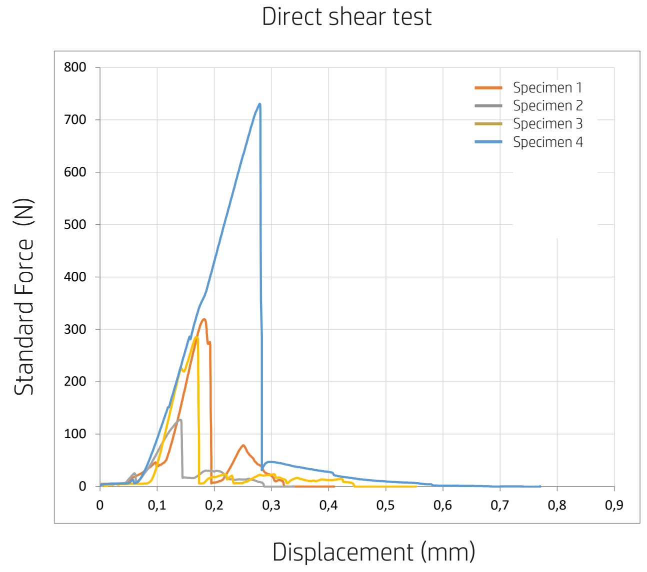


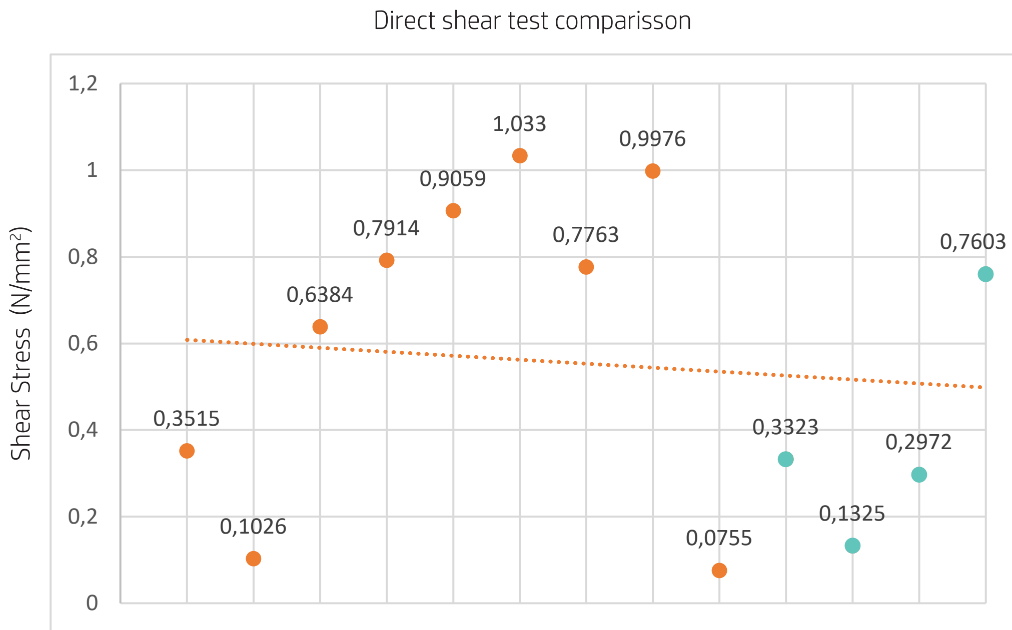
Figure 130: Overview of the two 4 Point bending tests. Test 1 resulted in a higher average flexural strength but only consists one interface. Test 2 results in a lower interface bending strength.

CONCLUSIONS SHEAR:

- The test results indicate that the glass surface roughened with a 60 grit polishing machine, despite having lower surface roughness compared to the manually carved surface, exhibits a higher shear stress capacity (flexural strength).
- A higher surface roughness alone does not necessarily correlate with higher shear stress capacity in the glass-concrete interface. Other factors such as the method of roughening (machine-made vs. manual) and possibly the uniformity or nature of the roughness pattern may influence the interfacial shear strength more significantly.
- The method of surface preparation (machine-made vs. manual roughening) significantly affects the shear stress capacity of the interface.
- The results suggest that the quality or nature of roughness (how the roughness is distributed or structured) may be more critical than the sheer quantity (depth or height) of roughness when it comes to enhancing the interfacial shear strength.



- The graph indicates that the glass part remains somewhat constrained within the concrete due to interlocking, even after detachment starts occurring
- Despite reaching a point of detachment, the interlocking form allows the glass part to continue bearing some load without fully breaking away from the concrete. This partial load transfer indicates that the interface can still provide some structural integrity and resistance to displacement even after initial failure.



60 grit polished in one direction

Diagonal cut with a dremmel

7.6 MANUFACTURING

7.6.1 3D PRINTED SAND MOULD

Glass castingwhich involves pouring molten glass into moulds, allows for the creation of monolithic glass components in nearly any shape and cross-section. However, in practice, the full potential of cast glass for architectural applications remains largely unexplored (Oikonomopoulou et al., 2020).

Choosing the right manufacturing method can also minimize the need for post-processing, thereby reducing manufacturing costs and production time (Oikonomopoulou, 2019). The selection of the mould is crucial and depends on the number of identical elements required and the desired precision. For hybrid designs, the choice of mould is influenced by the architectural design.

When designing a repetitive pattern or a panel with identical glass elements, casting in a permanent steel mould is preferred. For mass production, steel or graphite moulds, known for their high accuracy, are the best choices. Steel moulds provide high precision (±1 mm tolerance) and eliminate the need for extensive post-processing (Goppert et al., 2008). Additionally, a repetitive component geometry simplifies production and assembly, reducing manufacturing costs due to the limited number of high-precision steel moulds required and a standardized production process.

In contrast, a free-form design pattern involves unique glass elements, each requiring a unique mould per panel. Disposable molds are more efficient for single component or small batch castings, as they are significantly cheaper than permanent moulds, making them the preferred choice for free-form designs (Oikonomopoulou, 2019).

Since this thesis focuses on creating free-form transparency, the manufacturing process for disposable moulds will be elaborated upon.

There are several options for disposable moulds; however, this thesis selects 3D-printed sand moulds as the most promising choice for the industrialization of hybrid panels. This section will explain the reasons behind this selection in detail.

For unique, complex, or variable components, disposable moulds should be chosen due to their low manufacturing cost, despite requiring more preparation time and post-processing. A promising technology in this area is the use of 3D-printed high-accuracy sand moulds. Research and experimental work by Bhatia (2019), Damen (2019), Ioannidis (2023), and Oikonomopoulou, Bhatia, et al. (2020) on 3D-printed sand molds (3DPSM) for glass casting has shown promising results, highlighting the potential of this method for customized solid glass components. The main advantages of 3DPSM are their low manufacturing cost, high precision, and size accuracy, along with relatively short production times.

The high level of accuracy and size precision of 3DPSM offers significant potential for creating desired interlocking shapes in complex free-form geometries for hybrid panels. Small-scale surface roughness patterns with superior precision can be incorporated into the mould design

Currently, the need for manual post-processing (polishing) to address surface roughness is a drawback of this manufacturing method (Ioannidis, 2023). Applying coatings to the mould can improve surface quality and reduce its roughness. In this thesis, the surface roughness resulting from an uncoated sand mould can actually benefit the interlocking surfaces of a glass unit in a hybrid composition. For producing glass elements with specific roughness for interlocking surfaces and better surface quality on exterior surfaces, 3DPSM with coatings applied to specific areas offers an effective solution for manufacturing free-form glass units.

Due to limited time in this research, it was not possible to prove that a certain roughness on the glass surface, resulting from the use of sand moulds, improves adhesion to concrete. In theory, this offers potential and warrants further investigation.

Several design considerations must be taken into account when designing a 3D-printed sand mould (3DPSM). Based on literature, investigations, and thesis work, the following actions should be considered:

- The maximum printable size for a sand mold is 2200 x 1800 x 600 mm (ExOne, 2021). For larger pieces, the mould can be split into sections, which also facilitates the release of the glass unit after casting (Ioannidis, 2023). Since the sand mold consists of two positive halves, it requires holes for clamping the molds together.
- Anopeningforpouringmoltenglassintothemould. Vent pipes to prevent air bubbles from being trapped inside the mould.
- Avoidance of sharp edges.

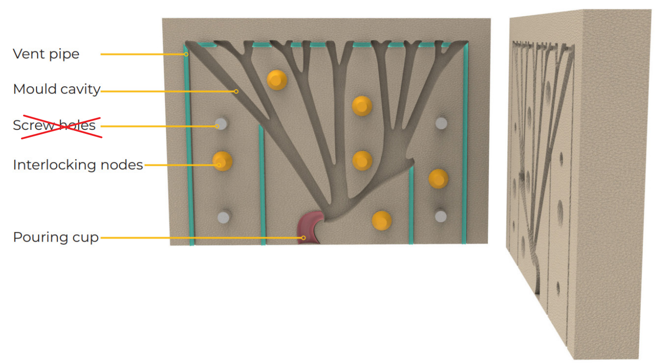


Figure 140: Design considerations of a 3D printed sand mould implemanted for a final design (Bhatia, 2019).

- A minimum thickness of 3 to 4 mm in any section of the mold, with an added thickness of 15 mm around the periphery of the geometry (Bhatia, 2019).
- Application of coatings for high surface quality. For the best surface quality of glass when using kiln casting as production method, Arkopal B 5 is the most promising and results in the highest surface quality (Ioannidis, 2023).
- Use an outer frame to constrain the interlocking sand mould pieces. Stainless steel nuts and bolts will fuse and make it impossible to unlock the mould (Bhatia, 2019).

Figure 140: Avoid using bolts and screws. They will fuse and can't be removed, making the demoulding process impossible (Bhatia, 2019).

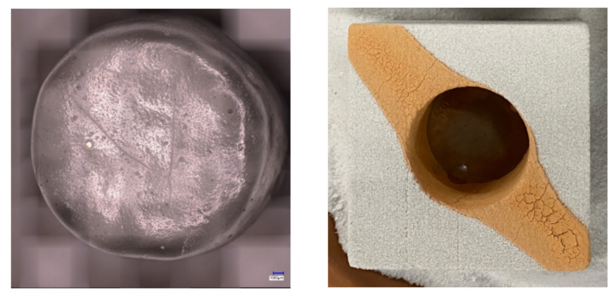


Figure 140: Arkopal B 5 as most promising coating on quartz sand mould, with an annealing schedule at 807 °C conducted in thesis work of (Ioannidis, 2023).

This part will discuss the method used to create cast glass elements for a hybrid facade panel, highlighting its potential for implementation in the built environment.

3Dealize, Concr3de, Voxeljet, and ExOne are companies that have already utilized this technology to cast complex metal objects.

Traditional sand moulds require two positive halves, which is a common approach used in hot pouring or kiln casting (with a flowerpot). In these kiln cast method, the heavy weight of the flowerpot on the weaker sand mould can cause the mould to break in the oven as it becomes weaker when heated (Bhatia, 2019). However, this design innovatively uses cullets directly laid into the sand mould, requiring only one positive half. This method prevents the mould from breaking in the oven, ensuring greater stability and reliability during the casting process.

The production of the sand mould can be described in five steps (figure ...) (ExOne, 2021).

Figure 140: Breakage of the sand mould during firing due the weight of the flowerpot and the weaker sand mould (Bhatia, 2019).

File preparation (1)
A digital file is processed in preparation software, sliced into print layers, and transferred to the machine as a print-ready file.

3D printing (2)
For each layer, a thin layer of fine sand is applied on the printing table where a liquid binder agent is selectively applied by a computer-controlled head. The process is repeated until the object is complete. By applying binder only on the negative of the object the final mould is produced.

Microwave curing (3)
The print is placed in a microwave oven for drying. This is considered better than a conventional oven as requires less time and allows for more reliable drying from the inside out.

Automatic desanding (4)
Excess sand is then removed at first using an automated process

Finishing (5)
Fine de-sanding is performed manually with the use of pressurized air.

1 → 2 → 3 → 4 → 5 →

File preparation | 3D Printing | Microwave Curing | Automatic Desanding | Finishing

Figure 140: Production Line of a 3D printed sand mould by (ExOne, 2021).

Utilizing a desanding station and microwave, this production line becomes cost-effective and allows for the connection of multiple printers in a manufacturing cell (see figure). The integration of robotic core removal, fine desanding, and quality inspection further enhances the process, opening opportunities for expanded automated processing. This makes it highly scalable for the industrialization of freeform customized glass components in the built environment (ExOne, 2021).

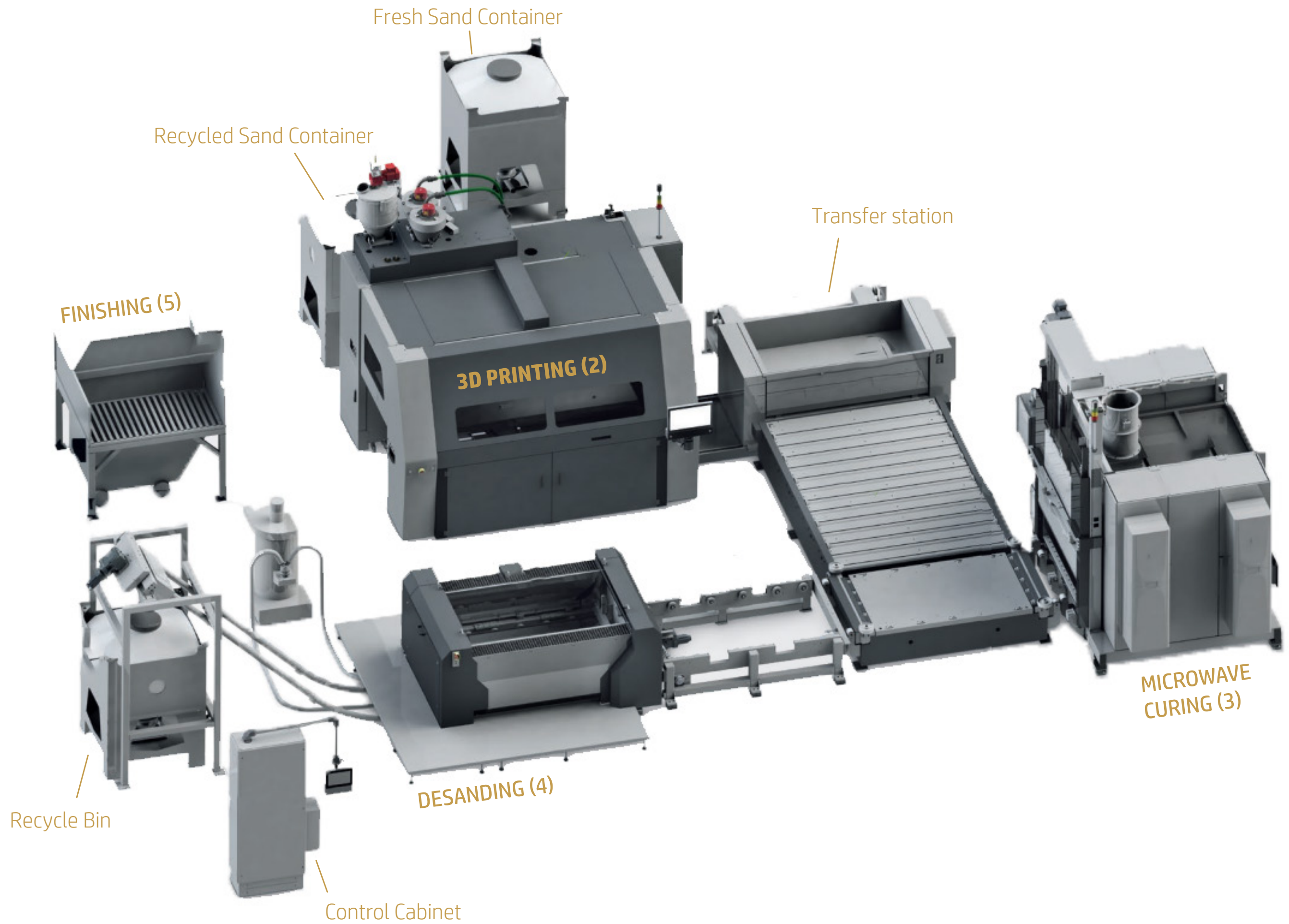


Figure 140: Automated Production Line of 3D Printed Sand Mould (ExOne, 2021)

7.6.2 KILN CAST GLASS MANUFACTURING

After the sand mould is printed, glass cullets are placed on top of the mould and melted inside an kiln-oven. The aesthetic appearance of the solid cast glass unit is determined by the selection of cullets.

In the experimental part of this thesis, fully tempered float glass was utilized, processed at a firing temperature of 1120 degrees Celsius. Initial findings from the interlocking interface analysis indicated promising potential; however, the bonding strength observed was still insufficient for practical implementation. That is way exploring alternative glass compositions is still a viable design option.

Soda-lime glass was specifically selected due to its favorable matching of thermal expansion properties with concrete, a crucial consideration in structural applications. So alternative soda-lime glasses are preferred for further exploration. Art glass is one of those possible good alternatives. It has a formulated soda lime composition, and it can melt at a lower temperature (which is also more sustainable). Discussed with Bristogianni, she explains the ease of manipulation by artists of art glass. This glass is "soft" and is easier for artists to manipulate it. To do so, they usually add more flux and then a bit of alumina to compensate for the mechanical properties. flux are usually alkali (Na_2O, K_2O, Li_2O), which can also contribute to potentially mitigate the risks associated with alkali-silica reaction (ASR).

A more sustainable approach for a glass compositions is chosing recycled cullets. Although the interface of concrete with recycled glass is not validated, it shows good sustainability potential. Various companies, such as Maltha Recycling Nederland, AGC Belgium, and Magna Glaskeramiek, along with experimental procedures conducted at TU Delft, demonstrate the potential of using recycled glass cullets for kiln cast glass elements (Bristogianni & Oikonomopoulou, 2022).

Glass is in theory 100% recyclable (Oikonomopoulou, 2019). When crushed into cullet, it can be returned to the melting furnace and recycled indefinitely in a closed-loop process without any loss of its properties (Bristogianni & Oikonomopoulou, 2022).

Magna Glaskeramik, for example, produces cast glass panes from 100% recycled waste, which are fully recyclable back into the glass production cycle after use, promoting a circular approach to glass panel manufacturing. By sintering recycled cullets without the addition of binders or the use of pressure, and relying solely on temperature and time, panels made entirely of glass are created. The maximum panel size produced by Magna Glaskeramik is 3500 x 1500 mm with a thickness range of 15-40 mm.

For hybrid facade panels consisting of glass and concrete, the size limit of the glass parts is therefore 3500 x 1500 mm, as this is currently the maximum size accommodated by kiln cast ovens.

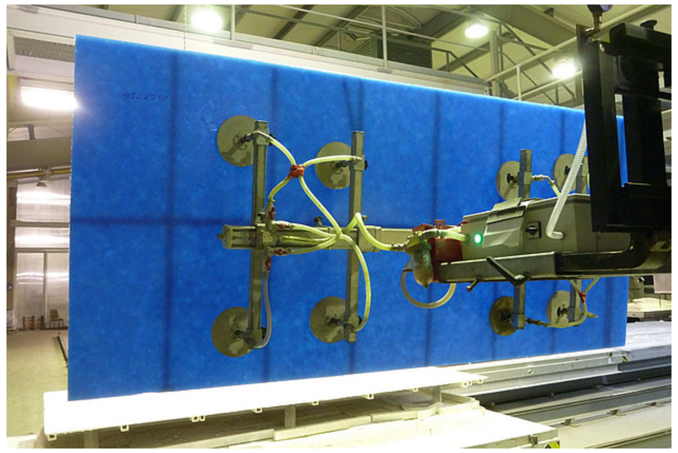


Figure 135: Maximum panel size (3500 x 1500mm) made from 100% recycled glass cullets by MAGNA Glaskeramik.

For the interlocking part of the glass elements, both tests and literature indicate that a higher level of macro-scale roughness is necessary. Barou (2023) demonstrated that a toothed saw pattern significantly enhanced both load-bearing and displacement capacities. This pattern should be integrated into new interlocking form designs. Figure [X] illustrates an innovative approach to the design process for an improved interlocking form that accommodates the limitations inherent in kiln-cast glass manufacturing.

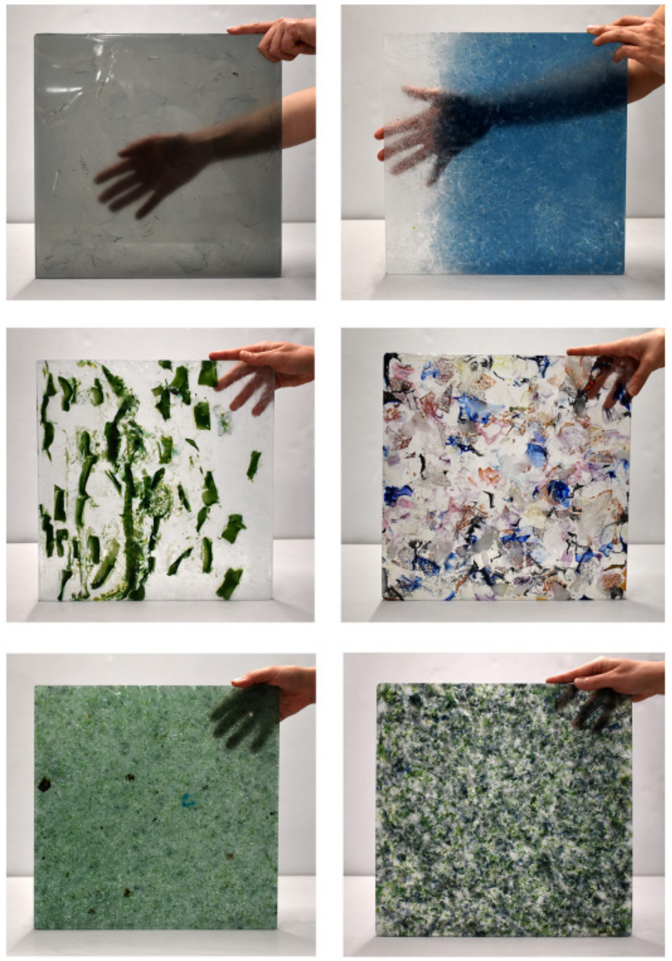


Figure 135: Bristogianni (2022) showing te possibliity of using recycled glass waste cullets for kiln-casting glass panels.

Additionally, this thesis explores how increased surface roughness improves concrete adhesion. Experimental results did not validate a strength improvement at the micro-level of surface roughness, highlighting an experimental gap that warrants further investigation. For instance, a more dimpled surface can significantly increase the contact area, thereby enhancing adhesion. Given the high-quality print capabilities of 3D-printed sand molds, such roughness features can be easily incorporated and imprinted into the design (see Figure [Y]).

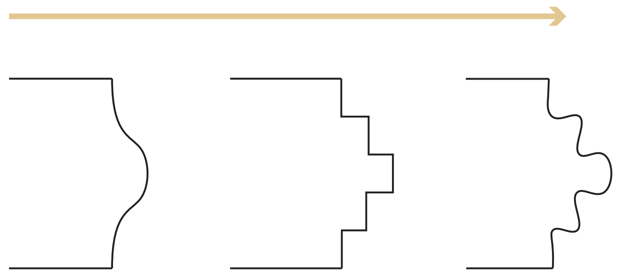


Figure 135: Example for a new interlock design based on the findings of the experimental part.

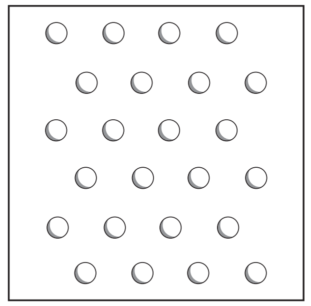


Figure 135: A dimpled surface increases the contact area and still keeps a round shape which is preffered for brittle materials and in cast glass manufacturing.

The hybrid design approach, without the use of additives, facilitates the disassembly of materials with minimal processing requirements, primarily involving filtering and cleaning. This streamlined process allows glass cullets recovered from disassembled panels to be reused for creating new hybrid panels, thereby promoting a circular design approach (figure..).

By avoiding additives in the production of hybrid panels, the materials retain their purity and integrity, simplifying the separation and recovery of glass cullets at the end of a panel's lifecycle. This approach not only reduces environmental impact by minimizing waste but also supports sustainable practices by continuously cycling materials back into production without degradation in quality or performance.

The production line for this process already exists and implements scalable industrialization of cast glass production in kiln ovens using desired cullets. This setup ensures efficient utilization of resources and consistent quality in the manufacturing of glass panels. By integrating advanced technologies and efficient processes, such production lines enable the transformation of raw cullets into high-quality glass panels suitable for making a hybrid facade panel. This approach not only supports sustainable practices but also meets the demand for customizable in combination with the 3D printed sand moulds.

Making the glass part for a hybrid facade panel hereby contributes to using environmentally responsible building materials in the construction industry.

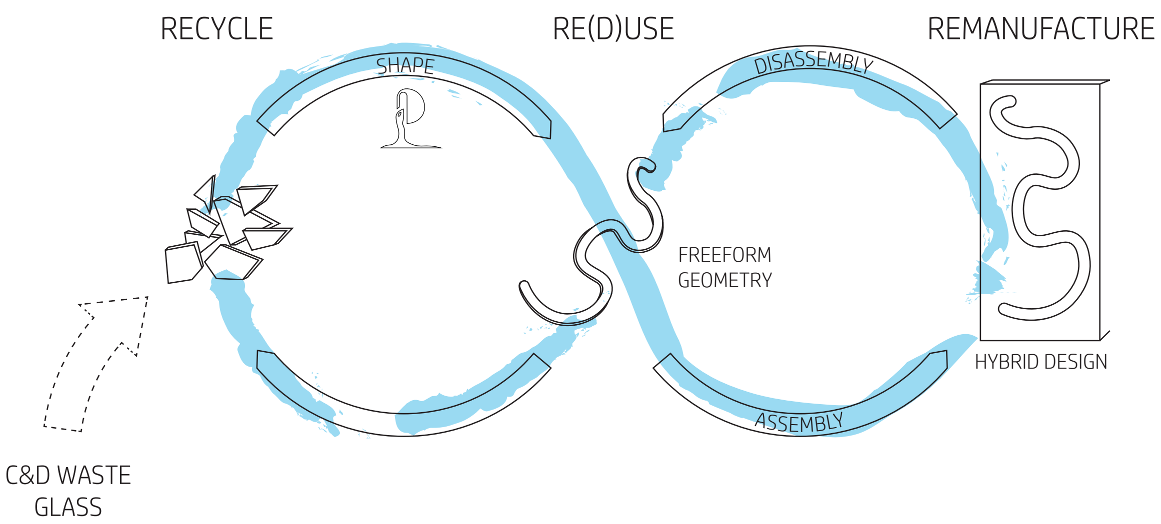


Figure 135: Closed loop diagram for the glass part of a hybrid facade panel.

7.6.3 CONCRETE MANUFACTURING

The selected concrete, ideal for industrialization and implementation, is a hybrid mixture of Glass Fiber Reinforced Concrete (GRC) and Ultra-High Performance Concrete (UHPC) with supplementary cementitious materials (SCMs) to mitigate the risk of Alkali-Silica Reaction (ASR). This approach is expected to produce façade panels that are not only structurally robust and aesthetically pleasing but also capable of withstanding prolonged environmental exposure.

However, the addition of plasticizers to increase workability must be approached with caution. Using plasticizers with an already workable UHPC composition can result in excessive fluidity, as observed in the initial experiments of this thesis. In these cases, the aggregates and cement separated from the water, leading to bleeding.

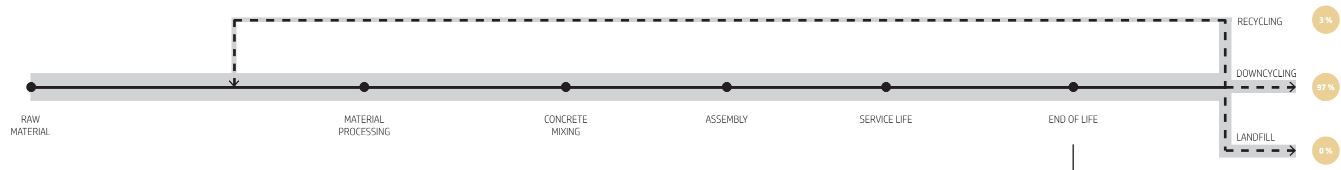


Figure 135: Current life cycle of concrete in the buidl environment used for facaed panels.

1) DE-CONSTRUCTION & DEMOLITION
2) TRANSPORT
3) WASTE PROCESSING
4) DISPOSAL

Figure 135: Industrialisation of a prefab concrete panel.

After the service life of the hybrid panel, the concrete component can be filtered, crushed, and recycled to supply cement for new concrete mixtures. This recycling process contributes significantly to the sustainability of industrial practices by reducing the need for virgin resources. According to research by Tam and Tam (2020), recycled concrete aggregates (RCA) from construction and demolition waste (CDW) can effectively replace natural aggregates in concrete production, thereby conserving natural resources and reducing landfill waste.

While this recycling approach marks a crucial step towards sustainability, it does not achieve a fully closed-loop system due to technological and logistical constraints in recycling all construction materials. Nevertheless, these initiatives represent important strides in managing CDW, a substantial global waste stream.

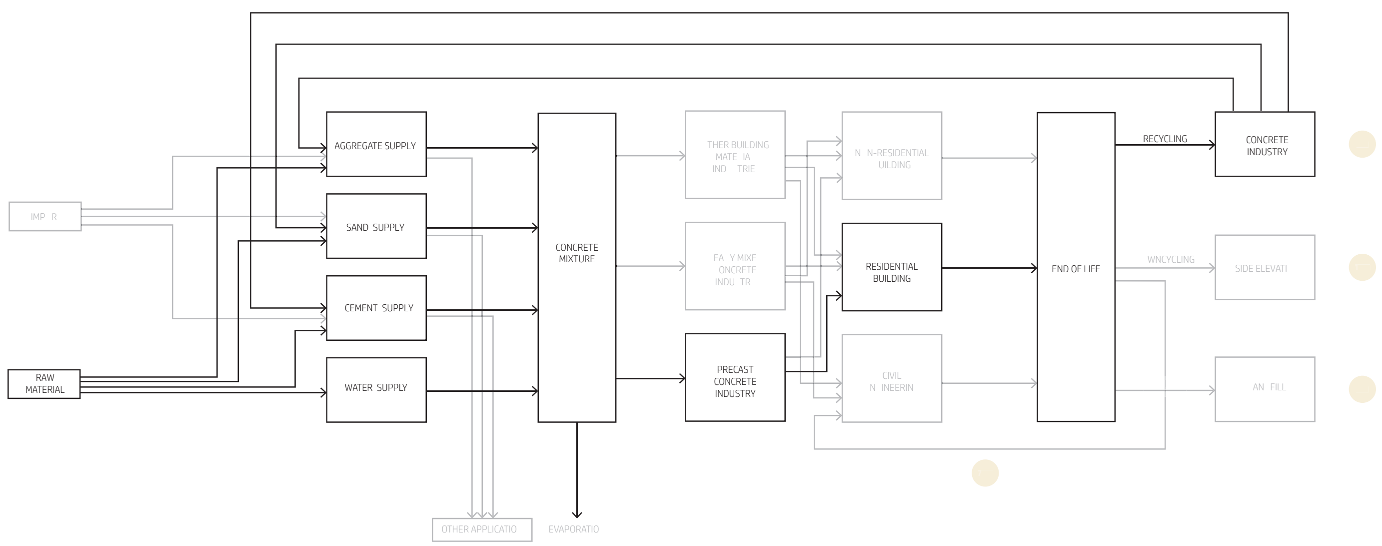


Figure 135: Closed loop diagram for the glass part of a hybrid facade panel.

7.6.4 ASSEMBLY ORDER

The construction of hybrid precast facade panels involves the integration of both concrete and glass elements, each requiring specific processes and temperature controls during their manufacture.This is crucial when determing an appropriate assembly sequence.

The glass used in this thesis, Soda-lime glass,has a melting point that typically ranges from 1350°C to 1400°C (see section 3.3). In contrast, concrete begins to lose its structural integrity at significantly lower temperatures. Research indicates that concrete experiences a substantial loss of strength and may undergo severe degradation when exposed to temperatures above 800°C (Neville, 1996).

The higher melting point of soda-lime glass compared to the thermal degradation point of concrete dictates that the glass component must be manufactured first. Once the glass has cooled and solidified, it can be incorporated into a frame, after which the concrete can be cast around it. This method ensures the structural integrity and optimal performance of both materials in the final hybrid precast facade panel.

An important aspect of designing a concept for a hybrid panel is the step by step production line. This showcases the assembly sequence for industrialisation. On the next pages the assembly order of a hybrid panel is shown.

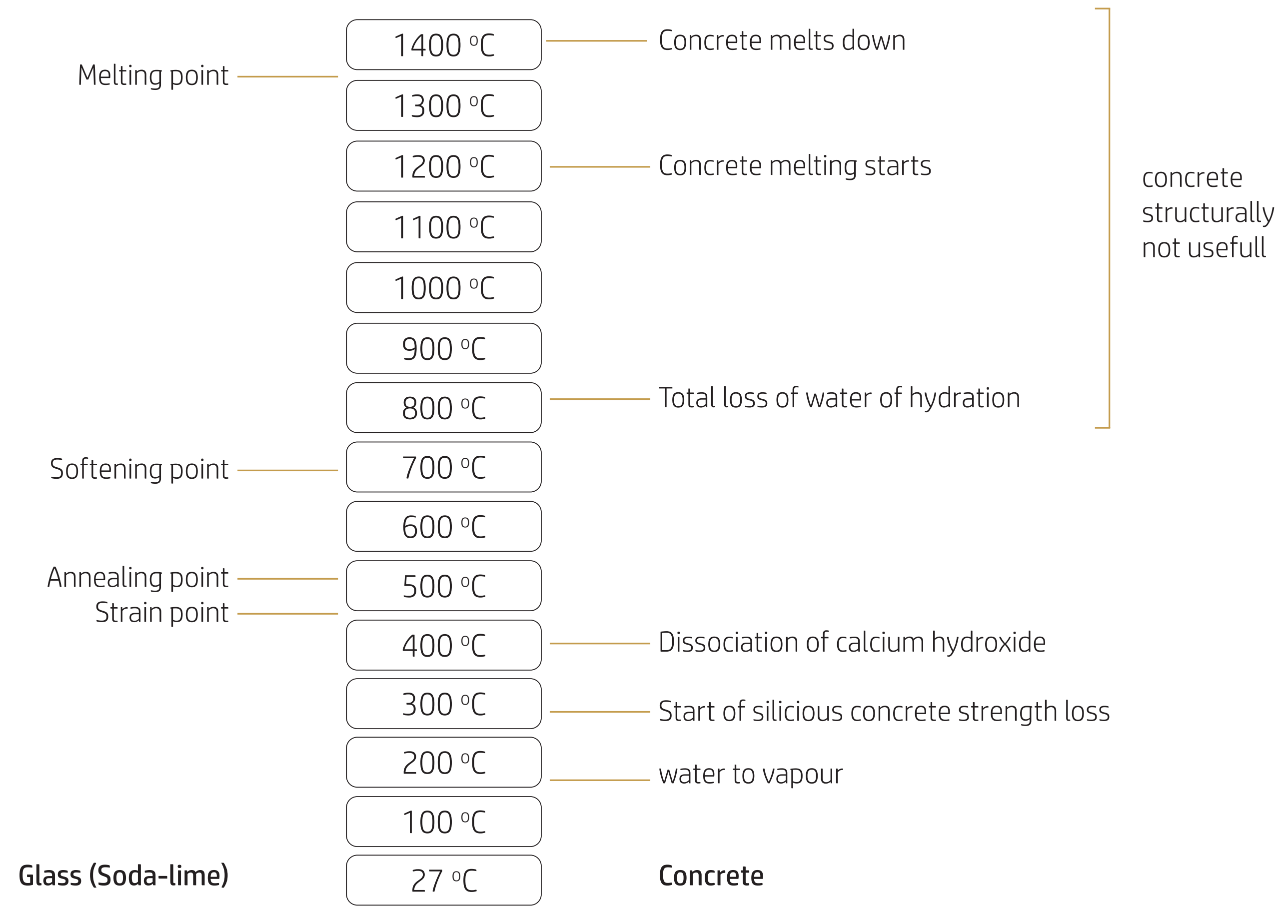
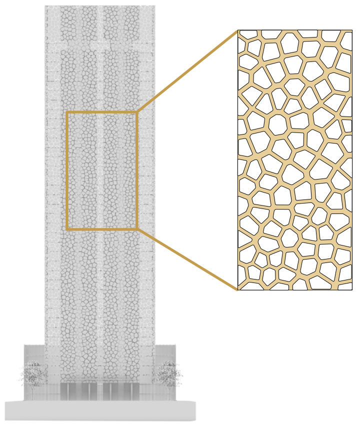
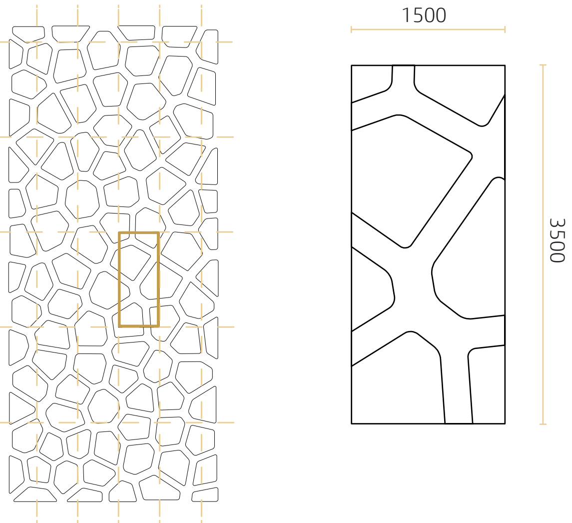


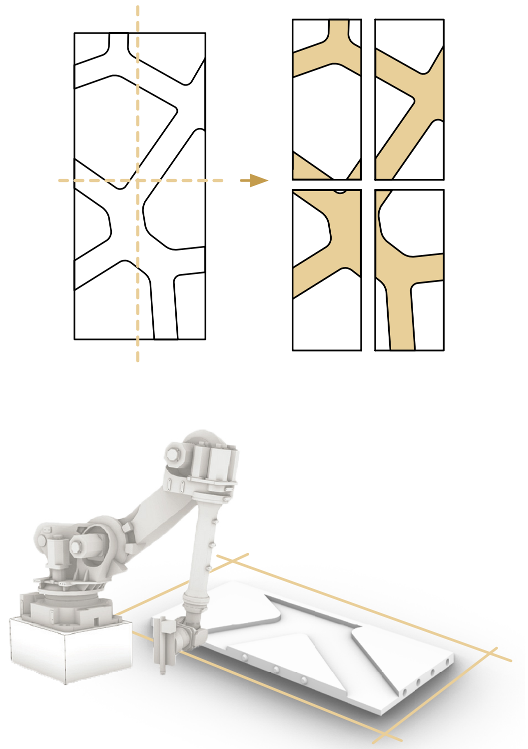
Figure 135: specific temperature properties for glass and concrete, showing the higher melting point of soda-lime glass compared to the thermal degradation point of concrete.



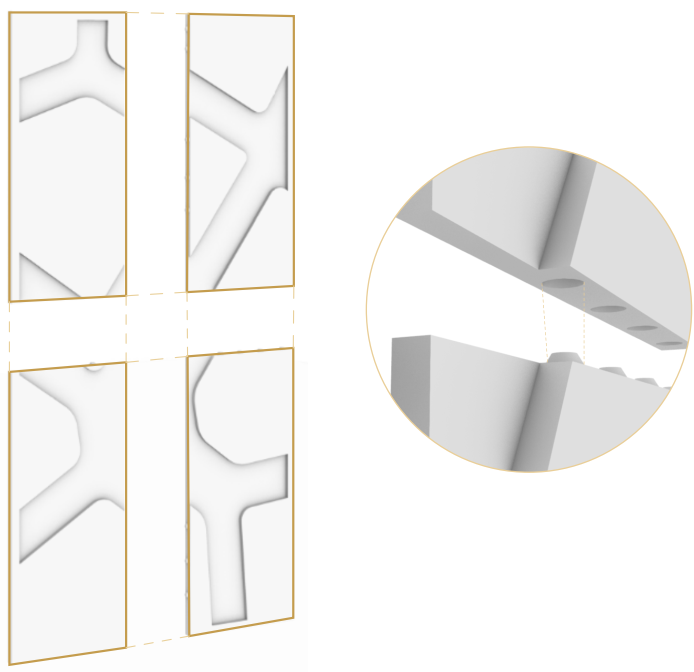
STEP 1:
the production process starts with a design of the facade.



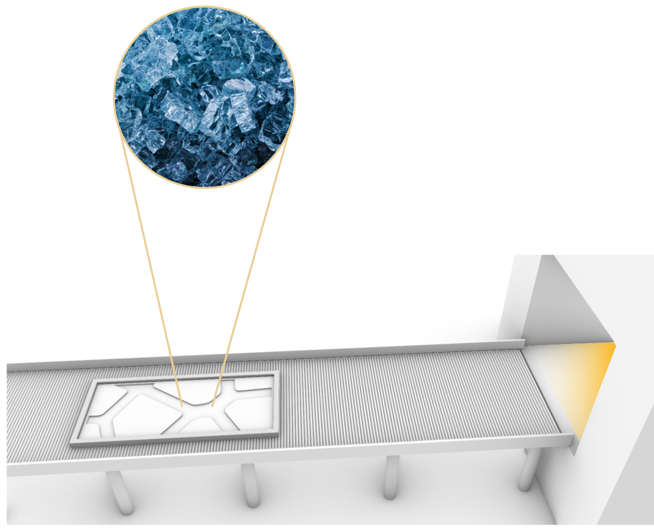
STEP 2:
The grit size of the facade panels is based on the maximum size of the Kiln cast oven by MAGNA Glaskeramik, which is 3500 x 1500.



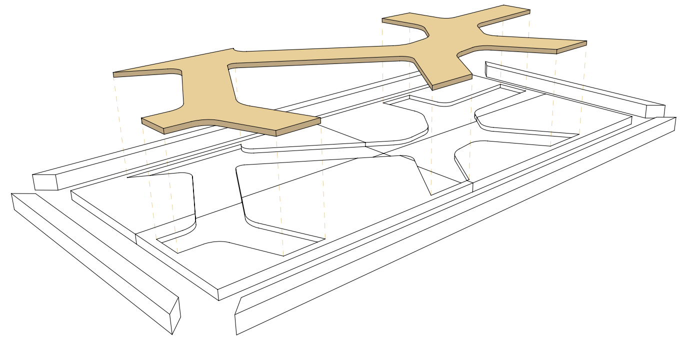
STEP 3:
Since the maximum mould print size is 2200 x 1200 mm the panel need to be divided into printable pieces. Moulds can now be designed with parameters (surface roughness & interlocking form) and printed.



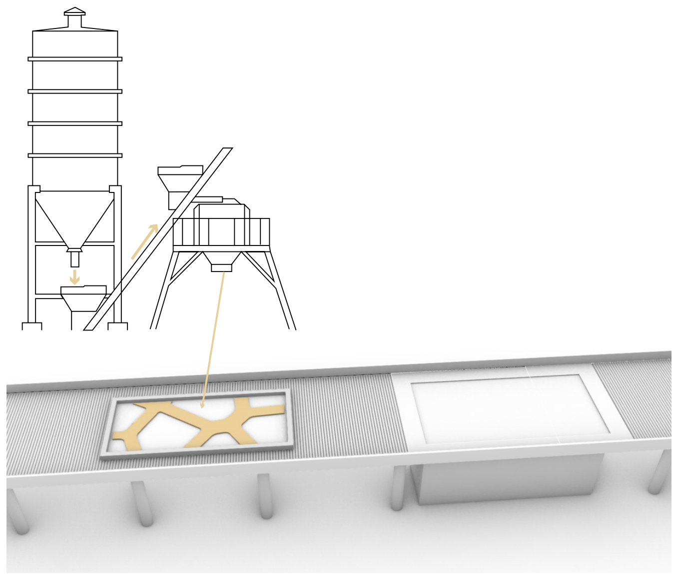
STEP 4:
After printing, the sand moulds can be assembled by using an interlocking nodes.



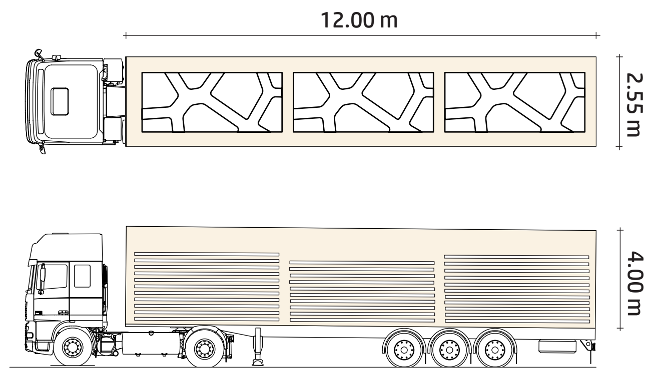
STEP 5:
The sand mould pieces are hold together by a fire resitant frame. The frame helps withstand hydrostatic pressure build up during casting. After connecting the frame, glass cullets can be placed inside the sand mould.



STEP 6:
After annealing and cooled down, demoulding starts. The glass element can now placed in the frame to pour concrete



STEP 7:
The glass element is fixed in a frame. Concrete is poured used a few milimeters above the glass element. After pouring the concrete is compacted. The glass is completely clamped so it wont vibrate when at the shaketable.



STEP 8:
If the panels are cured they can be finished. Polishing and inspectation. If they are checked they can be transported to the site.

The Seagram Building in New York City, standing at 150 meters tall, is an iconic example of an old fully glazed office building. Originally designed with single glazing, it faces sustainability challenges related to heat gain. To address this issue, the architect incorporated a sunscreen system that allows for three operational states: fully open, half closed, or fully closed. However, these sunscreens often obstruct views during the summer months.

To enhance its sustainability and aesthetic appeal, a curtain wall system is proposed for the existing facade. This new building skin would support a free-form design approach, both internally and externally, potentially improving thermal performance while maintaining or enhancing the building's visual appearance.

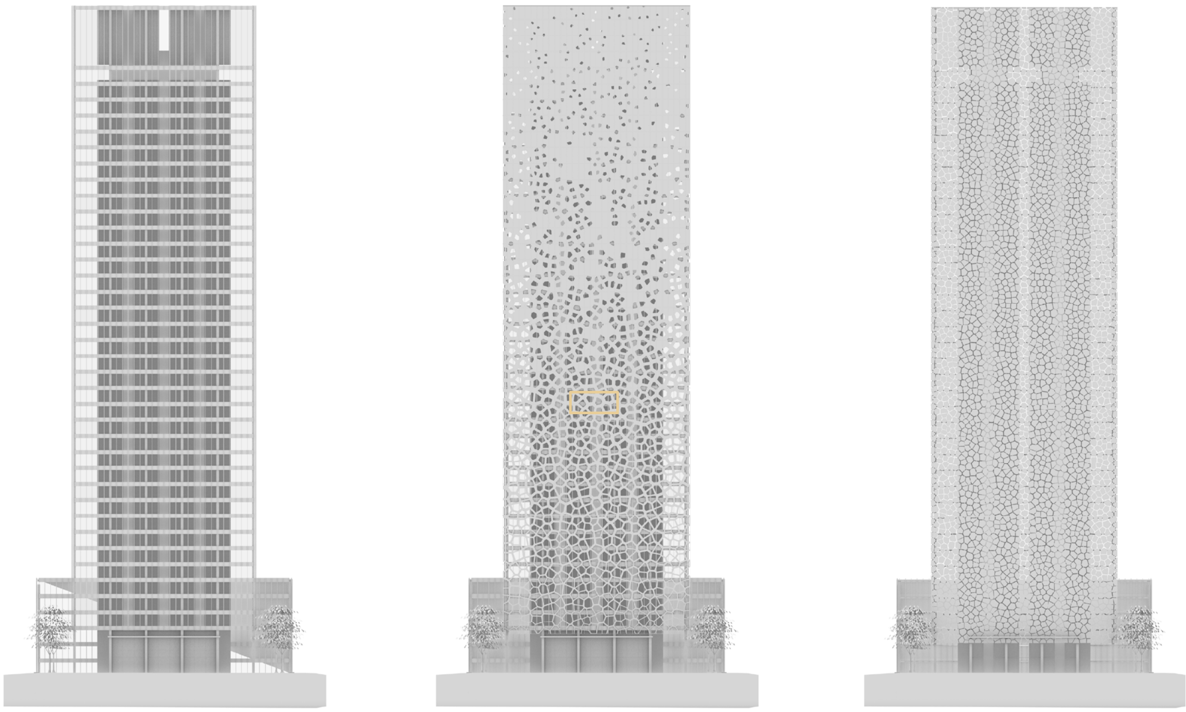
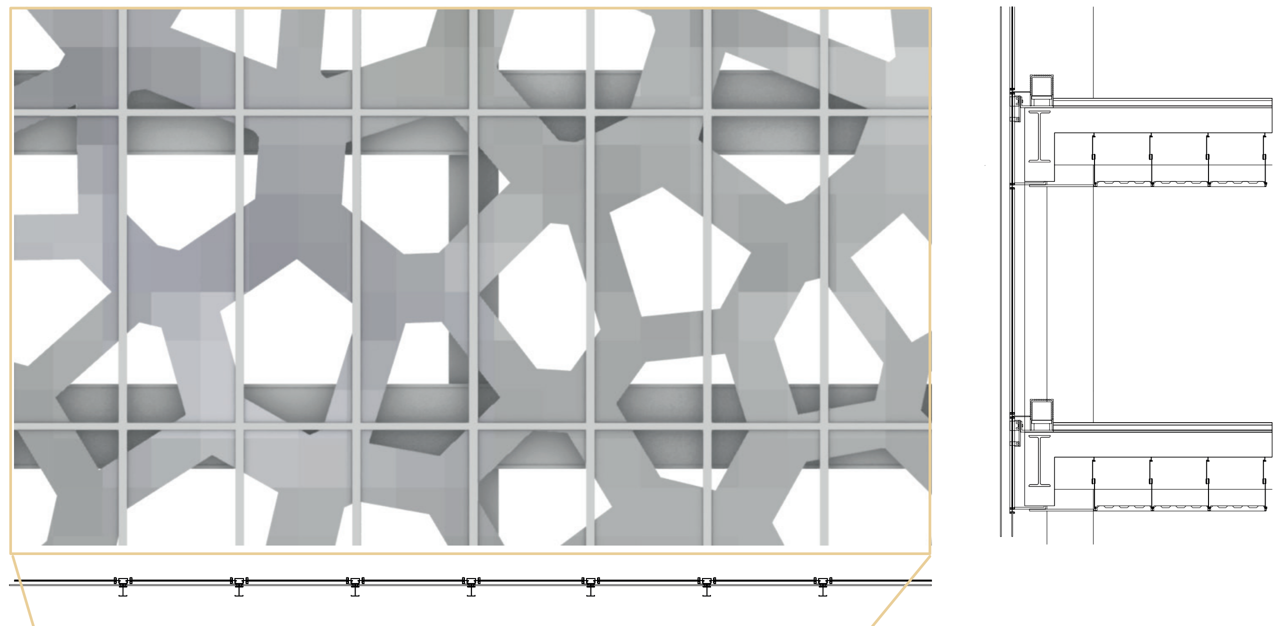
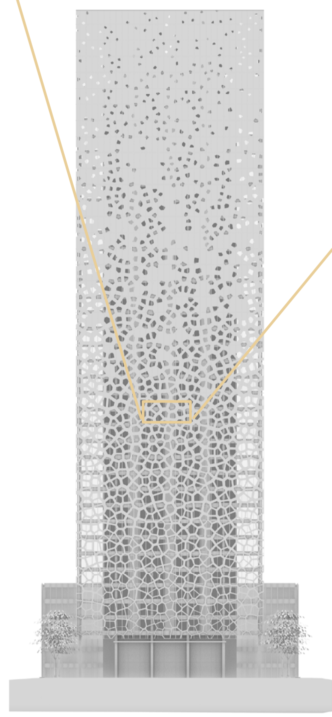
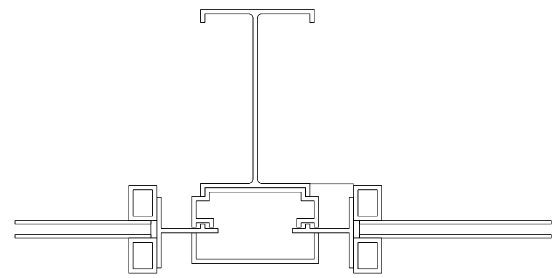


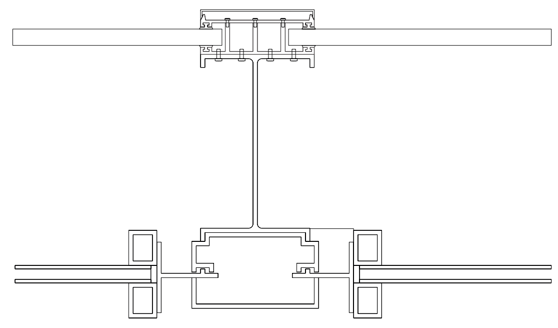
Figure 135: specific temperature properties for glass and concrete, showing the higher melting point of soda-lime glass compared to the thermal degradation point of concrete.







Current facade design



Facade design including a hybrid panel.

This example highlights the implementation of a hybrid facade panel, a concept applicable to numerous fully glazed buildings. By integrating a curtain wall system as facade detailing, the hybrid panel can replace existing windows without requiring additional structural modifications. This approach offers a straightforward method to enhance building performance and aesthetics, making it adaptable for retrofitting older structures with modern, energy-efficient solutions.

The modular nature of unitized curtain wall systems can significantly reduce installation time compared to more traditional construction methods. Prefabricated hybrid panels can be quickly assembled on-site, expediting the overall construction process and reducing labor costs.

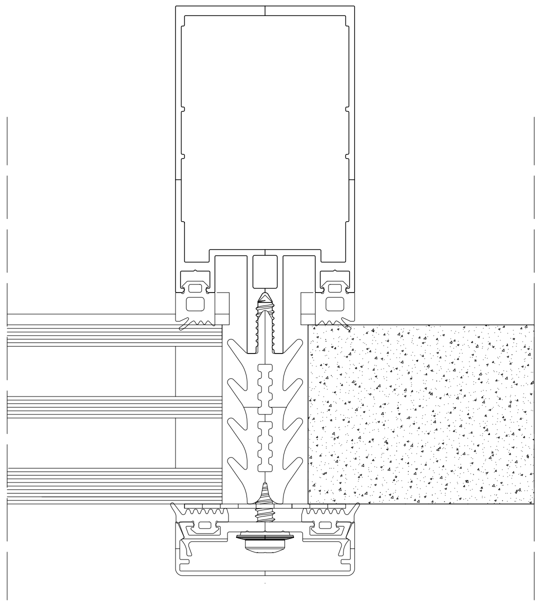


Figure 136: Detail of a curtain wall system with regular triple glazing on the left and a hybrid facade panel on the right.

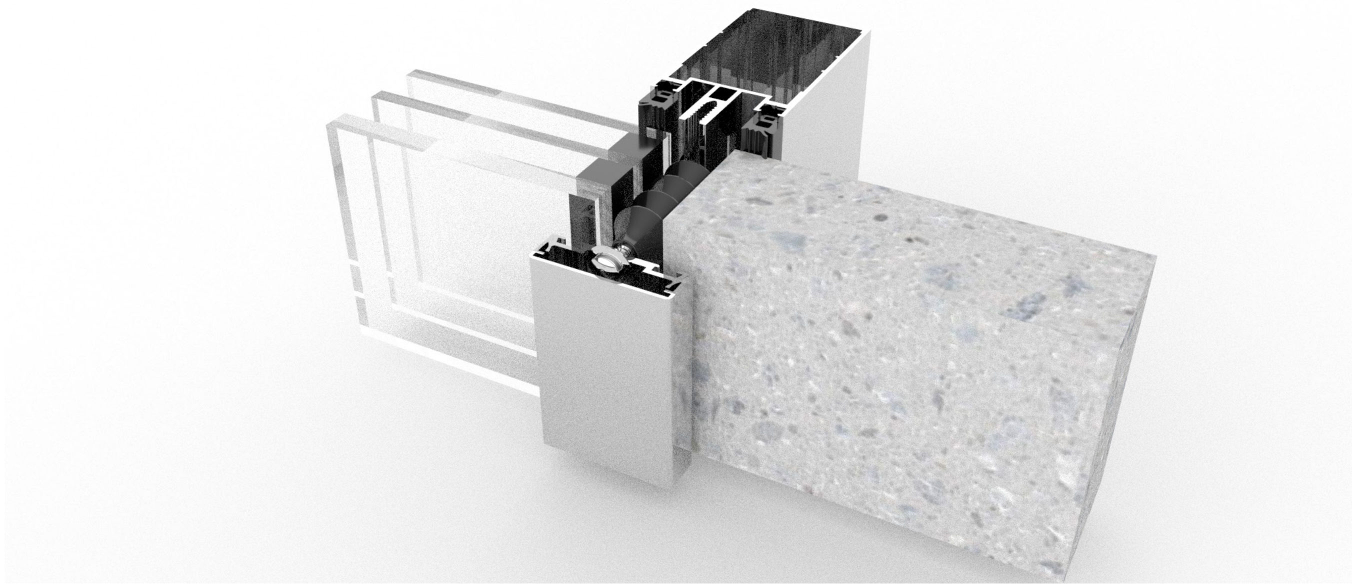


Figure 137: A hybrid facade panel can be placed and mounted exaclty like a current glazing with a curtain wall system.

7.7 END OF LIFE

Hybrid precast facade panels, consisting of concrete and glass, present unique end-of-life opportunities due to the absence of adhesives or glues at the interface, resulting in a panel composed of two monolithic materials. This design allows for an efficient separation and recycling process, contributing to a sustainable closed-loop manufacturing system.

When a hybrid panel reaches the end of its life, either due to damage or the need for removal, the concrete and glass components can be separated effectively:

Separation: The monolithic nature of the materials allows them to be mechanically broken apart without the complications introduced by adhesives or other bonding agents.

Filtering and Crushing: Once separated, the materials are processed through a filtering machine that sorts the concrete and glass. Each material is then crushed into smaller pieces suitable for recycling.

The crushed concrete can be repurposed as a raw material for cement production. This process involves using the recycled concrete aggregate (RCA) to replace a portion of natural aggregates in new concrete mixtures

The cast glass elements from the panels, being free from adhesives and impurities, are highly suitable for recycling. Unlike laminated float glass structures, which often contain interlayers that complicate recycling, the pure glass from these hybrid panels can be directly re-melted and used as a raw material in new glass production. This not only conserves resources but also ensures the glass remains in a continuous recycling loop without degradation of quality.

The sand moulds used in the glass casting process also adhere to principles of circularity. After the fabrication process, these moulds disintegrate into sand, which can be reused in sand printers to create new moulds.

The recycling processes for both concrete and glass in hybrid panels exemplify a closed-loop manufacturing system. By reusing both materials in the same production line, the process achieves a circular design approach. Despite the traditional perception of concrete and glass as unsustainable materials, this innovative interlocking method demonstrates potential. It leverages the inherent properties of both materials, ensuring that hybrid panels contribute to sustainable construction practices.

In conclusion, the end-of-life management of hybrid concrete and glass panels showcases an effective circular approach. By designing for disassembly and recycling, and utilizing the unique properties of both materials, the system supports environmental sustainability and resource efficiency. In the diagram below the circular loop of the production process is shown (figure):

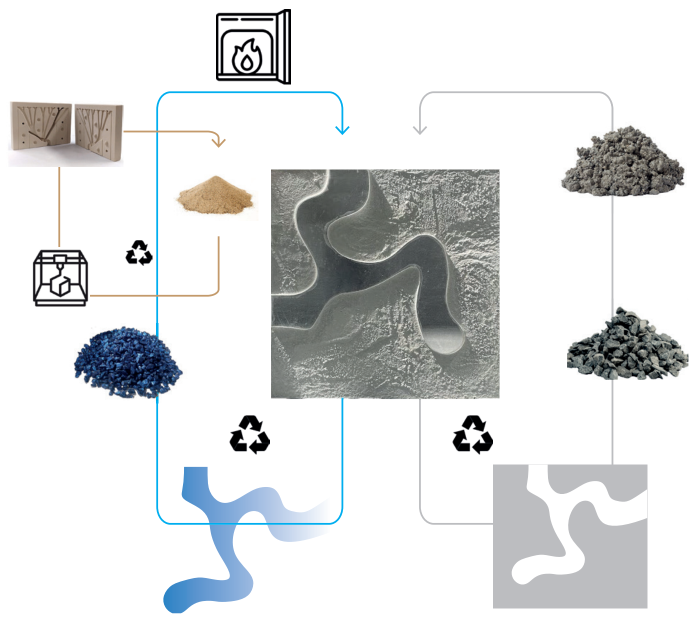


Figure 135: End of life potetnial diagram of a hybrid panel.

8

CONCLUSION & DISCUSSION

8.1 CONCLUSIONS

Creating design freedom to escape monotony. You see it rarely, and especially not in a hybrid context. A new architectural design language is formed by materials that can be shaped into any form. However, when these materials are difficult to bond together, it becomes more challenging. This study is driven by the fascination with making the impossible possible and the quest for improved direct interface adhesion between concrete and glass. Here, an opaque material can be bonded to transparent glass without the use of an intermediate layer, adhesive or frame.

An optimal direct connection involves multiple facets, including surface roughness, contact surface, material composition, and interlocking form. Literature and experimental research have shown that an innovative glass joint is possible between concrete and kiln-cast glass. This shows that what TU Delft has explored through experimental research for the Kintsugi facade of MVRDV is partially structurally feasible. This thesis contributes to the goal of structural validation and design guidelines for free-form transparency, with a hybrid facade panel as the ultimate objective.

The primary focus of this thesis is the structural validation of the concrete-glass interface through direct adhesion. The challenge lies in the chemical properties of the two materials, which result in poor adhesion, making the interface the weakest point in a hybrid form. By manipulating factors such as surface profiles and shapes, a strong interface can be created. Optimizing forms and surface profiles is not new in interlocking structures, but its application in a concrete-glass interface has not yet been tested. This research demonstrates the possibility of this interface for architectural applications, allowing for free-form transparency, but more research is needed for concrete conclusions and real implementation steps. This study represents the first steps towards the possibilities that this bondless innovation offers.

In the search for a transparent and an opaque material that allows free forms in a hybrid context, two materials were chosen primarily for their shapeability, minimal waste generation, durability, and aesthetics. Individually, they are both strong structural building materials, but together, the interface strength is very low. Many parameters influence the strength of this interface, but there has been little to no coherent research conducted on this topic. This served as the starting point for two parallel investigations. The first is the experimental research of different interface parameters, and the second is research by design for implementation and feasibility possibilities.

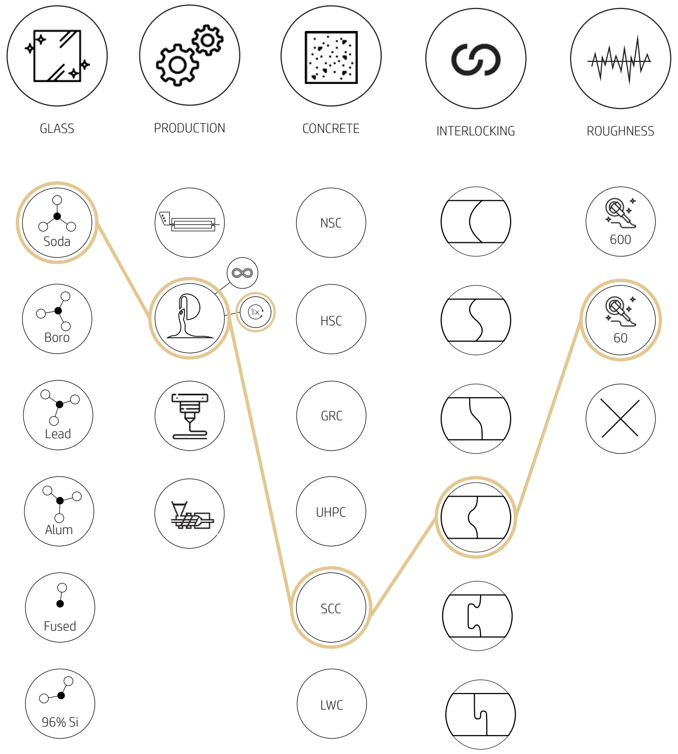


Figure 141: Comprohensive overview of the design development.

EXPERIMENTAL RESEARCH

The experimental research comprised three components aimed at developing a stronger interface between concrete and glass. Enhancing the strength of this interface opens up more possibilities for hybrid applications. The three tests focused on exploring various material compositions and production methods, different interlocking shapes, and different surface roughness levels.

The research into the concrete composition was driven by the need to match the thermal expansion of both concrete and glass to prevent cracking and increased stress at the interface. A self-compacting mortar with CEM III showed the best potential for its lower pH and use of more sustainable materials compared to CEM I. The lower pH indicates a lower alkali content and matches the lower pH value of the glass composition. To precisely determine the thermal expansion of the concrete composition, a dilatometer test should be conducted (for which there was no time in this research). If the thermal expansion is too high compared to the glass, additives such as limestone fillers and silica fumes could be introduced for lowering the thermal expansion coefficient. Adding a plasticizer enhances the workability of the concrete, making it self-compacting thus improves its shapeability and eliminating the need for vibration on a vibrating table, thereby reducing the risk of breaking or shifting the glass in the mould.

Testing interlocking shapes resulted in an interface with a belly shape, which provides a larger surface area and movement constraints in two directions. Although this design shows increased stress concentrations at 90-degree corners, the interface strength remains higher than the internal stress failure threshold, making it a non-critical issue at present. Due to time constraints, only one belly shape was tested. Structural testing demonstrated improved adhesion strength under shear force (bending after P4), but further experimentation is needed to optimize the belly shape.

Surface roughness plays a significant role in the adhesion strength of a concrete-glass interface. While an unpolished cast glass element has a higher overall surface roughness (Ra) and potential for better adhesion due to leftover particles from the mould, this was not the case. Cast glass polished with a grit 60 exhibited better adhesion. This is because the roughness, although lower in height, had more peaks, increasing the overall surface contact. Surface contact area is crucial, possibly even more so than roughness. The roughness was tested at the micrometer level, but the next step is to test roughness at the millimeter level. This would increase the contact surface even more. Moreover, achieving micrometer-level roughness in the glass mould is challenging, whereas creating millimeter-level roughness through shape manipulation holds more potential. (Specimens for this next phase are prepared and will be tested next week.)

In conclusion, the study's findings indicate promising directions for enhancing the concrete-glass interface through material composition, interlocking shapes, and surface roughness. Further testing and refinement are necessary to fully optimize these parameters for practical applications.

RESEARCH BY DESIGN

The hybrid approach shows significant structural potential for integration into facade panel designs. Although the current design area is limited, the findings indicate that through interface design, there is potential for achieving free-form transparency. The results of the experimental research provide valuable input for establishing design boundaries for applying a hybrid interface in facade panels.

With these design boundaries defined, designers have the freedom to create free-form shapes within this interface area, enabling the development of a new architectural design language. Currently, the design guidelines are only applicable to the same concrete and glass composition. Further research and structural validation are needed to allow for more flexibility in the selection of concrete and glass materials.

The interface design enhances adhesion strength. Once the concrete is bonded to the glass, it provides sufficient strength. However, the current percentage of perfect adhesion remains too low to implement the hybrid interface in practical applications.

The interface design enhances adhesion strength. Once the concrete is bonded to the glass, it provides sufficient strength. However, the current percentage of perfect adhesion remains too low to implement the hybrid interface in practical applications. the experimental research on shear stress capacity revealed no design limitations for a hybrid panel, indicating its structural viability. However, further testing is required to expand the design area, particularly in terms of bending behavior (bending stress) as this will have the most impact on the panel. The determination of deflection as part of the design boundaries hinges on finding the Young's modulus of the hybrid composite, which represents a crucial step forward in the research agenda. Moving forward, the exploration of Young's modulus will serve as a pivotal next step in advancing our understanding of the structural performance and design possibilities of hybrid panels.

SUSTAINABILITY

The development of a hybrid panel consisting of concrete and glass presents a promising approach to sustainability. The direct bonding method, which eliminates the need for adhesives, facilitates the disassembly and 100% recycling of both materials at the end of their service life. Furthermore, the raw materials for the panel can be derived from recycled concrete and recycled cullet glass waste, contributing to a highly environmentally friendly production process.

Concrete typically has significant emissions associated with the production of cement and reinforcement. However, in this design, the absence of reinforcement and the use of cement partially composed of by-products from steel production highlight viable sustainable solutions for concrete.

For cast glass, the primary source of emissions is the extended furnace time required for annealing. By imposing design guidelines that limit the maximum dimensions and weight of the glass, emissions during production can be reduced. Kiln-casting has the advantage of utilizing recycled cullet glass waste, producing minimal waste, and ensuring that the glass can be recycled again after its use.

Overall, this hybrid panel showcases substantial potential for sustainability through innovative material usage, recycling capabilities and interface design, highlighting a forward-thinking approach to environmentally conscious design in construction.

8.2 DISCUSSION

One of the main challenges of this project is time. Due to the timeframe of this thesis and the numerous facets of this research, only a limited number of tests could be conducted. In this study, the concrete always had a curing time of seven days. These time constraints have restricted the scope of the research, which is evident in the number of total results for the combined interface design strategies.

There are too many facets to cover everything comprehensively. Therefore, initial assumptions were made, which could be reconsidered in future studies. The focus was primarily on interface design parameters. However, for better results, it would be beneficial to also investigate the materials themselves more thoroughly. Concrete, in particular, is a complex subject. Given my limited knowledge of concrete, a concrete expert would be essential to guide such a study. Cast glass was chosen for this thesis due to its freeform possibilities and lack of waste generation. However, it requires more post-processing and is much more challenging to scale than float glass production. When a hybrid facade panel as a curtain wall system becomes a reality, float glass would be a more logical choice in terms of manufacturing and production costs and time.

One of the key aspects of facade panel design is the thermal insulation it provides. This aspect was not considered in this thesis. Therefore, this hybrid facade panel could not be implemented in the Netherlands as it stands. The facade panel in this thesis was only used to demonstrate structural feasibility, not to determine if it could actually replace double or triple glazing.

This hybrid interface can also be used in other architectural applications, such as interior walls or partitions. A direct adhesion of a concrete-glass interface offers more opportunities in various forms.

8.3 RECOMMENDATIONS

For further research on a direct connection between glass and concrete, I make the following recommendations:

- An important next step for this research is to further scale up the results. the more results the better you can understand and predict the behaviour of a hybrid interface
- Using geopolymer instead of concrete: This material has ceramic properties that can be sintered with glass when both are placed in the oven together. This results in a gradual composition and forms a sintered functionally hybrid material. The interface becomes graded and therefore acts more as one material.
- Testing different types of glass and concrete: For example, art glass instead of float glass. Art glass contains more flux. Fluxes are usually alkali (Na_2O, K_2O, Li_2O), which have more similar properties to concrete, potentially improving adhesion. Although the mechanical properties may be reduced, they can be enhanced with additional modifiers.
- Finite element modeling and simulations: Use advanced computational methods to model and simulate the behavior of the glass-concrete connection under various loading and environmental conditions. This can help predict performance and identify potential failure modes before physical testing.

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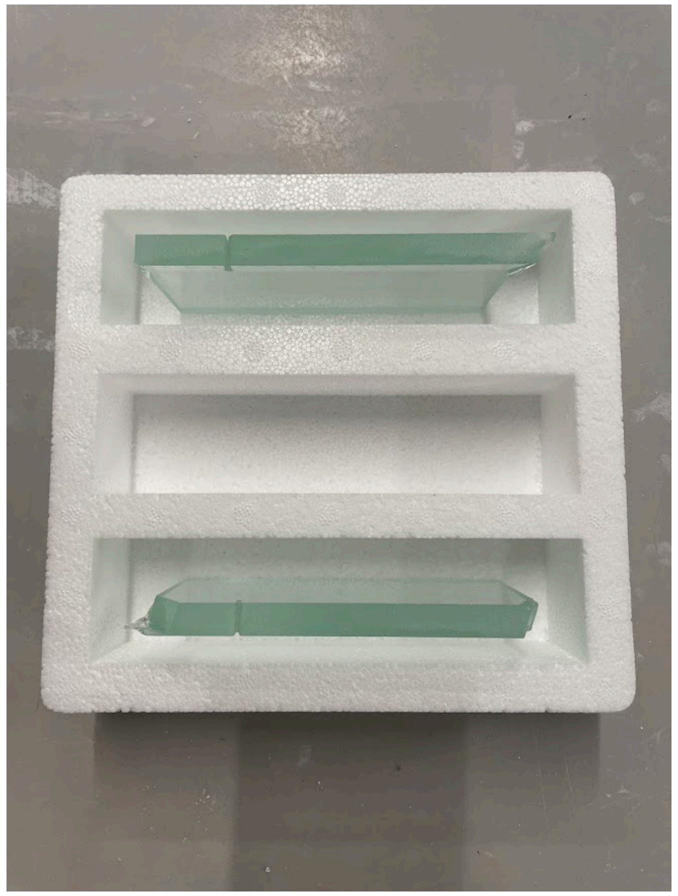
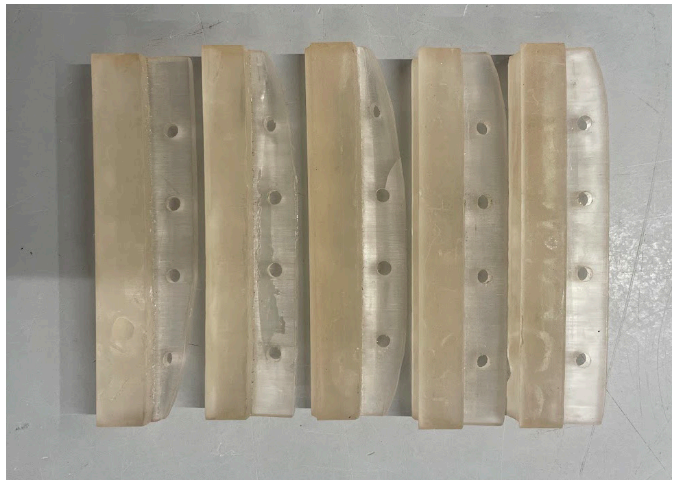
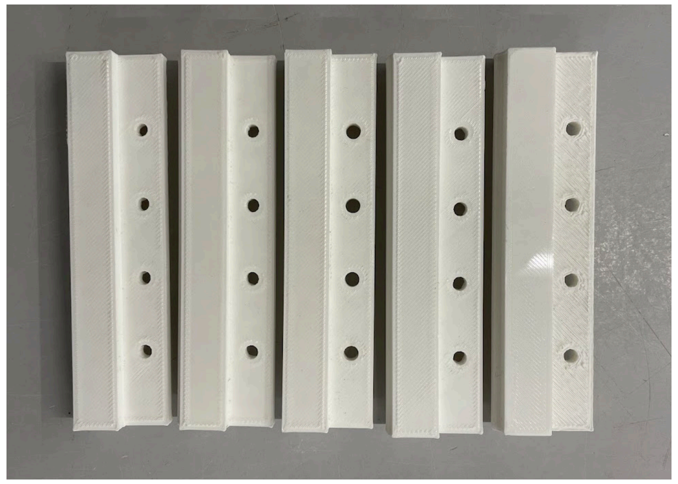
APPENDIX







PERFORMANCE CRITERIA FOR FREE-FORM FACADE MATERIAL SELECTION				
STRUCTURAL	PHYSICAL	CHEMICAL	SUSTAINABLE	EFFICIENCY
Density	Thermal conductivity	Combustibility	Embodied energy	Material costs
Tensile	Expansion coëfficient	Weather resistance	Recyclable	Shape ability
Yield	Heat capacity	UV-resistance	Durability	Accessible
Compressive			Manufacturing waste	Aesthetics *

COMPARISSON MATRIX - OPAQUE MATERIALS

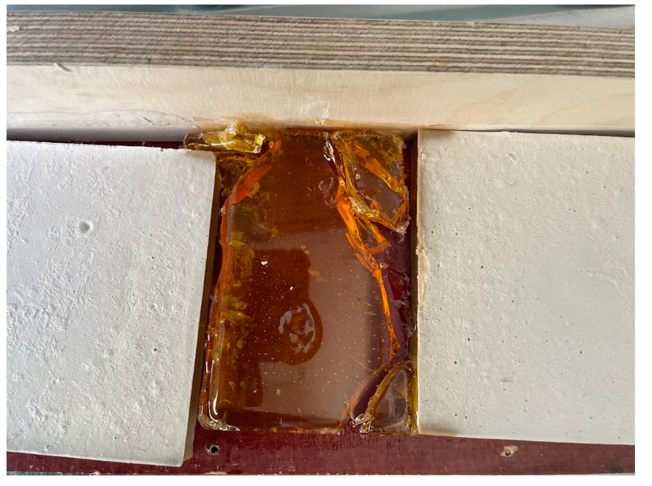
		Structural				Physical		Chem	
importancy factor criteria value	1 Density kg/m3	2 tensile N/mm2	1 yield N/mm2	2 Compressive N/mm2	1 thermal (U) W/mC	4 expansion Ustrain / C	1 Heat capacity J/kg.C	2 Combustibilty	1 Weat
Minerals & Stone (stone)	2300	2 - 25	2 - 25	55 - 255	5,4 - 6	3,7 - 6,3	840 -920	excellent	exce
Fired Clays (brick)	2000	6,9 - 14	6,9 - 14	69 - 140	0,4 - 0,8	8 - 11	750 - 850	excellent	exce
Cement & Concrete (concrete)	2400	1,1 - 1,3	1 - 1,2	13 - 30	1,65 - 2,6	8 - 12	835 - 1050	excellent	exce
Polymer Composite (FRP)	1850	207 - 304	207 - 304	207 - 257	0,42 - 0,51	8,64 - 33	1020 - 1120	good	exce
Thermoplastics (tpPVC)	1360	38 - 46	37,6 - 45,5	37 - 44,3	0,147 - 0,209	65 - 81	1000 - 1100	poor	exce
Natural Materials (wood)	550	2,27 - 6,13	1,26 - 3,58		0,218 - 0,382	2 - 11	1660 - 1710	fair	fair
Alloys (non-ferrous) (aluminium)	2700	288 - 571	241 - 520	245 - 521	135 - 185	22,7 - 24,6	879 - 999	excellent	exce
Metals (ferrous) (stainless steel)	7700	515 - 1300	257 - 1140	252 - 1200	14 - 24,9	10,8 - 16,5	450 -510	excellent	exce

COMPARISSON MATRIX - TRANSPARENT MATERIALS

IMPORTANCE FACTOR

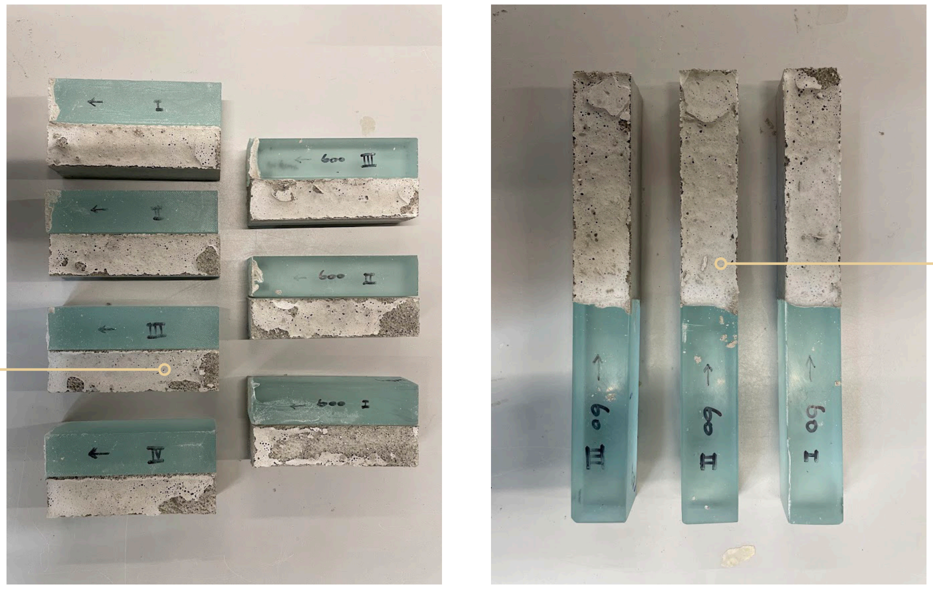
FACTOR	DEFINITION	EXPLANATION
1	Equal importance	Two criteria contribute equally to the objective
2	Moderate importance	Criteria slightly favour one performance over other
3	Strong importance	Criteria strongly favour one performance over other
4	Extreme importance	The criteria favouring one activity over another is of highest possible

nical			Sustainable				Efficiency		
	1	3	3	3	4	4	4	1	4
her resistar	UV-resistance	Embodied energy MJ/kg	Recyclable potential	Durability	Manufacturing waste (I - V)	Costs EUR/kg	Shapebility	Accesible	Aesthetics*
llent	excellent	8,24 - 9,11	yes	excellent	good	1,2 - 1,41	good	good	excellent
l	fair	101 -111	yes	excellent	good	3,8 - 4,30	good	excellent	fair
l	excellent	107 - 118	no	good	good	1,59 - 2,22	excellent	good	excellent
llent	good	250	yes	excellent	excellent	17 - 23	good	excellent	fair
l	fair	115 - 127	no	excellent	good	2,7 - 4,76	excellent	fair	excellent



6/9 samples did not adhere

Only 60 grit adhesed after the first pouring



#1

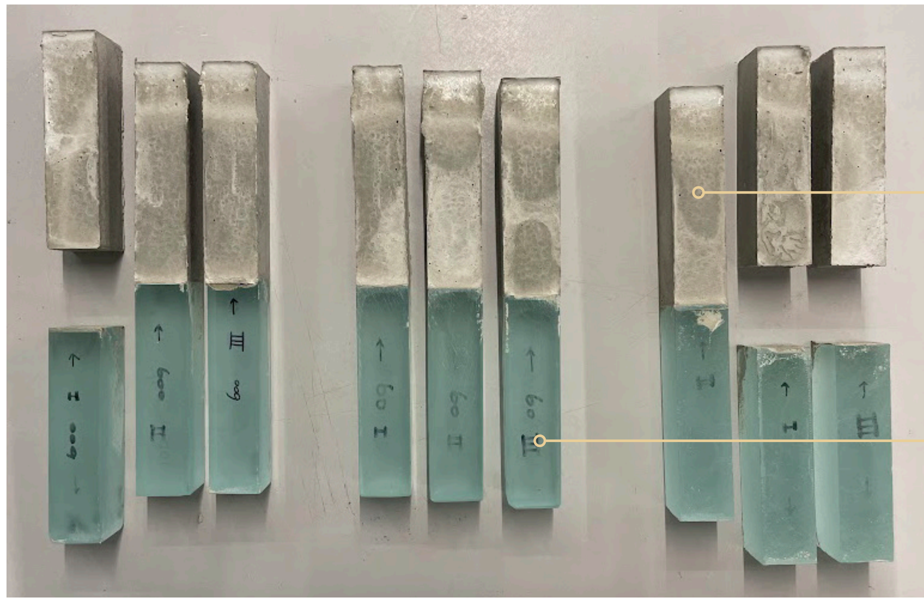
Debonding led to an imhomogenous mixture (probably after compacting too long)

again 6/9 samples did not adhere

#2

Homogenous smooth surface of the concrete

A homogeneous concrete mix provides the best bonding result. 6/9 samples have adhered.



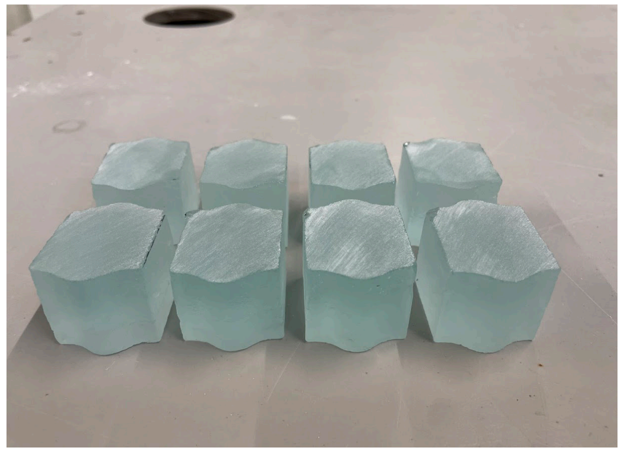
#3

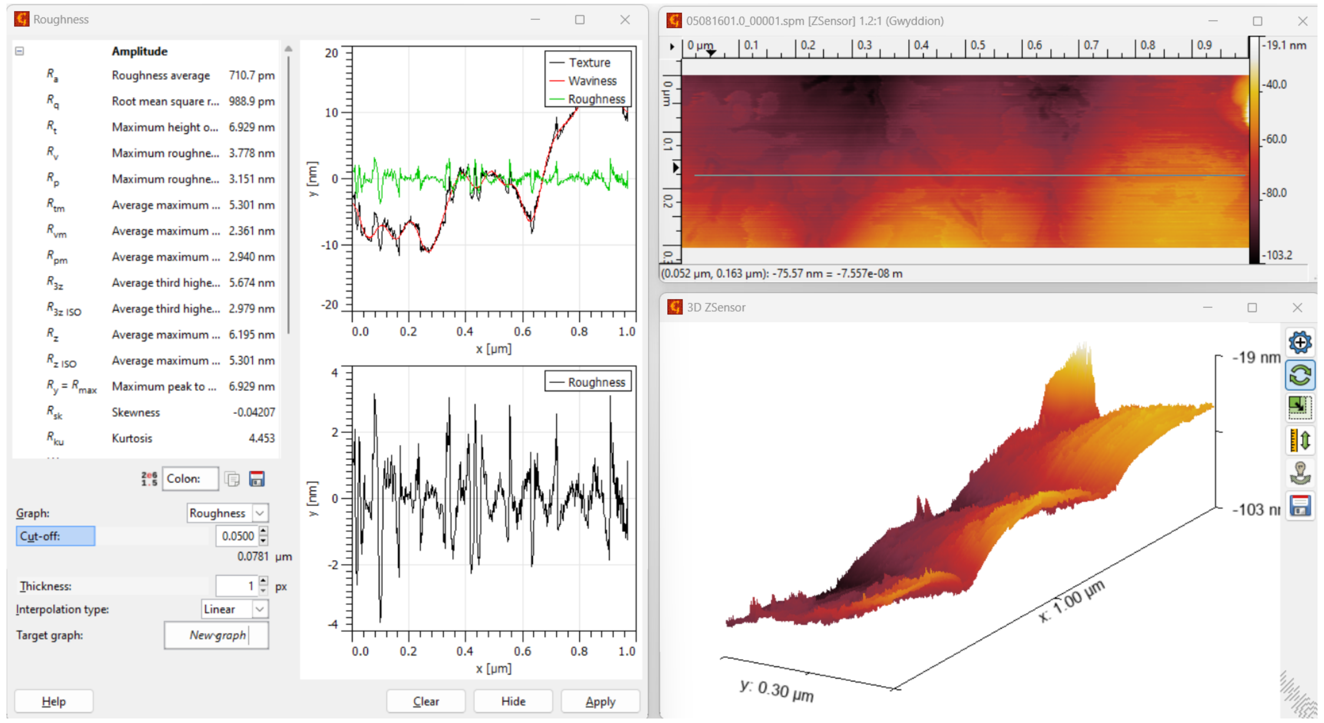
		Unpolished			60 grit			600 grit		
		Specimen 9	Specimen 8	Specimen 7	Specimen 6	Specimen 5	Specimen 4	Specimen 3	Specimen 2	Specimen 1
	Contact Surface Area (mm²)	904	905	899	922	925	849	822	872	916
Pouring 1	Adhesion	NO	NO	NO	YES	YES	YES	NO	NO	NO
Pouring 1	Mixing	1	1	1	1	1	1	1	1	1
Pouring 1	Test Result Flexural trength (MPa)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pouring 2	Adhesion	NO	NO	YES	YES	YES	NO	NO	NO	NO
Pouring 2	Mixing	2	2	2	2	2	2	2	2	2
Pouring 2	Test Result Flexural trength (MPa)	-	-	0,32	0,90	0,82	-	-	-	-
Pouring 3	Adhesion	NO	YES	NO	YES	YES	YES	YES	YES	NO
Pouring 3	Mixing	2	2	2	2	2	2	2	2	2
Pouring 3	Test Result Flexural trength (MPa)	-	1,35	-	1,90	1,43	1,48	1,30	1,82	-

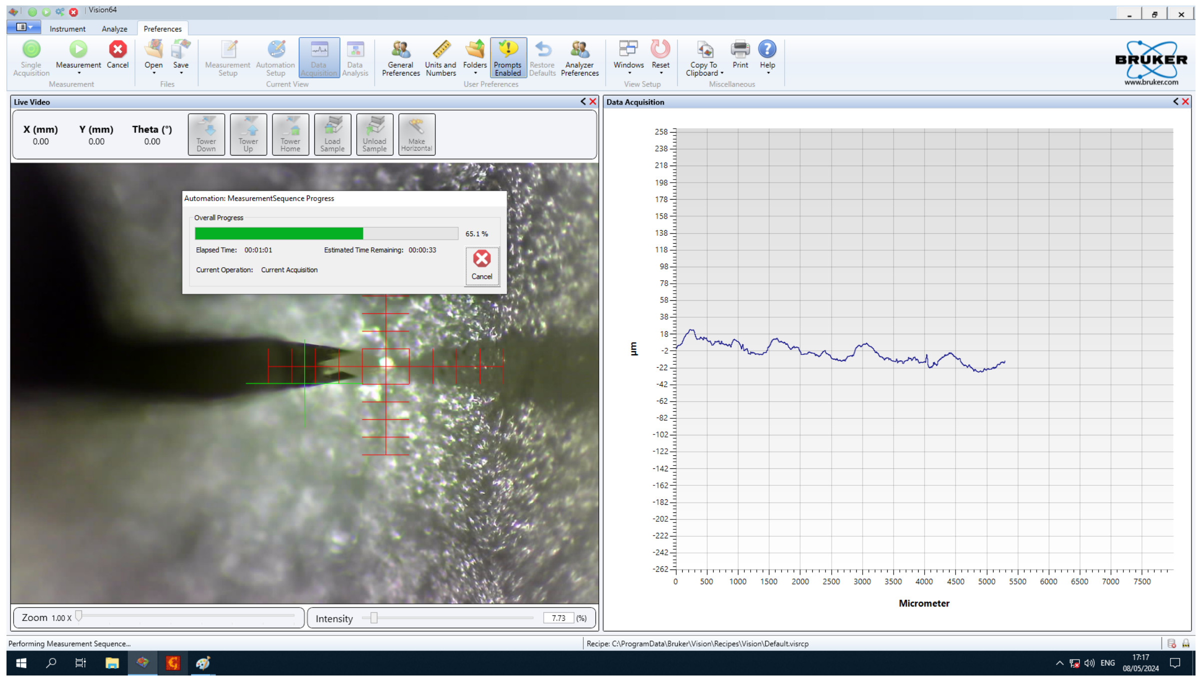
Overview of results for the different pouring and adhesive strength of a concrete-glass interface with different surface roughnesses.

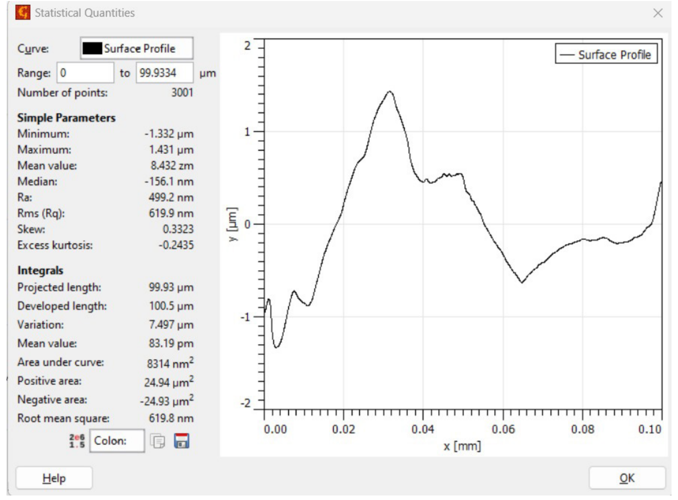
1st four-point bending experiment: Kilncast glass beams 30x30x240mm, 110/220mm supports						
Glass type	Specimen description	Forming temperature (°C)	No. of tested specimens	Flexural strength (MPa) Minimum	Maximum	Average flexural strength (MPa)
	Fully Tempered float	1120	3	40.9	46.5	43.9

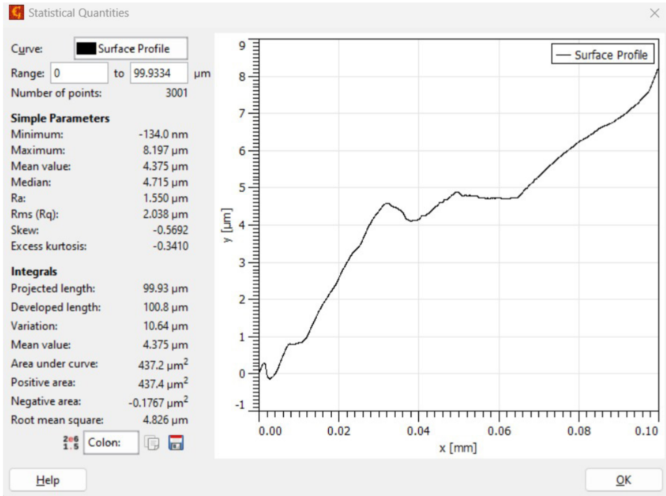
2nd four-point bending experiment: Kilncast glass beams 30x30x240mm, 100/200mm supports						
Specimen description	Forming temperature (°C)	No. of tested specimens	Flexural strength (MPa) Minimum	Maximum	Average flexural strength (MPa)	Average E modulus (GPa), LVDT calculation*
Fully Tempered float	1120	6	33.5	50.8	43.7	59.3

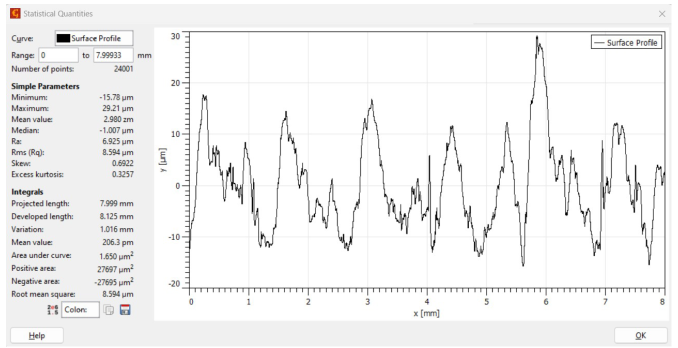


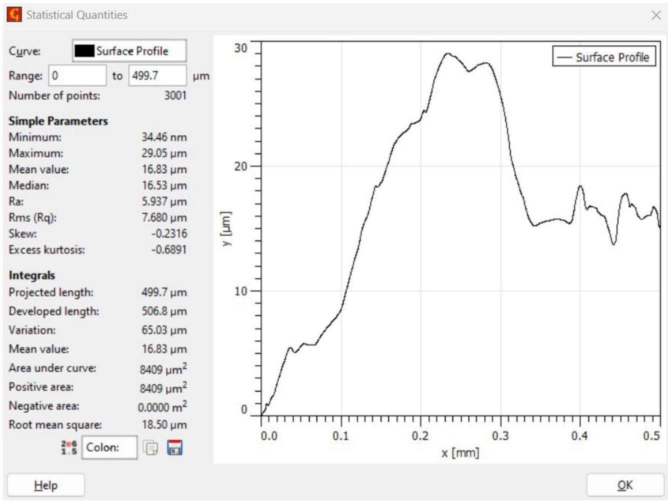


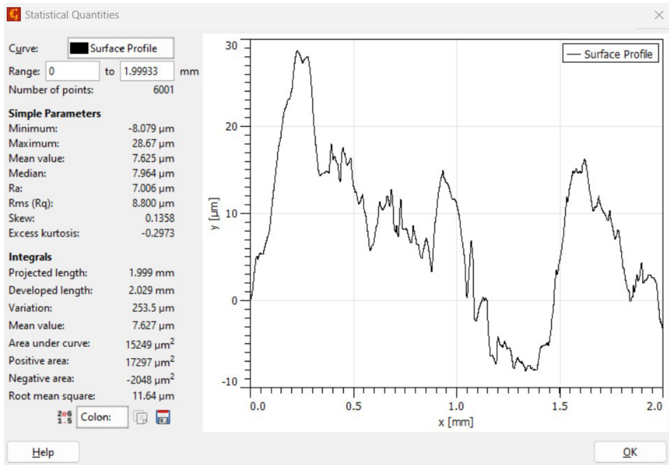


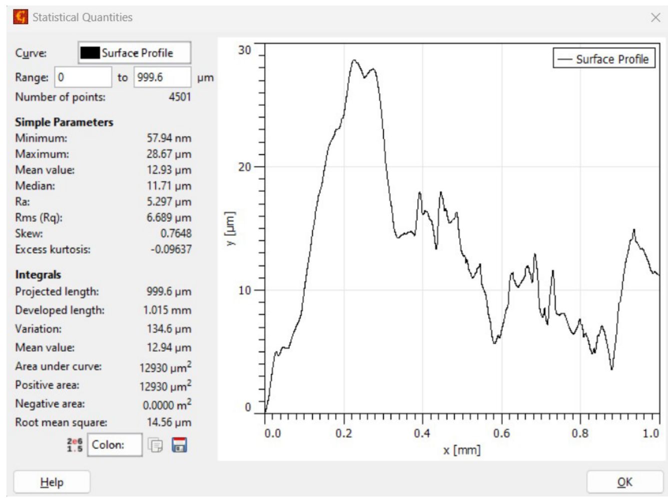

Statistical Quantities
Curve: Surface Profile
Range: 0 to 99.9334 µm
Number of points: 3001
Simple Parameters
Minimum: -1.332 µm
Maximum: 1.431 µm
Mean value: 8.432 zm
Median: -156.1 nm
Ra: 499.2 nm
Rms (Rq): 619.9 nm
Skew: 0.3323
Excess kurtosis: -0.2435
Integrals
Projected length: 99.93 µm
Developed length: 100.5 µm
Variation: 7.497 µm
Mean value: 83.19 pm
Area under curve: 8314 nm²
Positive area: 24.94 µm²
Negative area: -24.93 µm²
Root mean square: 619.8 nm
Colon:
Help
OK
Surface Profile
y [µm]
x [mm]


Statistical Quantities
Curve: Surface Profile
Range: 0 to 99.9334 µm
Number of points: 3001
Simple Parameters
Minimum: -134.0 nm
Maximum: 8.197 µm
Mean value: 4.375 µm
Median: 4.715 µm
Ra: 1.550 µm
Rms (Rq): 2.038 µm
Skew: -0.5692
Excess kurtosis: -0.3410
Integrals
Projected length: 99.93 µm
Developed length: 100.8 µm
Variation: 10.64 µm
Mean value: 4.375 µm
Area under curve: 437.2 µm²
Positive area: 437.4 µm²
Negative area: -0.1767 µm²
Root mean square: 4.826 µm
Colon:
Help
OK
Surface Profile
y [µm]
x [mm]


Statistical Quantities
Curve: Surface Profile
Range: 0 to 7.99933 mm
Number of points: 24001
Simple Parameters
Minimum: -15.78 µm
Maximum: 29.21 µm
Mean value: 2.980 zm
Median: -1.007 µm
Ra: 6.925 µm
Rms (Rq): 8.594 µm
Skew: 0.6922
Excess kurtosis: 0.3257
Integrals
Projected length: 7.999 mm
Developed length: 8.125 mm
Variation: 1.016 mm
Mean value: 206.3 pm
Area under curve: 1.650 µm²
Positive area: 27697 µm²
Negative area: -27695 µm²
Root mean square: 8.594 µm
Colon:
Help
OK
Surface Profile
y [µm]
x [mm]


Statistical Quantities
Curve: Surface Profile
Range: 0 to 499.7 µm
Number of points: 3001
Simple Parameters
Minimum: 34.46 nm
Maximum: 29.05 µm
Mean value: 16.83 µm
Median: 16.53 µm
Ra: 5.937 µm
Rms (Rq): 7.680 µm
Skew: -0.2316
Excess kurtosis: -0.6891
Integrals
Projected length: 499.7 µm
Developed length: 506.8 µm
Variation: 65.03 µm
Mean value: 16.83 µm
Area under curve: 8409 µm²
Positive area: 8409 µm²
Negative area: 0.0000 m²
Root mean square: 18.50 µm
Colon:
Help
OK
Surface Profile
y [µm]
x [mm]


Statistical Quantities
Curve: Surface Profile
Range: 0 to 1.99933 mm
Number of points: 6001
Simple Parameters
Minimum: -8.079 µm
Maximum: 28.67 µm
Mean value: 7.625 µm
Median: 7.964 µm
Ra: 7.006 µm
Rms (Rq): 8.800 µm
Skew: 0.1358
Excess kurtosis: -0.2973
Integrals
Projected length: 1.999 mm
Developed length: 2.029 mm
Variation: 253.5 µm
Mean value: 7.627 µm
Area under curve: 15249 µm²
Positive area: 17297 µm²
Negative area: -2048 µm²
Root mean square: 11.64 µm
Colon:
Help
OK
Surface Profile
y [µm]
x [mm]


Statistical Quantities
Curve: Surface Profile
Range: 0 to 999.6 µm
Number of points: 4501
Simple Parameters
Minimum: 57.94 nm
Maximum: 28.67 µm
Mean value: 12.93 µm
Median: 11.71 µm
Ra: 5.297 µm
Rms (Rq): 6.689 µm
Skew: 0.7648
Excess kurtosis: -0.09637
Integrals
Projected length: 999.6 µm
Developed length: 1.015 mm
Variation: 134.6 µm
Mean value: 12.94 µm
Area under curve: 12930 µm²
Positive area: 12930 µm²
Negative area: 0.0000 m²
Root mean square: 14.56 µm
Colon:
Help
OK
Surface Profile
y [µm]
x [mm]

Nils Wulfsen I 4561090 I TU Delft 2023-24