Silica

A circular material paradigm by 3D printing recycled glass

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Silica examines the making of 3D printed tiles from recycled container glass. This paper describes an interdisciplinary exploration into how robot-controlled extrusion can offer new material practices by which to fabricate glass elements of an architectural scale. We pursue working with recycled container glass powder - a waste product derived from the reprocessing of recycled container glass - to contribute to circular development within an interdisciplinary artistic development context in the meeting between architecture and glass design. The project has two aims. On the one hand, it builds an in-depth understanding of the parameters of fabrication and devising means by which to control these through digital design methods and their interfacing with robotic fabrication processes. On the other hand, it critically questions the architectural, aesthetic and performative properties of these material practices and their embedded methods.

Keywords: *Robotic fabrication, Digital design systems, Circular economy, 3D Glass printing, New material practices*

INTRODUCTION

Silica examines the making of 3D printed tiles from recycled container glass (Fig. 1). By developing methods for robot controlled extrusion of glass paste and its firing (Fig. 2), we develop new practices by which to fabricate glass elements of an architectural scale. The project examines the recycling of container glass powder - a waste product derived from the reprocessing of recycled container glass - and contributes to the construction of circular design principles. The project is undertaken as an interdisciplinary collaboration between architecture and glass design and merges scientific and artistic methodologies. Silica is a collaboration between members of CITA and glass artist Maria Sparre-Petersen.

CONCEPTUAL FRAMEWORK: GLASS AS AN ARCHITECTURAL MATERIAL

Glass is one of the heroic modernist materials. In his text "Glass: The Fundamental Material of Modern Architecture" written in 1935, Le Corbusier calls for a second machine age in which technologies of manufacture would restore mankind's harmonious relationship with nature. In this lineage, glass as a transparent and essentially non-present material allowed a new conception of architecture as intimately con-

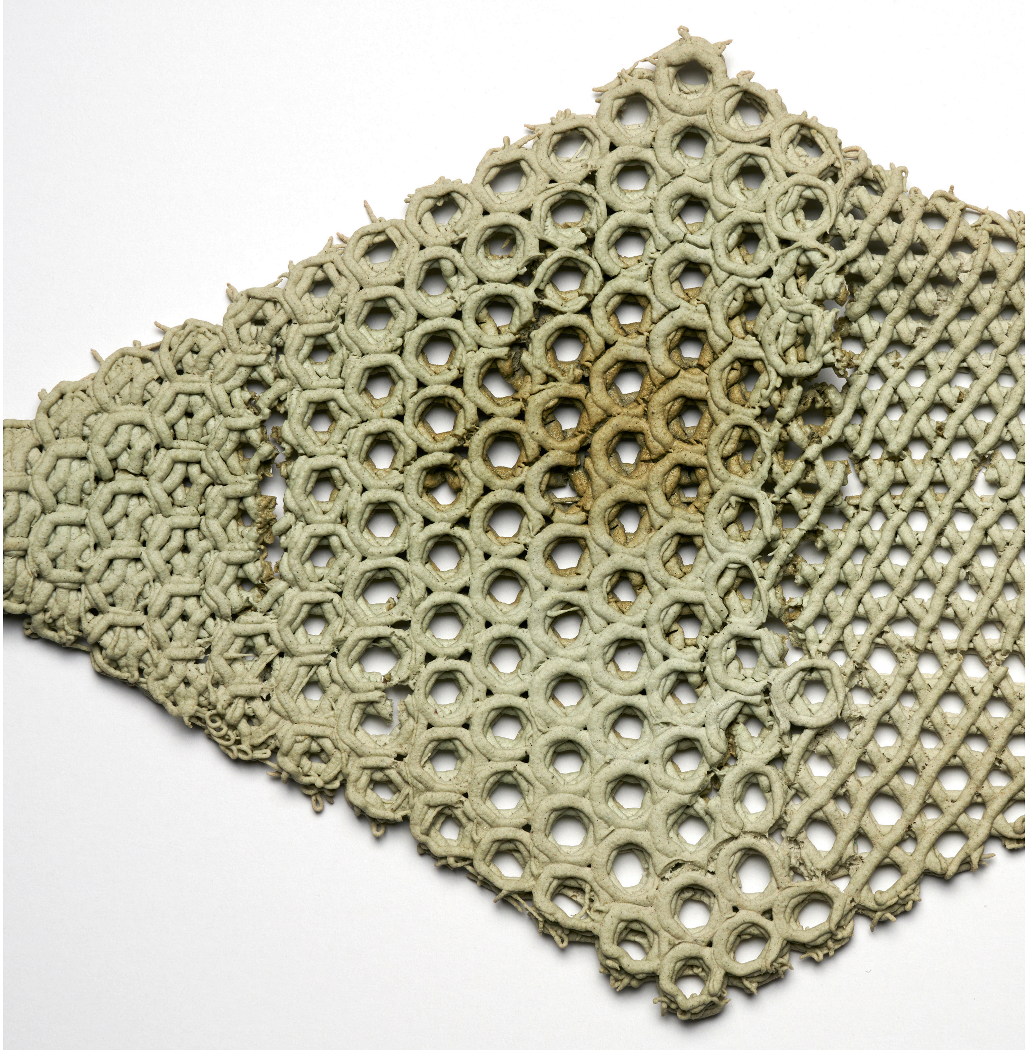


Figure 1
Silica: 3D printing
recycled soda glass

nected to its surrounding environment. Maison de Verre acts very differently. Conceived and built by Pierre Chareau in the years 1929 - 31, Maison de Verre is a cornerstone in modernist history. While celebrated for its use of prefabricated glass block walling, it presents the curtain wall not as an open surface, but rather through a translucency dramatically changing as interiors are lit at dusk. Silica takes point of departure in this parallel material opportunity. By examining the 3D printing of recycled soda glass, we explore the making of translucent and opaque glass tiles for architectural application.

In Silica, the ambition is two fold. Firstly, it develops a new material practice in which recycled soda glass powder is mixed with a natural binder in order to create a thick extrudable paste. Secondly, it develops robotic controlled additive extrusion methods by which to form the paste. By building on a paté de verre process, we employ a mould-less fusing process to form and then sinther the glass. The project uses the architectural tiles as a particular site of investigation. Here, we leverage two key properties of the process; the ability to print very fine layers thereby enabling a filigree porous structure and at the same time make the most of a chiefly two dimensional extrusion process. The choice of the tile as an architectural element allows us to contextualise the material investigation within an architectural scenario that leverages new architectural expressions. When printed thinly the material is translucent. The central reason for this is the material resource of recycled soda lime glass powder.

RECYCLING - GLASS IN A NEW CONTEXT OF PRODUCTION

Silica is understood as a first probe into rethinking how we address recycling in architecture. The vision and ambition of the large framing project is to develop the conceptual, design-based and fabrication-based methods for printing architectural structures locally with recycled materials from demolished buildings. As such, the project ties into wider efforts to redress contemporary industrialised processes and invent the sustainable practices that can rethink how materials are sourced, how they are used and how they are recycled.

Figure 2
3D printing process
followed by firing

Concepts of Circular Economy, Cradle to Cradle Design or Integrated Design, as reflected in the UN Sustainable Development Goals, aim at defining design paradigms that challenge the "take, make and dispose" approach of the conventional linear economy, and instead increase awareness of resource circularity, sustainable production and the reconciliation of economic, environmental and social goals (Valero & Valero 2010). Glass recycling in artistic applications has previously been explored by Oseng (Oseng et al. 2009) and Siikamakki (Siikamäki 2006), both through traditional fabrication processes, while the new technological developments afford a wider range of aesthetic opportunity. This idea of reconciliation echoes Le Corbusier's call for restoration of a harmonious relationship between mankind and nature. As we stand before the fourth machine age - industry 4.0 - we find ourselves repeating an appeal for using technology to re-find an environmental alignment, but with a new agenda and a new sense of urgency. The robotic manufacturing offers opportunities for three dimensional printing that are impossible using traditional glass casting techniques, hence, potentially afford new aesthetics as well as structural functionality when we begin to build tacit as well as technical knowledge of how the material can be adapted to the technology. In this first venture into the research we have been able to accomplish the first step of adjusting material to fit the equipment, laying a foundation for exploration of more complex three dimensional structures.

MATERIAL

Glass is 100% and infinitely recyclable without loss of material qualities (Fig. 3). As such it presents an interesting case for circular resource thinking as opposed to materials like ceramics and concrete that can not resume earlier material states after being transformed through firing and curing.

Figure 3
Soda lime glass is a highly recycled material. In Europe 74 % is recycled. Sweden, Belgium and Slovenia recycle more than 95 %. On the global scale recycling amounts to 35%. For every six tons of recycled glass used as an alternative to virgin materials in production processes, carbon dioxide emissions are reduced by one ton. Over a ton of raw materials are saved for every ton of glass recycled. Besides reducing emissions and consumption of raw materials, recycling extends the life of plant equipment, such as furnaces and saves energy as energy consumption drop about 2-3% for every 10% cullet used in the manufacturing process [1].

Globally, the call for new sustainable material practices for glass production is urgent. Glass is made of sand and sand is a finite resource. Due to the exponential increase in the use of concrete and flat glass in the building industry we are running out of buildable sand resources (Bendixen et al. 2019). Currently, waste glass from the demolition of buildings has not so far found any use in the production of new flat glass (2). As requirements in terms of purity of raw materials for the production of flat glass are extremely high, waste glass from buildings becomes in most cases landfill (3). Silica presents ways to recycle glass waste in an architectural context. For our experiments we work with recycled container glass, which has the same molecular structure as flat glass, it is already being recycled at an exemplary rate in a functional circular system in most European countries, it is abundant, cheap and readily available in most parts of the world, hence the project is potentially applicable on a global scale, which is important with regard to impact.

This material choice also makes the project very different to other efforts in 3D printing glass. In recent years, attempts at printing glass have been successfully completed by Markus Kaiser (4), in his artistic project Solar, where he built a 3D printing rig, powered by the sun, that sintered glass directly on site in the desert. MIT media lab has developed a melting kiln that extrudes clear glass similar to a regular 3D printing process (Klein et al. 2015). RISD has created a system with a platform that moves underneath a vessel with a hole, filled with hot glass that runs through the hole and forms a somewhat chaotic geometry (5) and KIT is printing the glass through a complex process combining nano technology, polymer support structures, light- and heat sintering (6).

In difference to these processes Silica develops a two-part process in which the 3D extrusion of the glass paste takes place before the firing, exploring mainstream equipment that allows knowledge sharing with a broader research community. Furthermore, the crystal class explored at MIT, RISD and RIT offers clarity and transparency, while the architectural opportunities are limited because of the chemical composition of crystal glass that is more brittle, has less impact strength, cannot be recycled in the regular recycling stream and is more sensitive to temperature than the recycled sodalime glass from containers and windows, used in this research. Aesthetically, the opportunities of the sodalime glass combined with the fusing technique are quite different from those of the crystal glass. When printed in a thin layer the material is translucent while when the material is printed in several layers the sintered glass becomes opaque due to the devitrification of the glass. This allows us to control the translucency through layering. Furthermore, the extrusion process allows small scale control of deposition and therefore a highly detailed forming of each deposited layer allowing us to control the structure of the print and introduce interstices between print lines. By introducing dyes to the material paste we can also grade colour across the extrusion process. In Silica, these processes are combined to form complex elements that change in translucency, colour and structure expanding the understanding of how glass is used and how these new meanings may influence future circular visions within architecture.

TECHNIQUE

The innovation in Silica is both its circular material logic as well as its forming process. Through experimentation we have developed and understood how these parameters change as the material composition varies and how the robotic fabrication process can be steered through design algorithms.

A core innovation is the developed sustainable structural additive, which the glass powder needs to work with the printing process. Tests with water and glue proved unsuccessful, hence, we settled with a flour/water/glass mixture that mimics clay which works well with the robotic digital design process. As opposed to clay that shrinks as a solid body during the firing process the flour in this mixture burns away and leaves a porous structure. When the material is too thin this causes disintegration of the tiles (Fig. 4).

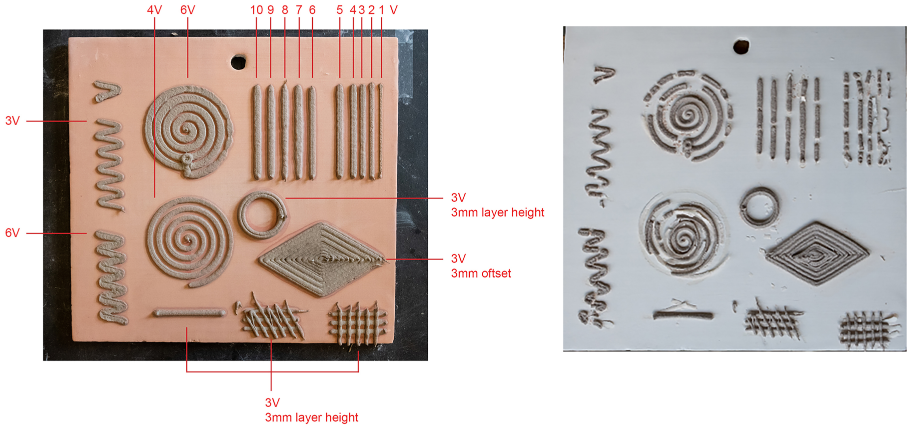


Figure 4
Topology tests of print and firing parameters. Several parameters, such as duration and max temperatures of the kiln program, layer thickness, connectivity, distance between nodes determine, whether the prints shatter during firing or not.

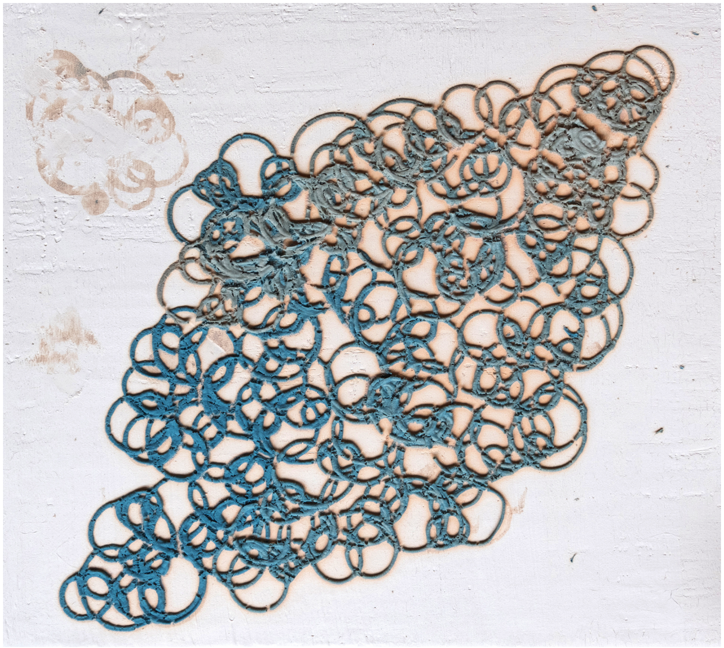


Figure 5
Adding graded colour to the glass paste

To avoid this, experiments conducted with different geometrical layouts during the 3D printing, as well as with more layers in each print led to the conclusion that several layers of mixture has better structural coherence, though too many layers make the structure warp and collapse. Using the fusing process with the equipment available at the KADK, we have achieved successful results with this material at a small scale. A real life situation would require rigorous systematic development of technique and material in order to secure reliable results in a large-scale production. While this is not the scope of the project we do suggest it may be a viable route for future architectural projects.

An opportunity in this process of making is the adding of colours. For this purpose, we have used ceramic stains that fire up to 1300 degrees Celsius. By varying the amount of stains added to the material mixture, which regulates the saturation of the colours. Furthermore, we have investigated ways of creating continuous colour gradients by filling varying colours in the same printer cartridge (Fig. 5).

The paste is 3D printed through an extrusion process. For this process, we have developed bespoke tools for extrusion that allow us control over the flow rate (Fig. 6). The set-up consists of a robotic arm with an attached tube that feeds the glass paste from the printer cartridge. A linear actuator ram feeds the paste to a ViscoTec dispensing pen attached to the end of the robotic arm that allows us to stop and start the printing procedure according to the design and gives us control of fine printing. Glass has an inherent capacity to become 6 mm thick upon fusion, which coincides with the fact that the mixture needs a high concentration of flour in order to flow properly through the dispensing device and avoid pulling apart in the firing. The print paths are therefore scaled to these inherent material properties.

Once the print is completed, the material is fired in a ceramic kiln. Through experimentation we have found that the best temperature for sintering is 950 o C. Where higher degrees improve sintering, the material sticks to the separator and the layout of the pattern is blurred. Due to devitrification, a termo-chemical process that transforms the glass from an amorphous to a crystalline molecular structure, the fired material is no longer classified as glass. Nevertheless, if the material is recycled it will still be compatible with soda lime glass and be able to turn back into the amorphous glass state if fired at higher temperatures. During the firing process, the material contracts which may cause points of cracking if the material cannot contract uniformly. To prevent this breakage, we have developed methods of using the design of the patterns to strategically deposit the material for controlling the contraction (Fig. 7).

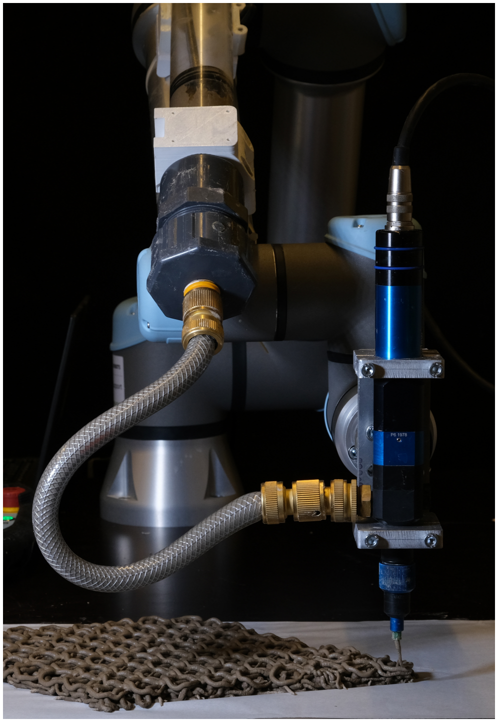


Figure 6
Final printing setup printing tool using a self developed cartridge system for glass paste and a professional volumetric dispensing system.

Figure 7
Contraction in the firing process

DESIGNING THE SILICA PATTERNS

In order to control the thermo-chemical material behaviour, we have chosen to work with long continuous line patterns to generate the toolpaths for the tiles. The needed consistency of the paste for the kiln firing procedure lowers the general precision during the printing process. Working with continuous lines requires less stopping and starting of the extrusion process and a higher degree of precision. Through experimentation, we have learned that working with directionality, continuity, density and overlapping allows us better control of the deformation during the kiln firing process. Inspired by spirograph drawing in which seemingly complex continuous lines are controlled through simple mechanisms, we have developed a system for creating continuous patterns, which can be steered by adjusting the amount of self-intersection points in defined areas to vary the density and thickness of the tiles. The entanglement of the lines create adhesion between the layers, which bond through pressure of gravity in the kiln. Working with longer continuous lines also gives the opportunity to load varying colours into the printer cartridge to produce seamless colour gradients throughout the tiles.

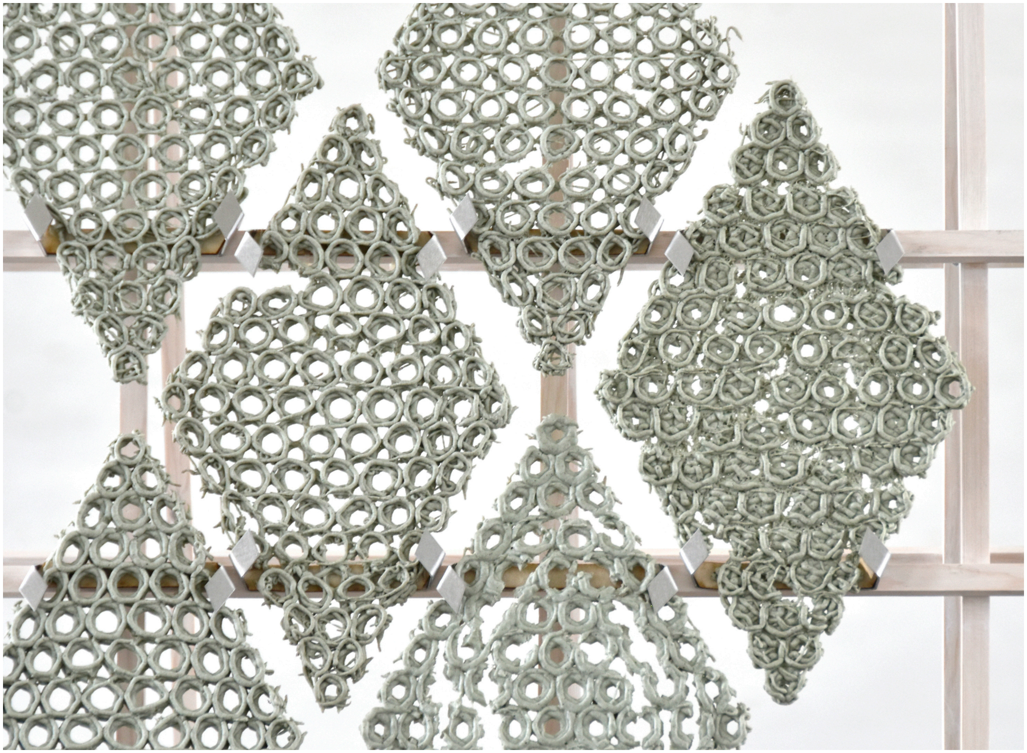
To test the material in an architectural scenario we have developed a shingle system by which the tiles are assembled into an architectural skin. The tiles are graded in their pattern, controlling the porosity in respect to light penetration. Bespoke brackets attached to an underlying scaffold are carrying the tiles in custom angles to avoid joining of fragile tile boundaries and to alter the experience of the screen from different viewpoints (Fig. 8). The prototype system consists of 11 individual tiles, varying from dense to sparse patterning, creating an overall screen.

CONCLUSION

Silica examines the 3D printing of glass materials through a two fold process. It develops a new material practice by mixing a new glass composite and creates novel forming processes. It builds an in-depth understanding of the parameters of fabrication and devising means by which to control these through digital design methods and their interfacing with robotic fabrication processes. At the same time, the project critically questions the architectural, aesthetic and performative properties of these material practices . By using the architectural typology of the tile as a place of investigation, we ask how these new material practices can suggest new ways of understanding architectural boundaries through conditions of porosity, translucency, colour and pattern. Combining two conditions, one creative, circular and technological, the other analytic, conceptual and designerly, we are interested in understanding how these new circular material practices extend existing architectural vocabularies in aesthetic, conceptual and practical ways.

Further research perspectives lie with further developing the composition, forming process and firing of soda-glass based pastes. Where robotically steered processes can allow for the forming of more 3-dimensional pieces it will be important to understand how these pair with adequate firing processes. At this stage our interest has been to understand the material in the context of architectural applications, then future research will examine applications across product design, industrial design and further architectural scenarios in which the open structures and inherent porosity can find further application.

Figure 8
Silica: assembling graded tiles. Tiles attached to scaffold with aluminum brackets



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The project is undertaken as an interdisciplinary collaboration between architecture and glass design and merges scientific and artistic methodologies. Silica is a collaboration between architects Mette Ramsgaard Thomsen, Martin Tamke and glass artist Maria Sparre-Petersen with research assistant Emil Fabritius Buchwald and architecture student Simona Hnídková.The team thanks Reiling A/S, who has provided 1 ton of waste soda lime powder as a donation to the project. Reilling is the sole processor of recycled glass in Denmark, supplying cullet for the container glass production company Ardagh Holmegaard A/S.

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