Glass fabrication

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ABSTRACT: In architecture, the prevalence of computational design and digital fabrication has led to an increase in exploration of casting modulated geometry using fabricated molds. However, the use of mold making strategies are often limited to casting materials that conform easily to mold geometry (i.e. concrete, plaster, resin, ceramics, etc.). It is rarely that fabrication strategies are used to explore materials with challenging behavioral properties such as glass. As a result, glass in its non-flat form has been underutilized in contemporary architecture. Because of its complicated physical behavior and the technical difficulties associated with the fabrication processes, architecture education often avoids exploring such medium. One key challenge with casting glass using fabricated refractory molds relates to understanding the behavior of glass under certain physical conditions and temperature profiles. If such parameters are not anticipated, the geometry of the final casted elements can be substantially different from the design intentions. This research argues that computation can be used to predict glass forming behavior under different temperature profiles, which can inform the design and fabrication processes. The goal is to highlight the importance of integrating the complexities of the physical reality into the design and fabrication processes, especially within the context of the educational experience. To contribute to this creative discourse this paper explores the limits of precision from computation to fabrication as it relates to casting glass. The objective is to design and test an algorithm for predicting edge/corner geometry of casted glass under different temperature profiles. Physical experiments are used to evaluate and recalibrate the prediction algorithm. Results show that the digital predictions are within acceptable tolerance and can be enhanced using data from physical experiments.

KEYWORDS: digital fabrication; glass casting; mold fabrication; computation; precision

INTRODUCTION

Material fabrication is emerging as an active interdisciplinary sphere for design exploration and research, in which, the quest for sustainable and environmentally responsible processes and products has never been more pressing. According to the United States Environmental Protection Agency (EPA) 2018 report, landfills in the USA received approximately seven million tons of glass waste (found in municipal solid waste (MSW) in 2015 and only 26.4 percent of all generated glass was recycled[i]. In this context, design solutions that utilize glass recycling innovations can be invaluable for promoting sustainable, healthy communities and can be instrumental in the responsible management of our resources and waste.

Glass is a fascinating and unique material. Due to its astounding visual, optical and structural properties, glass can be suited for many applications in art and architecture; providing a rich source for exploring new formative and performative possibilities. However glass in its non-flat form has been underutilized in contemporary architecture. Because of its complicated physical behavior and the technical difficulties associated with the fabrication processes, design fields often shy away from exploring such medium. Recently, the prevalence of computation and machining is providing new platforms for material testing and fabrication which are readily available to support creative inquiries into exploring new controlled processes and precise applications. To contribute to this critical discourse, this paper investigates solutions through testing methods for glass forming using open face molds; highlighting the importance of integrating the complexities of the physical reality into the design and fabrication processes. The goal is to explore the limits of precision from computation to fabrication as it relates to casting glass. In this context, digital predicting modelling provides valuable tool for simulating behavior to inform the actual physical fabrication. This research is set to design an algorithm for predicting edge/corner geometry of casted glass under different temperature profiles. Physical experiments are used to evaluate and recalibrate the prediction algorithm. The physical experiments were conducted within a context of an applied practical educational experience.

1.0 BACKGROUND

The discovery of glass can be highlighted as one of the most creative achievements of human history. By heating and melting a commonly abundant crystalline solid (sand), a new state of matter emerges that exhibits astonishing visual and physical qualities. Despite its solid form, glass is considered to be a liquid because of its non-crystalline structure. In the absence of any molecular structural order, glass can be defined as a “melted inorganic product that has cooled to a solid state without undergoing crystallization” (Beveridge, Doménech and Pascual 2005, 24). Because of its unique visual and optical qualities (transparency and translucency), glass as a unique medium offers many creative possibilities and the ability to fulfil to a wide range of aesthetic and functional needs. While there is a wide range of glass forming techniques (blowing, stretching, flashed glass, blow molding, pressed glass, etc.) this paper focuses specifically on forming glass using open face refractory molds (Martin 2006; Thwaites 2012). In this process, granular glass is places in refractory open face molds, heated to melt in a kiln and then annealed, cooled and removed from the mold. When glass softens, its molecules become mobile and flow and adapt to a mold’s geometry. With the increase of fusion temperature, the glass becomes less viscous; allowing it to flow easier filling more intricate geometry. As this viscous liquid cools down the molecules become rigid again and preserves the final geometry.

Today, glass as a building material provides an essential component of modern and contemporary architecture. Glass is mostly utilized in its sheet form (window glass) or structural glass (glass blocks), which serve primarily as part of the building envelop (Wigginton 2002; Eskilson 2018). Other mold forming processes (i.e. casting, glass slumping, etc.) are still underutilized in architectural applications. This research argues that the versatility of the mold forming processes can be invaluable for designers and architects; providing unique strategies for fabricating a wide range of innovative glass applications (Glass blind, glass walls, glass vessels, etc.). However, because of the challenging forming behavior of glass, it is essential that designers understand how glass geometry changes under different temperature and manufacturing parameters. In this context computation and predictive modeling provide valuable tools for simulating the behavior of glass based on data from actual physical experiments. Considerable amount of research into modeling, simulation and optimization of glass forming processes has been carried out. Most of this research, however, relates to container manufacturing by blow molding (Cormeau, Cormeau, and Roose1984; Cesar de Sa 1986; Burley and Graham 1991; Graham, Burley and Carling 1992; Groot, Giannopapa, and Mattheij 2011; Giannopapa, and Groot 2011) and to the fabrication and optimization of optical glass (Stokes 1998; Su, He and Yi 2011; Sarhadi, Hattel and Hansen 2014; Sarhadi, Hattel and Hansen 2015; Pallicity et al. 2015; Nguyen, Yuan, and Wu 2016; Zhou et al. 2017). In architecture, beyond the flat form, mold forming research has been very limited and mainly focuses on examining the structural aspects of glass (Patterson 2008; Lindqvist 2013) It is rarely that the limits of precision between computation and the fabrication of glass is examined. To contribute to this creative discourse, this paper explores computational strategies for the prediction and fabrication of a refractory mold system for forming glass.

2.0 MATERIALS AND METHODS

2.1. Research design

This research explores the limits of precision between design intentions, mold fabrication and the geometry of casted glass. Because of the challenging behavior of forming glass in refractory molds it is critical that fabrication processes are able to anticipate the accurate geometry of the final casted elements, which can be substantially different from the mold geometry and the design intention. This research argues that computation can be used to predict glass forming behavior under different temperature profiles, which then can be used to inform the design and fabrication processes. The goal of this research is to design an algorithm that is able to accurately predict edge/corner geometry of casted glass under different temperature profiles. Physical experiments are used to evaluate and recalibrate the prediction algorithm.

2.2. Scope and limitations

For the purpose of designing the algorithm as well as conducting the controlled experimentation, research scope is limited to testing edge/corner geometry of one type of glass with 96 Coefficient of Expansion (COE). Open face ceramic molds are used to cast glass tiles with thicknesses ranges between ¼ - ½ inch.

2.3. Theoretical and technical grounding: prediction chart

In order to understand and map the geometric behaviour of different corner/edge conditions of the casted glass, both a theoretical study and a technical pilot study were conducted. Results from both studies were used to inform algorithm design. The theoretical study was informed by different recommendations from the manufacturers of 96 glass. In the technical pilot study, 96 COE glass frit was placed in fabricated high temperature molds, heated in a glass kiln to different temp profiles (1300-1700F), annealed and removed from the molds. The goal is to create an accurate prediction chart for mapping the different geometric behaviour of edge/corner geometry of 69 COE casted glass in open face moulds with ¼ - ½ inch thicknesses. Figure 1 shows the final synthesized forming chart for casting the 96 COE glass under six different temperature profiles.

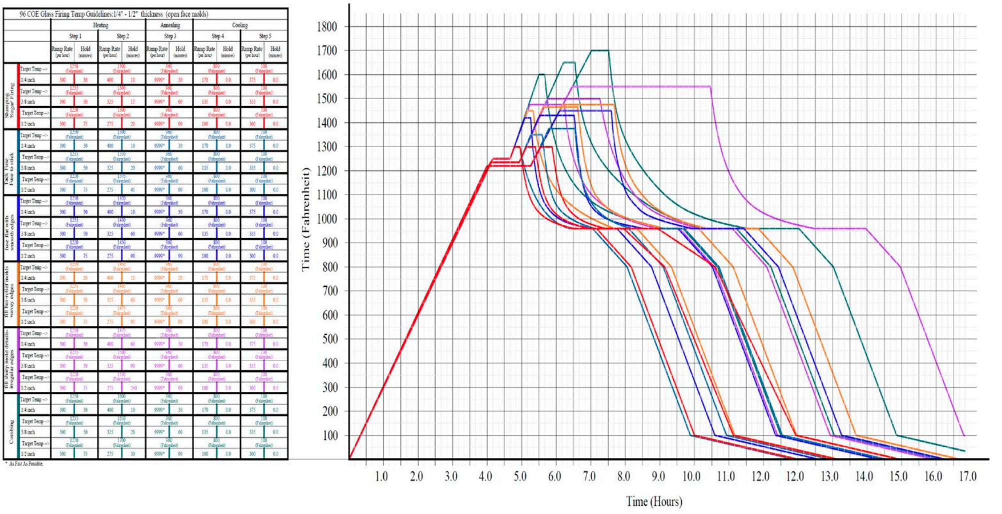


Figure 1. Casting behaviour chart of 96 COE glass under different temperature profiles. Source: (Ajlouni 2018)

2.4. Instrumentation

This research utilizes an algorithm designed by the author using C++ Programming Language to predict the edge/corner geometry of casted 96 COE glass under the different temperature profiles synthesized in Figure 1. The Open Graphics Library API (OpenGL) is used to render vector graphics and the OpenGL Utility Toolkit (GLUT) is used for implementing windowing application programming interface. Code editing was done using the Visual Studio Integrated Development Environment (IDE).

The algorithm is designed to predict the corner/edge shape based on two main parameters: corner/edge mold geometry and temp profiles. Figure 2 (left) shows a visual chart of the different edge/corner conditions under six forming temperature profiles. As an example, the predicted corner/edge of a right angle corner is shown in Figure 2 (right). By applying this prediction to different geometric patterns, it is possible to anticipate the edge condition of final casted glass geometry (Fig. 3).

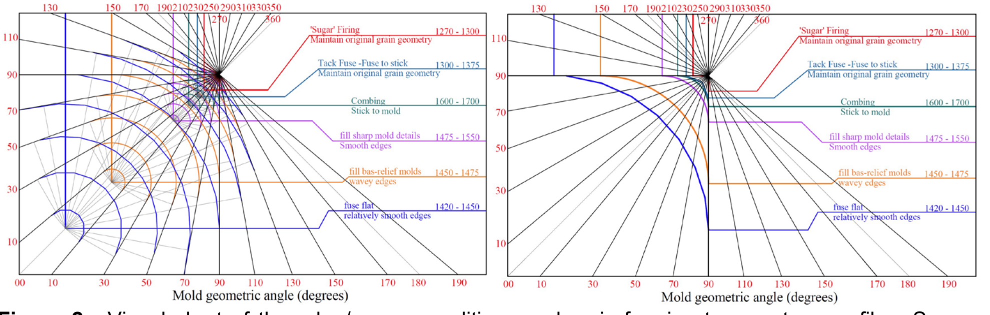


Figure 2. Visual chart of the edge/corner conditions under six forming temperature profiles. Source: (Ajlouni 2018)

3.0. PHYSICAL EXPERIMENTATIONS

Physical experimentations were conducted in the context of a glass casting class within an architecture academic experience. Five groups of students were tasked with casting glass tiles based on five different geometric patterns provided by the instructor (Fig. 4). The first three patterns (Fig. 4 a-c) are periodic and were constructed by repeating two basic units (Ajlouni 2008). The last two patterns (Fig. 4 d-e) are quasi-periodic and were constructed by using non-periodic relational networks (Ajlouni 2012, Ajlouni 2013). The different geometric arrangements allow for testing different corner/edge conditions while keeping all other experiments variables constant.

The goal of these experiments is to explore the limits of precision between the mold corner geometry and the resulted corresponding casted glass corner geometry. All experiments were limited to testing a temperature profile range between “fill bas-relief molds” (1450-1475) to “fill sharp mold details” (1475-1550). This temp range allows the fully fused glass edges to ‘flow’ filling corner details while not sticking to the molds. Experiments were designed to generate variations of the dependent parameter ‘output’ (glass edge/corner geometry) based on testing ranges of variations across two independent ‘input’ parameters (mold edge/corner condition and temperature profile). All other parameters are kept the same (constants) (glass type (96 COE glass), frit size, glass thickness (¼ - ½ inch), fusing temp range (1450-1550), tile size (1-2 inch wide), open face ceramic mold, fabrication processes, material recipes, firing kilns (Paragon glass kilns, Delphi Ceramic kiln, etc.). The process includes the design and fabrication of the open face refractory molds and casting the 96 glass frit.

3.1. Fabrication of refractory ceramic molds

Glass casting requires the fabrication of a mold system that is able to withstand a temperature profiles up to 1800 Fahrenheit. Ceramic materials provide great refractory medium that can withstand temperatures higher than 3000 Fahrenheit. More critically, ceramic molds have a lower coefficient of expansion than glass, which is essential to allow the release of the casted glass tiles from the molds. The process of fabrication the refractory mold is explained in the next few sections.

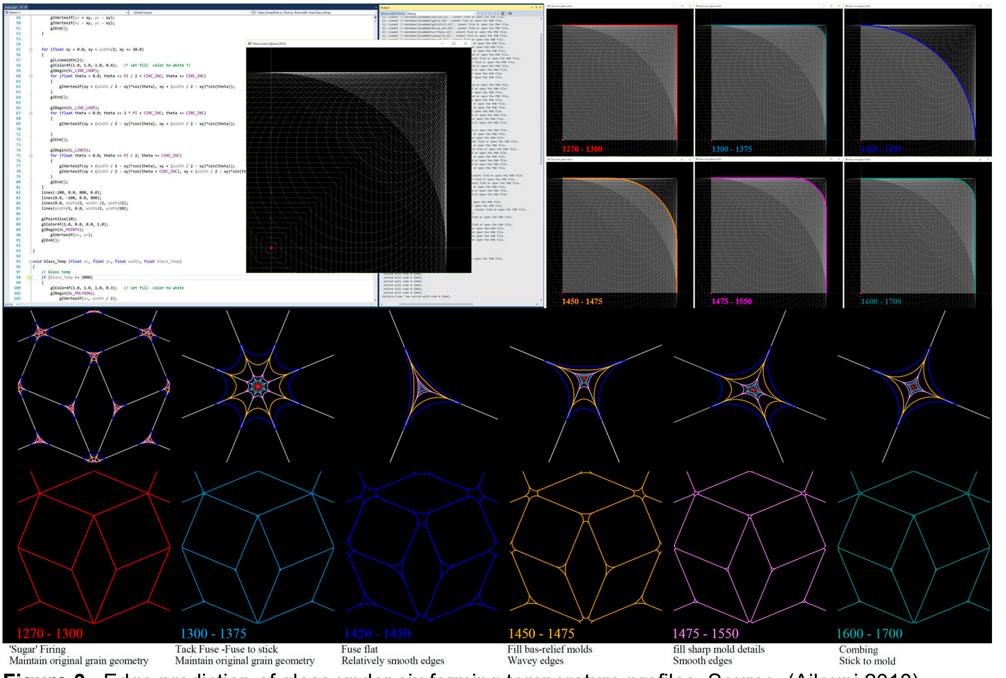


Figure 3. Edge prediction of glass under six forming temperature profiles. Source: (Ajlouni 2018)

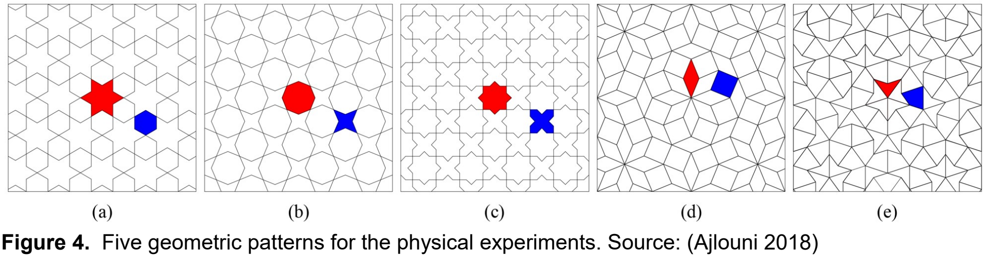


Figure 4. Five geometric patterns for the physical experiments. Source: (Ajlouni 2018)

Step #1: Design and machining of the master mold

The refractory ceramic mold making process starts by designing the master mold (positive) using a 3D modelling software (i.e. Rhinoceros 3D, 3D Max, etc.) The geometry of the master mold is designed with sloped edges to allow for easier release of the different castings. All molds were machined with a 3-axis CNC mill using a medium density polyurethane foam or machining wax. The molds were later sanded to smooth-out unwanted tool textures or sharp edges. Figure 5 (top) shows the final machined molds for repeated elements of the five different patterns.

Step #2 Slip casting the negative mold

Slip casting provides an excellent method for the fabrication of intricate and complex mold geometry. In this process, a liquid clay (slip) is poured into a plaster mold to form a layer of clay on the inside walls of the mold. After reaching the desired wall thickness, the excess slip is poured out of the mold and the clay is left to dry to a leather form before it can be released. The plaster mold (positive) is casted from a negative flexible mold material (i.e. rubber), which is casted from the CNC machined master mold (Fig. 5 (bottom)).

Figure 5. Top: The machined master molds. Bottom: Casting the plaster molds from a flexible rubber molds. Source: (Class reports)

Figure 6 (top) demonstrates the process of casting the ceramic mold (negative) using a positive plaster mold. Because the slip shrinks when drying, dusting the plaster mold with Talc was needed to help release the leather hard clay from the plaster mold. All experiments used the same slip recipe (cones 05-04 (1888 -1917 Fahrenheit). The dried ceramic molds were then fired in a ceramic kiln to a peak temperature of 1945 Fahrenheit.

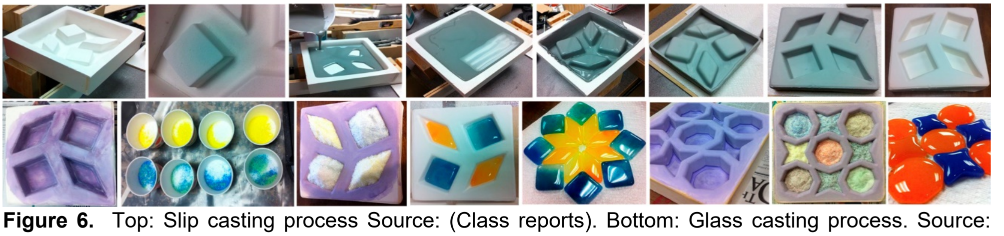


Figure 6. Top: Slip casting process Source: (Class reports). Bottom: Glass casting process. Source: (Class reports)

3.2. Casting 96 COE glass

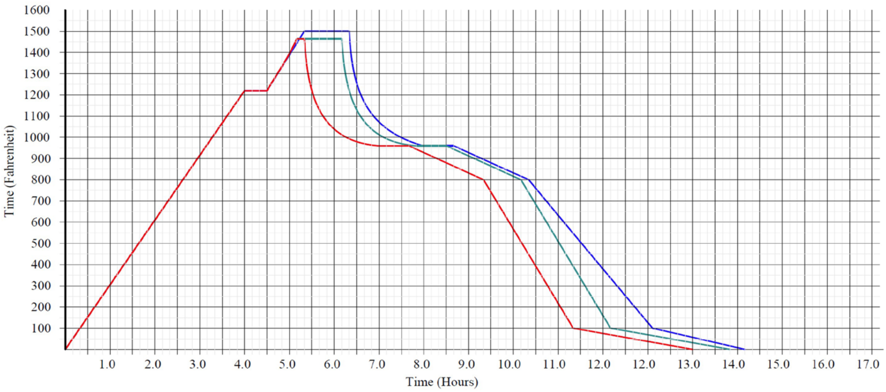
To help release the casted 96 COE glass from the ceramic molds, 3-4 coats of kiln wash was brushed on the molds cavities. The same granular glass frit size was used to fill the ceramic mold geometric cavities. The volume of glass frit was calculated by weight based on the desired final glass thickness (¼ - ½ inch) (Fig. 6 (bottom)). Glass was then fired in a glass kiln (Paragon) according to the temperature profiles in figure 7.

4.0. RESULTS AND DISCUSSION

In general, the five groups of experiments were successful in casting the repeated patterns using 96 COE glass. The molds were used multiple times without any visible signs of deformation or structural defects. All casted glass elements have smooth and shiny surfaces with no signs of stress or visible defects (bubbles, devitrification, cracks, etc.). The casted glass results from the five experiments are shown in figure 8. The results show that glass edge/corner conditions were visibly rounded and none has sharp edges or corners. Variations of edge geometry of the same casted elements were also visible, however these differences did not affect the overall visual coherence of the pattern.

In order to evaluate the predicted corner geometry, a random representative three tile sample for each pattern were selected and closely analysed. Figure 9 shows an overlap of the initial design (black line), the casted glass geometry (green Line) and the geometric prediction lines for three profile temperatures (1420 -1450: blue line, 1450-1475: orange line, 1475-1550: violet line).

The results show that the predicted edges seem to be more consistent with the physical results when the tile is a convex polygon, in which all interior angles are less than 180° and vertices are pointing outwards away from the interior of the shape. However, predictions were less consistent when, at least, one of its internal angles are more than 180° and the tile shape is concave. The change in internal angle from convex to concave resulted in an unexpected deformation of the line connecting the two vertices. This suggests that the algorithm needs to be recalibrated to anticipate this condition. The results also show that the thickness of the tile affected the accuracy of the results. Glass volume within the thinner profiles (¼ inch) was not enough to fill-in the cavities of the mold to reach the mold walls; resulting in a more rounded edges than predicted. Nevertheless, this can be avoided by raising the lower limit for glass thickness as well as making sure that glass volume is calculated correctly.



96 COE Glass Firing Temp: 1/4" - 1/2" thickness (open face molds)											
		Heating				Annealing		Cooling			
		Step 1		Step 2		Step 3		Step 4		Step 5	
Experiments		Ramp Rate (per hour)	Hold (minutes)	Ramp Rate (per hour)	Hold (minutes)	Ramp Rate (per hour)	Hold (minutes)	Ramp Rate (per hour)	Hold (minutes)	Ramp Rate (per hour)	Hold (minutes)
Full Fuse	Target Temp -->	1220 (Fahrenheit)		1465 (Fahrenheit)		960 (Fahrenheit)		800 (Fahrenheit)		100 (Fahrenheit)	
	Temp-Profile 01	300	30	600	10	9999*	40	100	0.0	350	0.0
	Target Temp -->	1220 (Fahrenheit)		1465 (Fahrenheit)		960 (Fahrenheit)		800 (Fahrenheit)		100 (Fahrenheit)	
	Temp-Profile 01	300	30	600	60	9999*	40	100	0.0	350	0.0
	Target Temp -->	1220 (Fahrenheit)		1500 (Fahrenheit)		960 (Fahrenheit)		800 (Fahrenheit)		100 (Fahrenheit)	
	Temp-Profile 02	300	30	600	60	9999*	40	100	0.0	300	0.0

* As Fast As Possible.

Figure 7. Temperature profiles for firing the glass-filled molds. Source: (Ajlouni 2018**).**

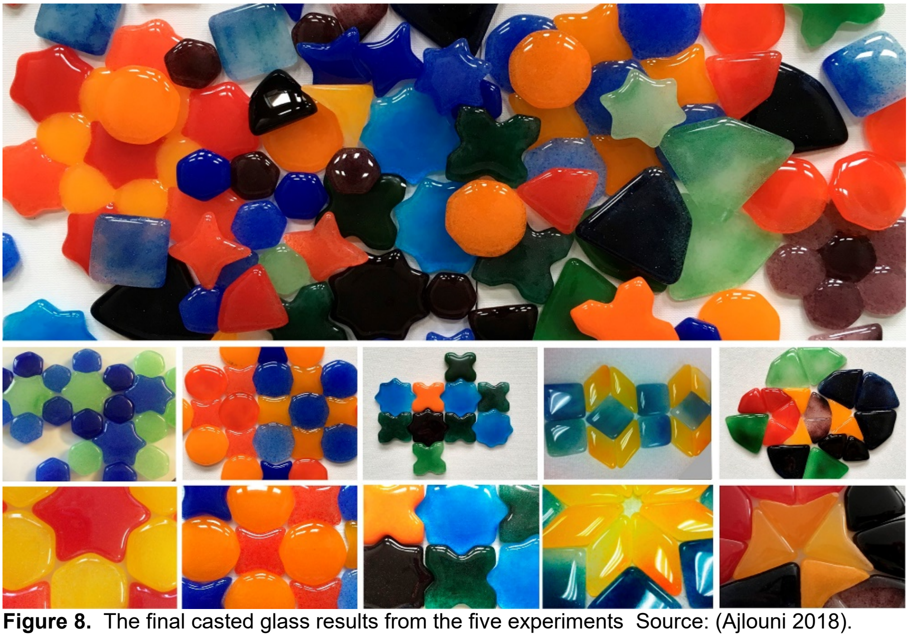


Figure 8. The final casted glass results from the five experiments Source: (Ajlouni 2018).

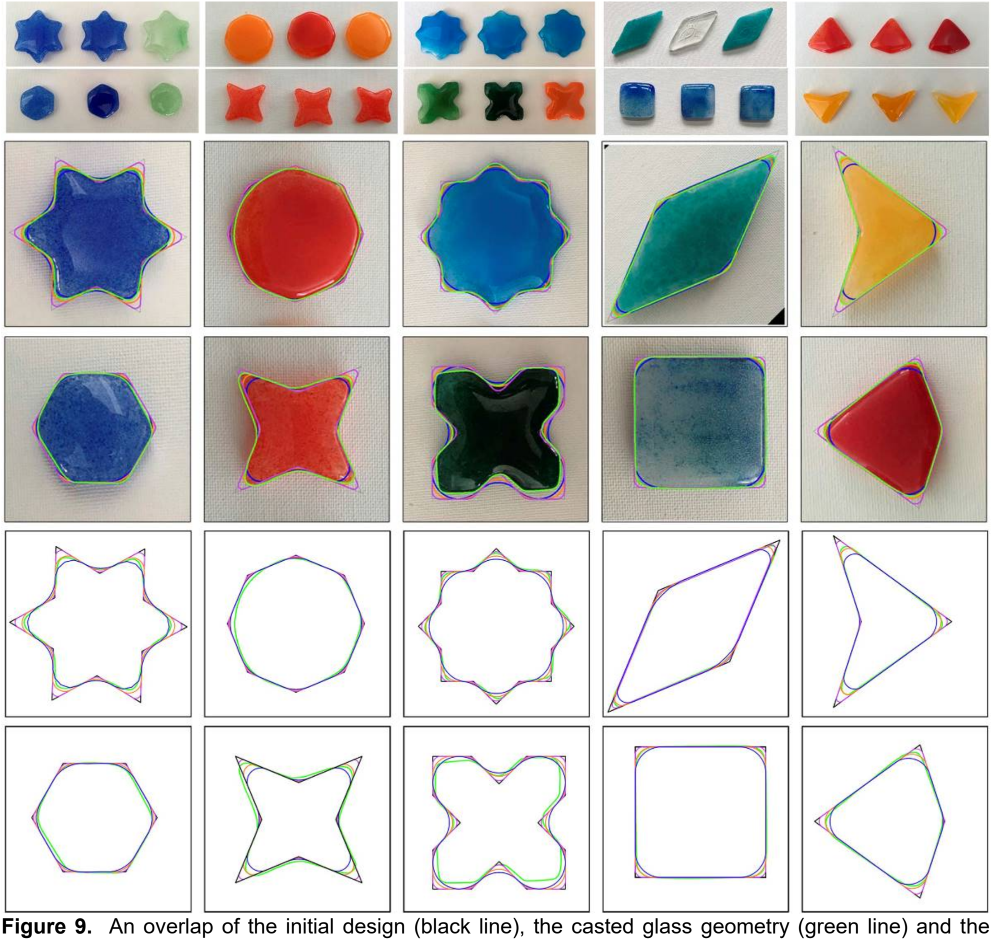


Figure 9. An overlap of the initial design (black line), the casted glass geometry (green line) and the geometric prediction lines for three profile temperatures (1420 -1450: blue line, 1450-1475: orange line, 1475-1550: violet line. Source: (Ajlouni 2018)

The physical results also suggest that the angle of tapered mold walls has some effect on the accuracy of the final casted edges. In the mold fabrication process, this slope was designed to allow an easier release of the final casted glass. While this factor (mold wall slope) needs to be accounted for in the calculations, more physical data is still needed to measure the deformation based on the degree of slope.

The experiments also show that when adding a texture relief on the surface of the tile, the sharp texture edges are rounded after casting (Fig. 10). In order to allow the viscous glass to capture the exact detailed relief and to fill-in all small cavities, the glass needs to be fired to a higher temperature (1750), which resulted in wetting the mold and glass edges were deformed because it stuck to the mold. Therefore, a delicate balance between design details and firing profile is needed to allow the glass to fill-in the mold cavities without sticking to its boundaries.

Figure 10. A texture relief on the surface of the casted tile. Source: (Ajlouni 2018)

In general, the results from the experiments provided enough evidence to validate the tested hypothesis, however, in order to account for all glass casting parameters, additional data from physical experiments are needed to fine-tune the predictive modeling algorithm.

CONCLUSION

This research was set to explore the limits of precision between design intentions, mold fabrication and the geometry of casted glass using refractory molds. It argues that in order to improve tools for computational design and making, architecture education needs to integrate the complexities of the physical reality into the design and fabrication processes. Computation was used to predict glass edge/corner forming behaviour under different temperature profiles. Results from the experimentations provided preliminary evidence to validate the hypotheses as well as to evaluate and recalibrate the designed algorithm. More importantly, the glass fabrication experiments provided the opportunity for the students to directly interface with glass as a design medium; highlighting the importance of integrating the behaviour and complexities of the physical material into the design, computation and fabrication processes. This paper also argues that it is only through integrating cross-disciplinary knowledge and skills and through adopting a systematic and scientific approach to materials investigation that innovative glass design solutions can be achieved. Future research includes adapting this process to test the deformation and slumping behaviour of different types of glass (i.e. Sodium-Calcium glass, Lead glass, Borosilicate glass, etc.). Specifically, future efforts will focus on understanding the forming behaviour of recycled-post-consumer glass, which presents an abundant resource for reusable material in architecture. Methods for incorporating post-consumer glass into contemporary design applications can be instrumental in saving energy, resources and time.

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ENDNOTES

[ii] https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/glass-material-specific-data.