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Self-forming curved moulds

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TECHNISCHE UNIVERSITÄT WIEN
Vienna | Austria

Diplomarbeit

Self-forming curved moulds: A case study of extruded polystyrene

ausgeführt zum Zwecke der Erlangung des akademischen Grades
einer Diplom-Ingenieurin unter Leitung von

Senior Artist Dr.in techn. Efstathia Eleni Baseta
E264/2 Institut für Kunst und Gestaltung
Dreidimensionales Gestalten und Modellbau

eingereicht an der Technischen Universität Wien
Fakultät für Architektur und Raumplanung
von

Ivana Susic
11921685

Wien am 3. April 2024

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Abstract

This thesis introduces a novel low-tech adaptable casting technique for production of double-curved non-uniform concrete panels. Presently, there are numerous studies into creating formwork for casting concrete in complex shapes and the techniques are ever evolving. However, flexible formwork has yet to find widespread industrial application. This thesis gives an overview of the current state of the art, looking briefly at traditional formwork, such as wooden and steel

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formworks, but focuses mainly on novel concrete casting techniques, such as Fabric formwork, 3D-printing, adaptable moulds, as well as subtractive formwork such as, CNC-milling and hotwire cutting.

Similar to the above-mentioned techniques, this thesis presents a concrete casting method using foam formwork, namely extruded polystyrene (XPS). The research explores how XPS becomes malleable when submerged in a solution of acetone and water. The XPS maintains deformation upon drying. This simple, low-tech approach makes it more accessible and, compared to CNC-Milling, it requires less material.

The research includes qualitative experimentation of 3 parameters. Firstly, the effects of different concentrations of acetone solutions on XPS. Secondly, variable thicknesses of XPS samples, and lastly, duration of the submersion of XPS samples into acetone-water solutions.

The research continues with the development of a fabrication process, which introduces a gravity-informed self-forming XPS mould. The method incorporates a geometric pattern within the extruded polystyrene, which controls the shape of the mould surface and subsequently the shape of the concrete results. This technique is tested and adjusted through a series of experiments, which conclude with a case study, presenting a possible application of the method. In the case study, 9 concrete façade tiles are fabricated.

From the research it is concluded that this technique is viable for the production of double-curved, non-uniform concrete elements.

Keywords: Concrete casting, Flexible Mould, Double-Curved Surfaces, Formwork, Extruded Polystyrene, Gravity-Informed, Self-forming

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Abstrakt

In dieser Arbeit wird ein neuartiges, anpassungsfähiges Low-Tech-Gießverfahren für die Herstellung von doppelt gekrümmten, ungleichmäßigen Betonelementen vorgestellt. Heute gibt es zahlreiche Studien zur Herstellung von Schalungen für das Gießen von Beton in komplexen Formen, und die Techniken werden ständig weiterentwickelt. Allerdings hat die flexible Schalung noch keine breite industrielle Anwendung gefunden. Diese Arbeit gibt einen Überblick über den aktuellen Stand der Technik und geht kurz auf traditionelle Schalungen wie Holz- und Stahlschalungen ein, konzentriert sich aber hauptsächlich auf neuartige Betongießtechniken wie Gewebeschalungen, 3D-Druck, anpassungsfähige Formen sowie subtraktive Schalungen wie CNC-Fräsen und Heißdrahtschneiden.

Ähnlich wie bei den oben genannten Techniken wird in dieser Arbeit eine Betongussmethode vorgestellt, bei der Schaumstoffschalungen verwendet werden, nämlich extrudiertes Polystyrol (XPS). Es wird untersucht, wie XPS verformbar wird, wenn es in eine Lösung aus Aceton und Wasser getaucht wird. Beim Trocknen bleibt die Verformung des XPS erhalten. Dieser einfache, technologiearme Ansatz macht es leichter zugänglich als Betonschalungsmethode und erfordert im Vergleich zum CNC-Fräsen weniger Material.

Die Forschung umfasst qualitative Experimente zu 3 Parametern. Erstens, die Auswirkungen verschiedener Konzentrationen von Acetonlösungen auf XPS. Zweitens die Auswirkung unterschiedlichen Dicken der XPS-Proben auf der Verformbarkeit und drittens die Dauer des Eintauchens der XPS-Proben in Aceton-Wasser-Lösungen.

Die Forschungsarbeiten werden mit der Entwicklung eines Herstellungsverfahrens fortgesetzt, bei dem eine durch die Schwerkraft bedingte, selbstformende XPS-Gußform eingeführt wird. Bei dieser Methode wird ein geometrisches Muster in das extrudierte Polystyrol eingearbeitet, das die Form der Oberfläche und damit die Form der konkreten gegossenen Objekte steuert. Diese Technik wird in einer Reihe von Experimenten getestet und angepasst, die mit einer Fallstudie abgeschlossen werden, in der eine mögliche Anwendung der Methode vorgestellt wird. In der Fallstudie werden 9 Beton-Fassadenfliesen hergestellt.

Aus den Untersuchungen wird geschlossen, dass diese Technik für die Herstellung von doppelt gekrümmten, ungleichmäßigen Betonelementen geeignet ist.

Schlüsselwörter: Betonguss, flexible Form, doppelt gekrümmte Oberflächen, Schalung, extrudiertes Polystyrol, Schwerkraft-gesteuert, selbstformend

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I'm also immensely grateful for the help and endless patience of the members of the team in the model building workshop, for providing amazing facilities and technical support to my somewhat strange undertaking.

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And finally, I am deeply thankful to my parents Slavica and Dejan Susic for your unwavering support, encouragement and understanding throughout this process. Thank you for always being available, day and night for any big or small issue. And a particular thank you to my brother Stefan Susic for our discussions and for believing in me.

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1 Introduction

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1.1 Motivation

As architects, we are all very well acquainted with extruded polystyrene foam. Many of us have used it to build quick models for the purpose of visualizing and understanding our ideas all throughout our years of study and beyond. We also know it very well for its highly insulating properties, as we oftentimes return to this material for insulation of the thermal building envelope as we design and plan different buildings.

This research project takes a novel, curious, and experimental approach to this well-known material. This new approach grew out of an artistic course called KÜP X (short for Künstlerisches Projekt X, Eng.; Artistic Project X) at the Vienna University of Technology. The course was led by Efilena Baseta, who encouraged experimentation with materials, and even combining them with other substances as a way of finding new approaches and uses for them.

It was known by then that acetone dissolves polystyrene, and this had even been used for modelmaking. These two materials were picked for some experimentation to see whether this could lead to some new findings. A semester was spent dropping pure acetone onto different polystyrene foams, until one day where water was added to the acetone and it was observed how the polystyrene went from a rigid foam to a soft material, that could be manipulated into any imaginable shape. This sparked a tremendous curiosity towards the material and its potential. Upon the conclusion of the course, the curiosity lingered and sparked the beginning of more in-depth research on this topic, becoming the framework for this thesis. In addition to the knowledge and intuitive understanding of the materials developed during the previously mentioned course, a desire to understand the materials and how they interact led to a myriad of material experiments that make up the foundation of this research.

The findings of these material tests, along with the understanding that this rigid material can become malleable, then upon drying goes back to being rigid, and that this is repeatable, inspired the application of this property as formwork for casting, which is also the sole focus of this thesis. The vast possibilities that the combination of these two materials offers are conveyed through the application of this method to produce concrete façade panels.

Although this thesis focusses on these findings and the development of this method for producing concrete formwork, this could prove to be a very versatile method for other applications beyond the field of architecture. While it is acknowledged that this material might not be the most environmentally friendly one, the hope is that this research might still offer a new perspective or inspire new ideas.

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2 Theoretical Framework

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2.1
Image of concrete being poured into formwork.

2.1 Concrete casting techniques

This thesis is a case study of extruded polystyrene as a flexible foam formwork for casting concrete elements. This chapter will focus on novel and innovative approaches for casting complex shaped concrete elements.

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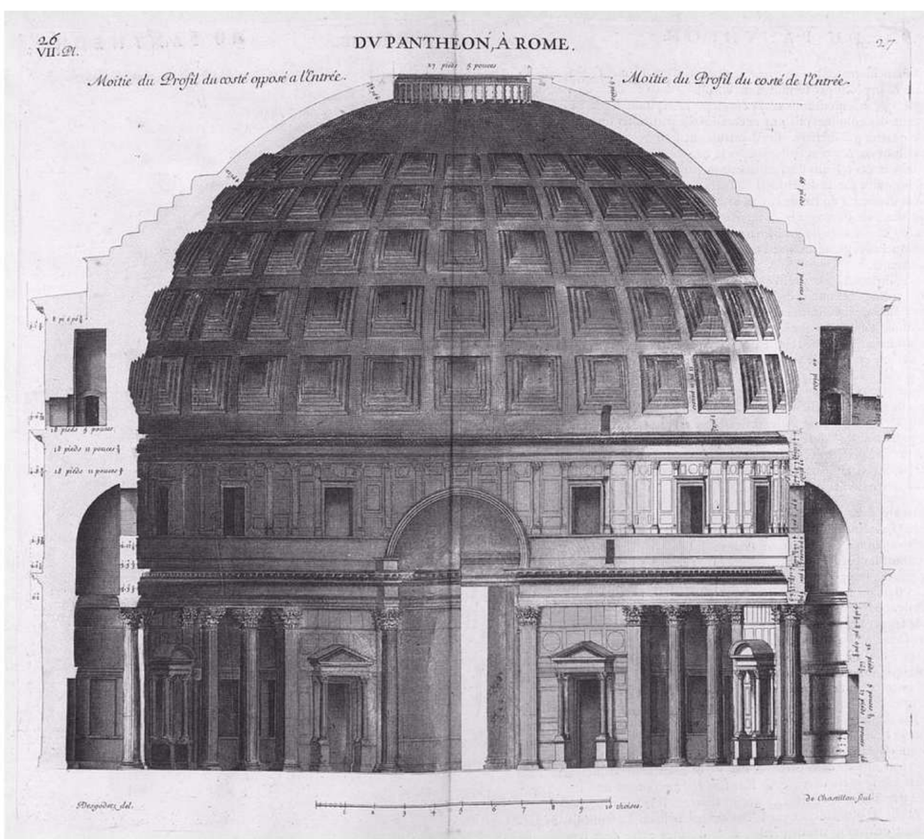
2.1.1 Historical overview

Concrete was first discovered and used in the Roman empire, where they would mix volcanic sand with water and a burned powder of limestone to create a substance with hydraulic properties. Once this material cured, it was very strong. This new material allowed the Romans to construct incredible structures and build their empire. Since wet concrete is not a solid building material, it needs a formwork to give it its shape while it cures and becomes self-bearing.



2.2
Section of Pantheon in Rome,
built between 25 and 27 BC.
Drawing by Antoine Desgodetz

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2.3
Example of wooden formwork for concrete casting.

1 Eiffel trading . (2024)

2 Gromicko, N., & Shepard, K. (2024)

3 Strickland, M. H. (2010)

4 Shah, M. S., Noor, N. M., Kueh, A. B., & Tamin, M. N. (2019)

Thus, the Romans where also the first to develop early concrete casting methods[1,2]. The Romans built a framework and shuttering from wood and reeds to cast vaults, arches, and domes from concrete. Today, we can still observe some examples of what they built in concrete: one of the most notable structures is the Pantheon in Rome[3].

Wooden formwork for casting concrete has been used throughout history and is still used today[4]. With the industrial revolution and steel becoming cheap and accessible, steel formwork for concrete casting started appearing. By the

1950's, steel became the commonly used material for formwork.
Later on, formwork made from aluminium also appeared offering a lighter formwork than steel.
Metal formworks are also still used today.
Both wood and steel formworks are rigid, which is good for simple, regular shapes, but is challenging when it comes to complex freeform shapes.
Historically flexible formwork in the form of textile moulding techniques for concrete casting has also been explored. Possibly one of the first uses of textile formwork was in 1899[5], where Gustav Lilienthal mounted a fabric between two floor beams and used it to cast a concrete slab. With the development of new synthetic textiles in 1960, which had a higher strength, higher durability and a lower cost, the interest in fabric formworks grew. Since then, many architects and engineers have worked on developing techniques for textile formworks. However, it has yet to find a widespread use in the building industry and still requires research.
With the arrival of plastic, new opportunities for concrete casting methods have appeared. The interest in using plastic as formwork for concrete casting has especially grown since the end of the 20th century and the beginning of the 21st. Plastics are generally lighter than traditional rigid formwork, i.e. wood and steel, and can be fabricated into more complex shapes, which makes it more flexible in terms of design. With the introduction of thermoplastic foams, many possibilities have emerged, especially when paired with digital fabrication. However, plastic formwork is not the most environmentally friendly material.
Some of the current concerns with any formwork, but particularly for freeform buildings and concrete elements, are the high costs associated with complex shapes, as this requires more intricate formwork to cast the concrete elements6[6].
Another concern is the reusability of complex formwork, as it can often only be used once due to either the moulding material being disposable, or the formwork not being needed more than once due to its complex shape.
There are many new approaches and research in this field, and new techniques are constantly being developed.

5 Li, W., Lin, X., Bao, D. W., & Xie, Y. M. (2022, February 6)

6 Kim, K., Son, K., Kim, E.-D., & Kim, S. (2014, June 27)

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2.4
Example of fabric formwork suspended on an external structure. HiLo, prototype built at ETH Zürich.
© Block Research Group, ETH Zürich / Naida Iljazovic

2.1.2 State of the art

2.1.2.1 Textile formwork

As mentioned above, textile formworks are nothing new. These formwork systems are ever evolving, and there are already many different techniques available for casting concrete[7].

7 Veenendaal, D., & Mark West, P. B. (2011, September 2)

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2.5
Concrete wall fabricated by smocking fabric.
Prototype by Annie Locke Scherer
Photo by Fredric Boukari

One of the more notable techniques for textile formwork is suspending the fabric on an external support and letting the casting material self-form within the formwork.

Another approach is using pneumatic fabric formwork. In this method, a membrane is connected to a foundation and then inflated with air. The air pressure is essentially what lifts the fresh concrete into a shape. This method has successfully been used to create concrete shell structures. Research has also gone into creating fabric formworks that are shaped internally through their structure

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2.6
Double-curved concrete façade elements produced by Stanecker, Penn Textile solutions and Institute of Textile technology, Aarchen University.
© Stanecker Betonfertigteilwerk GmbH

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either by knitting, sewing, or smocking the fabric. These create different patterns that allow for control of the cast concrete's shape. An example of this is a wall prototype being produced by creating a smocking pattern in a textile sheet and then casting concrete[8].

On a more industrial scale, fabric formwork is already used by the company Stanecker to create concrete façade elements. The technique was created in collaboration with the company Penn Textile solutions, as well as the Institute of Textile Technology at the Aachen University[9,10]. In this method, the concrete façade elements are shaped through drapable textile reinforcement.

The advantage of fabric formwork is the relatively low cost of fabric materials, as well as the method being low-tech, meaning it does not necessarily require any large-scale expensive infrastructure. Textiles also offer very flexible formwork, which can sometimes even be reused. However, the design freedom of textile formwork is limited to symmetrical and uniform shapes, and it is challenging to use when truly free-form formworks are in mind.

8 Scherer, A. L. (2021).

9 Dittel, G., Koch, A., & Gries, T. (2017, September 8)

10 Dittel, G. (2019, January 2)

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2.7
Adapa adaptive mould D200.
An elastic formwork surface is shaped by a grid of rods.

2.1.2.2 Adaptable fabrication technique

Although adaptive formwork has existed and been used in other industries, such as the aerospace and automotive sectors, it is still relatively new and experimental. The adaptable formwork consists of a flexible and elastic surface, which is deformed by a grid of underlying computer-controlled rods. The height of each individual rod in the grid can be controlled, and thereby create any freeform. Extensive research on this topic has been done by H.R. Shipper at TU Delft[11].

11 Schipper, H. R. (2015)

Meanwhile, the company Adapa[12] has already taken large steps to commercialize this manufacturing method. They produce large-scale industrial adaptable moulds, which have already been utilized in some construction projects.
The advantage of this method is that the formwork is reshapable, eliminating the need for several moulds for individual pieces, as the machine can just change the shape as needed and thereby greatly reduce material waste.
Casting concrete with an adaptable formwork system requires expensive infrastructure, as well as the expertise on this specific type of digital fabrication. Furthermore, although the technique allows for a great deal of design freedom and produces double-curved concrete elements, the shapes are limited to the height of the rods in the machine.

12 Adapa. (2024)

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2.8
3D Printed flexible formwork for casting of concrete elements.
by Brian Peters

2.1.2.3 Additive fabrication techniques

An additive fabrication technique is formwork which is created by the addition of material. This is essentially how 3D-printing works, where an object is created by adding layer by layer of material and fusing the layers. There are two ways of using this technique for concrete element manufacturing.
3D-printing offers a wide range of different filaments and processes, and the technology is constantly developing. This also means that formworks can be

customized and produced with any properties needed for the casting of concrete elements. An example of this is the flexible 3D printed formwork prototype by B. Peters at the Kent State University[13], which is used to precast concrete elements. The formwork printed in this research is flexible, and thus makes reuse possible.

Another approach is 3D-printing with concrete directly as the filament. In this case, a secondary structure is needed to support the printed concrete under its own weight and to control the outcome.

13 Peters, B. (2014)

2.9
3D-printed concrete in an adaptable mould. Prototype fabricated by 4TU at TU Delft.

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14 Costanzi, C. B., Schipper, R., Bos, F., Ahmed, Z., & Wolfs, R. (2017)

In the case of this prototype fabricated as part of the 4TU project at TU Delft[14], a temporary support surface is suggested in the form of a flexible mould, combining the previously mentioned adaptable formwork along with 3D printing of concrete.

The advantages of these techniques are the multitude of options for 3D-printing along with the process of addition of material, which offers a great deal of design freedom for the manufacturing of concrete elements. This also means that little material goes to waste. On the other hand, 3D-printing, like the adaptive formwork, also requires expensive high-tech machinery and specific know-how. Another challenge of 3D-printing as a fabrication method is oftentimes the scalability, as well as long production times due to the layering nature of the process.

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2.10
Example of 5-axis CNC-milling of wood.

2.1.2.4 Subtractive Fabrication techniques

The most common moulding techniques for complex shapes of concrete elements are subtractive fabrication methods, where the casting mould is shaped by removing material in the desired shape. Usually, this method is paired with a computer-controlled machine for digital fabrication.
One of these methods is robotic computer numerical control (CNC) milling of wood, plastic, or even metal. The CNC-milling machine has a rotating toolbit,

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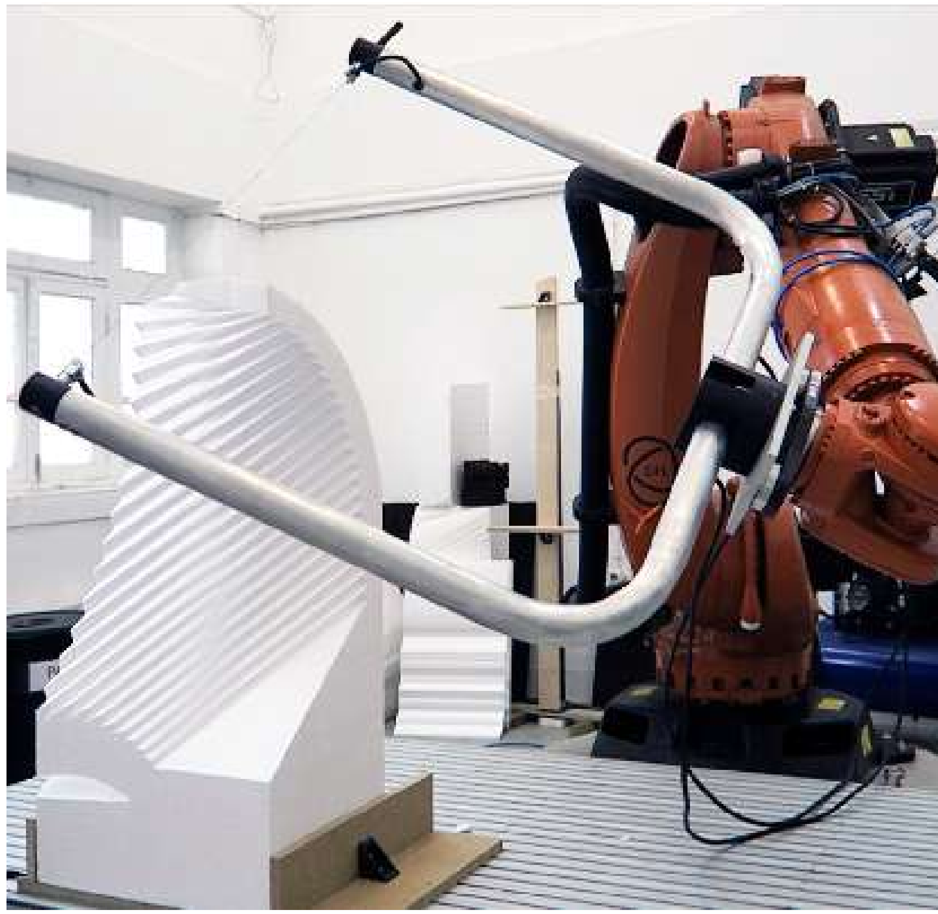

2.11
Robotic hotwire cutting of EPS. Fabrication of prototype by P. Martins, P. Campos, J. P. Sousa

which cuts away material in a defined pattern. In this way, the CNC-milling process can achieve a very high level of accuracy in the production of very intricate, complex shapes.

Another subtractive fabrication method is robotic hotwire cutting. As the name suggests, this method uses an electrically heated wire, to cut through materials. This also means that this method is restricted to materials that can be thermally cut. Thermoplastics, like expanded or extruded polystyrene, are oftentimes used for this. Automating the process of hot-wire cutting through robotics allows for the cutting in several axes, which is needed for complex patterns.

Similar to hotwire cutting, abrasive wire cutting uses a diamond threaded abrasive wire to cut through the formwork material. The wire is suspended between two rotating wheels, and the cutting process is also automated using robotics to control the wire in more axes. Benefits of the abrasive wire include that it is not limited to specific materials, and that it is faster compared to the two methods mentioned above.

The company Odico[15] is one of the first to develop machinery for large-scale

15 Odico. (2024)

2.12
Prototype fabricated using abrasive wire cutting by Søndergaard, et al. 2018

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2.13
Fjordenhus by Olafur Eliasson.
© Studio Olafur Eliasson

robotic CNC-milling, robotic hotwire cutting, and abrasive wire cutting. With their tools, several projects with complex, free-form shapes have already been realised, including a research prototype by Søndergaard[16] as well as the building "Fjordenhus" by Olafur Eliasson.

However, the subtractive fabrication method does present some challenges. To produce formwork in this way, high-cost infrastructure is needed. It also has a relatively long fabrication duration, particularly in the case of CNC-milling. The design freedom is also somewhat limited in the case of the wire techniques, as the wire restricts certain movements, e.g. some negatively double-curved surfaces. Additionally, as the subtractive method is based on removing material for the formwork, this does mean that the technique comes with a high amount of material waste. Researchers have come up with some solutions for the material waste, for example by optimizing the cutting process in a way where every leftover material piece is actually a part of the formwork.

This thesis will suggest another way of reducing the material waste, by only milling a superficial pattern into a moulding material, while the rest of the shaping can be contributed to the material properties and gravity.

16 Søndergaard, A., Feringa, J., Stan, F., & Maier, D. (2018, December 18)

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2.14
Workspace during thesis research. Shows preparations for material experiments.

2.2 Materials

This thesis is structured around the exploration of the interaction between extruded polystyrene and a water acetone solution. This chapter offers a brief outline of the primary materials that are explored and an intuitive observation on how they interact.

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2.15
Extruded polystyrene boards produced by AustroTherm.

2.2.1 Extruded polystyrene

Polystyrene exists in our surroundings in many different forms, usually as a solid or foam. It is a commonly used plastic and can be found everywhere from the medical to the automotive industry. Most people use it daily in the shape of e.g. protective packaging, containers, bottles, disposable cutlery, etc.

Polystyrene was discovered in 1839 by Eduard Simon[17], a German chemist in Berlin. He had distilled an oily substance from storax, the resin of a tree, which

17 Demselben. (1839)

he named styrol. After a few days, the styrol had turned into a viscous gel. Today, styrol is known as styrene and the gel-like substance it turned into was polystyrene. Polystyrene is a polymer, meaning it's a long chain of smaller building blocks called styrene monomers. The styrene monomer molecule has the chemical formula C8H8.

Even though styrene can be found in some trees and fruits, and polystyrene can form naturally from styrene as in Simon's case, polystyrene today is synthetically produced and is a massive branch of the petrochemical industry. Industrial styrene is derived from ethanol and benzene. To produce the long chains of styrene, i.e. polystyrene, the substance undergoes a process called polymerization, which presently is controlled by a propagation mechanism[18].

The polystyrene is then formed into small pellets, which can be further processed into the variety of different products mentioned above. Polystyrene in this form is colourless, hard, and brittle[19].This is also called general purpose polystyrene or GPPS and is relatively inexpensive to produce. Extruded polystyrene was first invented and patented in the 1940's by Otis McIntire. It was trademarked Styrofoam, which has become a synonym for extruded polystyrene. He added isobutylene to polystyrene, which caused bubbles to develop within the polystyrene, thereby creating the foam[20]. Since then, extruded polystyrene has become an important material, particularly in the building industry, and many more companies are producing the foam. While the process has improved over time, the basic logic has stayed the same.

The extrusion process starts by feeding the polystyrene pellets and additives into an extruder machine. Additives are different substances that add certain properties to the polystyrene foam, e.g. colourants, fire retardants, stabilizers, antioxidants, and, most importantly, the foaming agent[21].

The foaming agent is the additive that causes bubbles to form in the polystyrene,

20 Ray, M. O. (1950)

18 Wünsch, J. R. (2000)

19 PAGEV (2018)

21 Weber, H., De Grave, I., & Röhrl, E. (2000)

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which in the case of Styrofoam in the 1940s was isobutylene. This agent subsequently causes/creates the closed cell structure of the foam.

In the extruder machine, the polystyrene and the additives are mixed and blended under heat and pressure. The melted pass is then moved to a chamber, where the foaming agent within the melted mass causes the mass to foam up. The extruded polystyrene is then cooled down so that the structure sets. After it cools down, it is cut and sized and, depending on the product, it might also receive surface treatment[22].

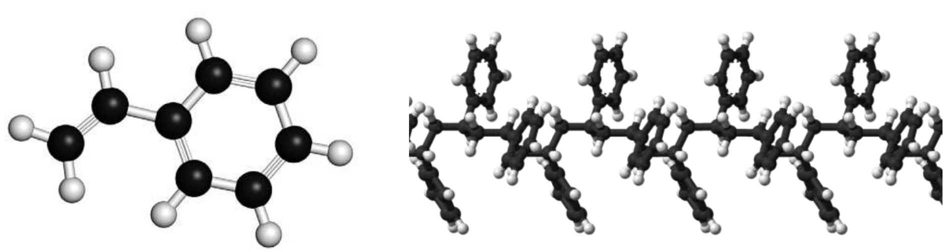
Depending on the product, extruded polystyrene usually consists almost exclusively of air (around 95%[23]). This makes the material very light, and the trapped air gives it great insulation properties. The heat conductivity of XPS usually lies between 0,03 - 0,04 Wm−1K−1. In contrast to general purpose polystyrene, extruded polystyrene is also a quite strong material.

For the purpose of this thesis research, the same extruded polystyrene product from the same company was used in all experiments, to keep that variable constant. This product is the Austrotherm XPS TOP 30 SF insulation boards[24]. The specific additives and blowing agents are unknown, although it does contain some form of colourant and flame retardant.

24 AustroTherm. (2023, 03 01)

22 Polyfoam XPS. (2024)

23 Chemical Safety Facts. (2018)



2.16
Left: visualization of a styrene molecule.
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Right: visualization of a polystyrene molecule.
Visualization found at Wikidwelling.

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2.17
Acetone used for experiments and fabrication.

2.2.2 Acetone

Acetone is a very common substance, which can be found everywhere in the environment, as it is naturally produced in plants and trees. It is even produced in humans[25] and animals as a byproduct of metabolism. Acetone is a common building block of organic chemistry, and it is the smallest and simplest of the compound group called ketones, which means it has a specific molecular structure. The chemical formular is (CH3)2CO.

25 CRC. (2016)

The liquid is easily recognizable. It has a strong distinct smell, which most people associate with nail polish remover. It is an organic solvent commonly used to break down or dissolve paints, varnishes, plastics, and synthetic fibres. On an industrial scale it is, among other things, used for production of lacquers paints cosmetics, pharmaceuticals, and as a precursor for the production of plastic and other chemical compounds[26].

The liquid was likely first produced by alchemists during the Middle Ages. It was obtained by dry distillery of metal acetates, which is achieved by combining acetic acid (e.g. vinegar) with a metallic base. The most common acetate used was lead acetate, and since metals used to be associated with planets, acetone was named "Spirit of Saturn". Historically, acetone was also used for both its solvent and flammable properties. Probably one of the earliest detailed descriptions of early production of acetone were published in 1610 by Jean Beguin, who established a school of pharmacy in Paris. It wasn't until 1832 that the empirical formula was determined by the chemists Jean-Baptiste Dumas and Justus von Liebig. In 1833, the name Acetone was proposed by chemists Antoine Bussy and Michel Chevreul by adding the suffix -one to the stem of the corresponding acid, in this case acetic acid. This was common practise for naming compounds at the compounds[27,28].

The first industrial production of acetone started during World War 1. In 1915, the chemist Chaim Weizmann had developed a method of producing acetone through the fermentation of glucose with the bacteria clostridium acetobutylicum. With the large demand for acetone to produce weaponry during World War 1, the British government scaled this production up to an industrial scale, and this practise spread to the United States and Canada as well. The process is known as the Weizmann process process[29].

26 Myers, R. L. (2007)

27 Gorman, M. (1962, January 1)

28 Gorman, M., & Doering, C. (1959, January 1)

29 Kauffman, G. B. (2024)

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These days, the large-scale industrial production of acetone is derived from petrochemical sources. The process that is most common nowadays is called the cumene-process, in which benzene and propene are used to produce cumene (or isopropylbenzene). In the next step, the cumene is oxidized, producing both acetone and phenol. One of the difficulties with the coproduction of acetone and phenol is the difference in the demand for the two substances. Other production methods also exist today. These include the dehydrogenation of 2-propanol and the oxidation of propene or diisopropylbenzene[30,31].

As for the physical and chemical properties of acetone, acetone is a clear, colourless, low-viscosity liquid with a very strong odour. It is completely miscible with water, solves with many other compounds, and is biodegradable. Pure acetone has a refractive index of 1,3588 and has a density of 0.7845g/cm3.

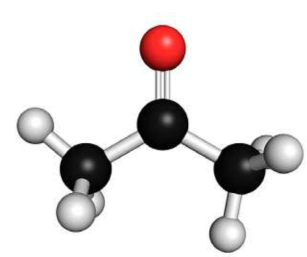
Most notably, acetone is very volatile and evaporates very quickly. Both the liquid and the vapour are highly flammable, which makes acetone hazardous. The vapours can spread to ignition sources and flash fire. Air mixtures with high concentrations of acetone vapours can also ignite at room temperature. However, the energy point of initiation of combustion is very high, so it is quite uncommon. Acetone can cause irritation on skin but is generally not considered particularly toxic. The vapours can cause dizziness and headaches[32].

The acetone used throughout this research is the acetone product produced by the company Meffert AG Farbwerke.

30 toppr. (2023)

31 Weber, M., Pompetzki, W., Bonmann, R., & Weber, M. (2014, January 31)

32 Akers, A. S. (2021, Juli 23)



2.18
Left: visualization of an acetone molecule.
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2.19
Pure acetone breaking down a block of extruded polystyrene. From the experiments conducted in the context of the KÜP X course.

2.2.3 Material coupling system

A chemical reaction happens when extruded polystyrene comes into contact with pure acetone. Acetone has solvent properties, and the acetone molecules penetrate the closed foam cells and weakens the structure that hold the polymer chains together. By observation, one notices that the polystyrene first swells before the material eventually starts to break down. What is left is a gel-like substance, which is likely polystyrene mixed with different additives added during the extrusion process. The polystyrene does not completely dissolve in the acetone. Currently, there are some studies looking into recycling this leftover substance of polystyrene with different organic solvents in different ways, e.g. as an adhesive[33].

33 Osemeahon, S. A., Usaku, R., & Ezekiel, E. (2022)

When the acetone is diluted with water, the strong effects on the polystyrene quickly change. Depending on the concentration of acetone, the effects differ. In low amounts, it does not seem to alter the properties of the extruded polystyrene at all. In high amounts, it breaks down in a similar fashion to the way it does with pure acetone, although it does appear to be slower. With the right ratio of acetone to water in the solution, the extruded polystyrene becomes soft and malleable, without signs of significant breakdown. The swelling of the material does still occur with some concentrations, without breaking down the material. This state of the material is essentially what this research is built up around.

Material experiments are conducted to determine the optimal ratio of acetone to water, that causes the material to soften. Furthermore, the optimal duration of the submersion and the impact of material thickness is tested as well.

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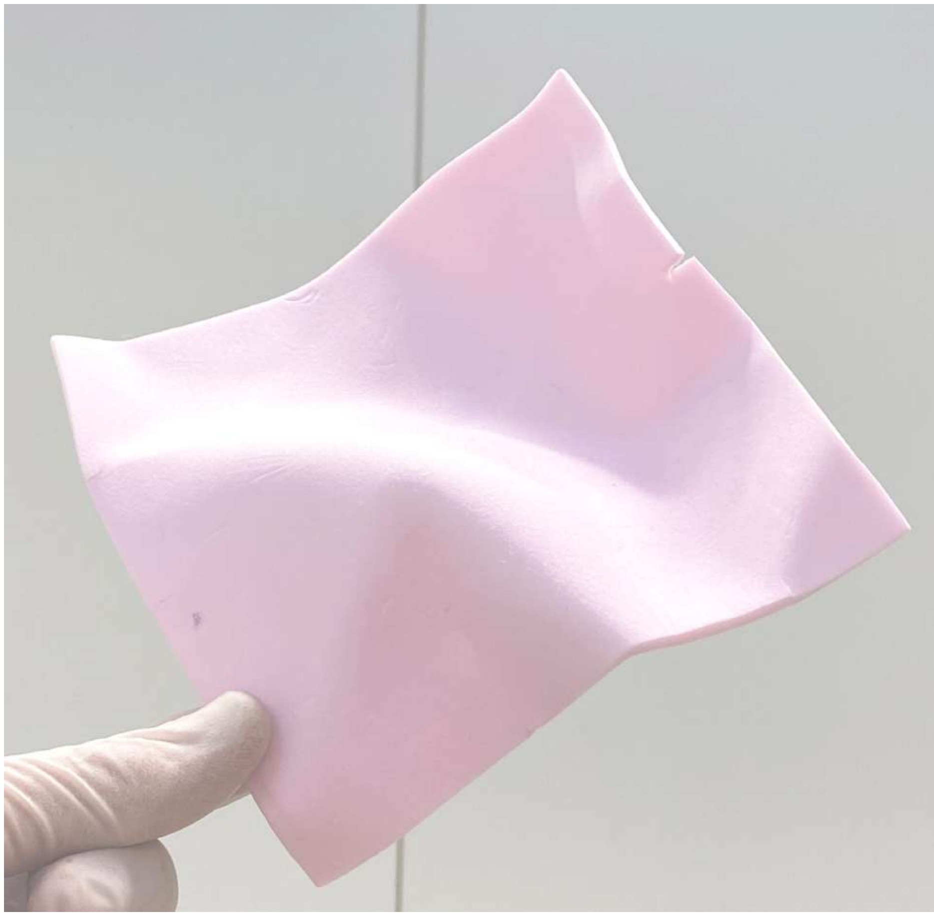

2.20
First sample deformed in water-acetone solution.
From the experiments conducted in the context of the KÜP X course. This lead to the thesis research.

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3 Material Experiments

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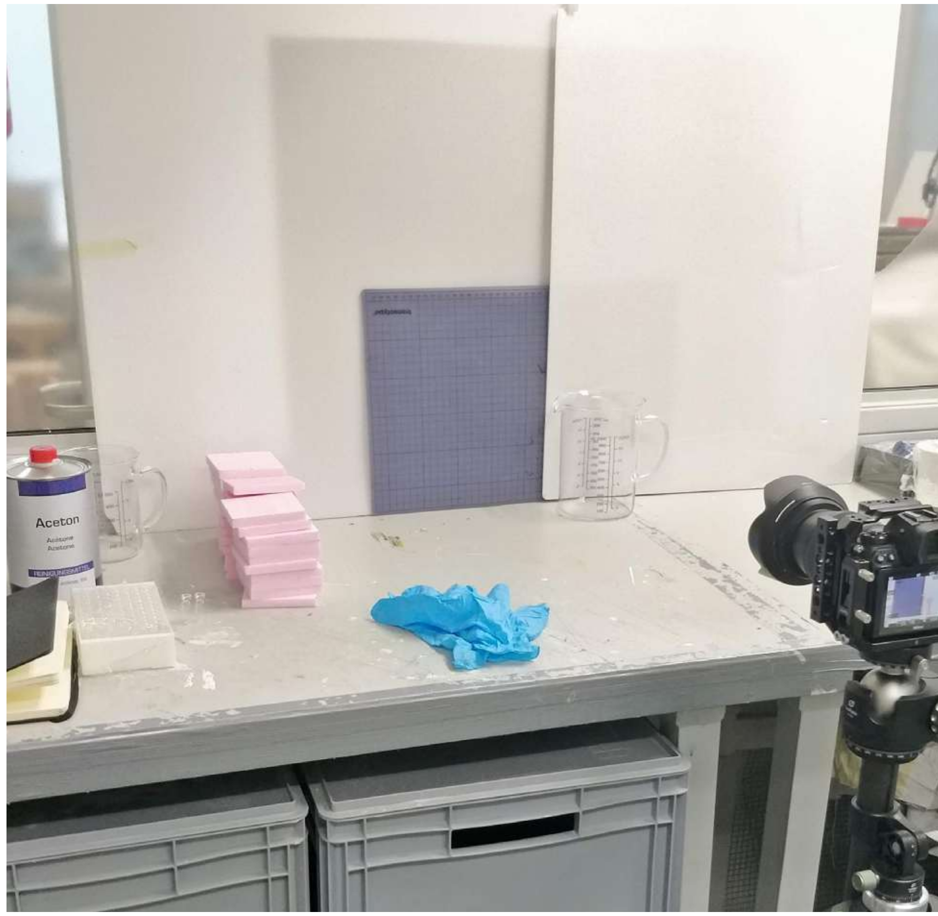

3.1
Setup for the material experiments.
Each experiment was filmed as documentation.

3.1 Setup

This series of qualitative experiments is built to better understand the specifics of how the two materials react to one another. 3 different series of material experiments are conducted to shed light on this.
First, a set of materials where different ratios of water and acetone are tested on identical pieces of extruded polystyrene for different durations of time. This is to establish how different concentrations of acetone impact the extruded polysty-

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rene and what impact the duration of the submersion of the XPS in the solution has on the material.

The second set of experiments focusses on exploring what impact the thickness of the extruded polystyrene sheets have on the malleability after the submerging process, and whether there are limitations to the thickness of the sheet, i.e. whether pieces with a thickness above a certain point cannot fully soak up the liquid, and thus not become malleable.

In the third series of experiments, the ability to not just deform and take shape, but also the ability to stretch a sheet of extruded polystyrene, is tested.

The experiments are prepared by hot wire cutting the pieces of extruded polystyrene into the desired size and shape. For the first set of experiments, 90 identical pieces of extruded polystyrene are used. For the second set, 16 pieces with varying thicknesses are needed, and for the third set, 9 pieces of varying thicknesses are needed. All pieces are identical in size 100 mm x 100 mm, except for the variations in thickness.

All 3 series of experiments are conducted using simple household items, such as measuring cups and beakers. For the last set of experiments, a spherical object is used, over which the sheets of extruded polystyrene are stretched into a double-curved shape. For documentation, a video camera is set up to record the effects.

All three series of experiments are conducted mixing a given solution of water and acetone in a measuring beaker. A sample of the mixture is taken for the measuring of the refractive index later on. A piece of extruded polystyrene is then submerged within that beaker for the given amount of time. It is then removed from the solution and deformed.

For the third series of experiments, a half-sphered object is milled in ureol and used in the experiments.

For safety measures, this research is conducted in a secure room, with a strong ventilation and without any power outlets or similar hazardous factors that could potentially lead to ignition of the acetone vapours. To prevent irritation of airways from inhalation of acetone vapours, as well as skin irritation, a mask and gloves are used during experimentation.

3.2
Snapshot from the end of the experiment at 80% acetone after 10 min submersion.

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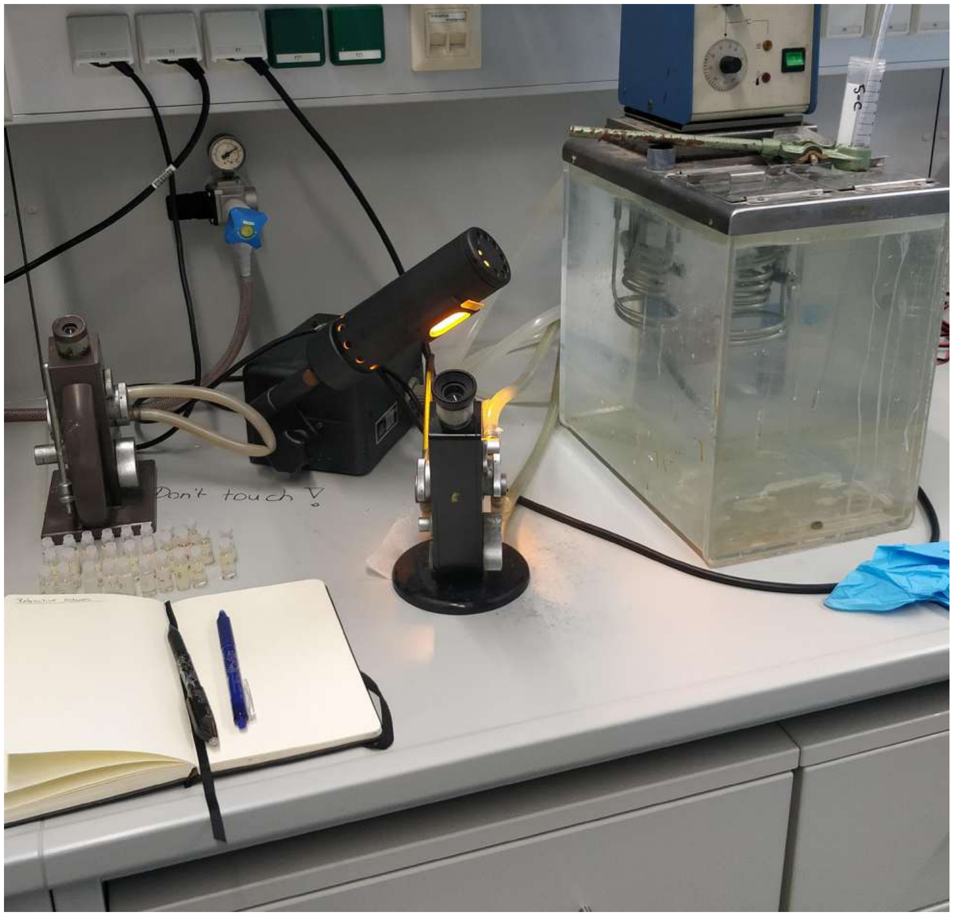

3.3
Workstation at the chemistry lab with the refractometer used for the measurements.

3.2 Concentration analysis & Refractive index

Acetone is a very volatile liquid that evaporates quickly. Additionally, water and acetone are measured and mixed in a regular glass measuring cup, which can lead to unprecise measuring, and so the optimal ratio for the experiments can be difficult to establish.

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To keep track of the concentration of acetone in the different solutions, the mixtures need to be comparable to one another by a measurable property that is going to differ depending on the concentration of acetone in the solution. For this purpose, the refractive index is measured and used. This is a property which is oftentimes times used to identify substances. The different solutions of water and acetone have different refractive indices.

The refractive index is a property of a substance which describes how light propagates through it. When light passes from one substance to another, its velocity changes. This change in velocity can be measured by a refractometer.

Before and after each experiment (approx. 1,5 h), a sample of the water-acetone solution is taken and later measured in a refractometer. In this way, it should be possible to estimate the actual concentration of the solution at the time of measurement. This can be done to test and keep track of the concentration levels throughout the experiments. By measuring the refractive indices of the experiments, it can also help identify the concentrations of the solutions that have the optimal effect on the extruded polystyrene, even if the measurements of the two liquids while mixing the solution is off, or acetone has evaporated after a period of time.

Once the three different material experiments are completed and the different samples for each experiment are collected, their refractive indices are measured and compared. The indices depend on various factors, including the temperature. The refractometer used for measuring in this study, is set to 25 °C. Prior to measuring the refractive index of each sample of solution used in the material experiments, the indices of pure water and pure acetone are measured. These values lie at 1,333 for water and 1,358 for acetone. The measurements for each sample are taken 3 times to account for possible errors while measuring and plotted into tables. The following tables and graphs show the results as well as a comparison to a study of refractive index of acetone-water solutions conducted in 2017.[34]

34 Upadhyay, M., & Lego, S. U. (2017)

3.4
Image of samples containing different acetone-water solutions from the experiments.

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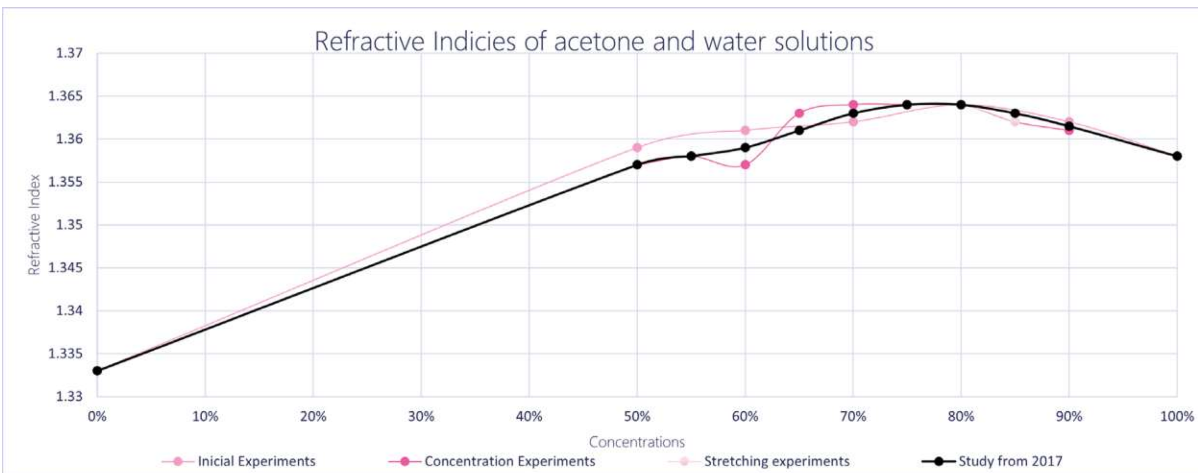
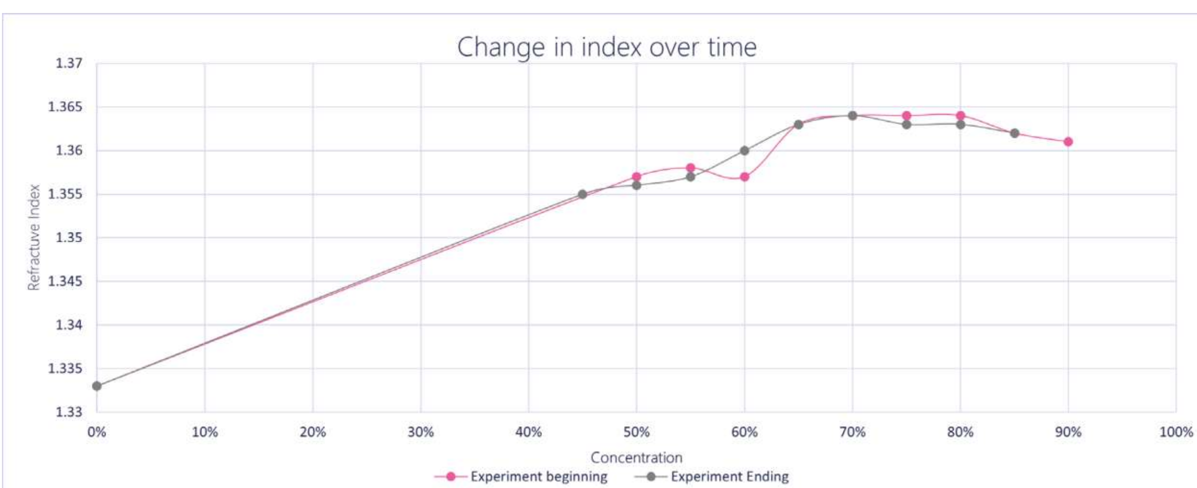
Inicial Experiment		Concentration Experiment				Streching & Sphere Expetiment		Study from 2017	
Concentration start	Index	Concentration start	Index	Concentration end	Index	Concentration start	Index	Concentration	Index
0%	1.333	0%	1.333	0%	1.333	75%	1.364	0%	1.333
50%	1.359	50%	1.357	45%	1.355	80%	1.364	50%	1.357
60%	1.361	55%	1.358	50%	1.356	85%	1.362	55%	1.358
70%	1.362	60%	1.357	55%	1.357			60%	1.359
80%	1.364	65%	1.363	60%	1.36	75%	1.364	65%	1.361
90%	1.362	70%	1.364	65%	1.363	80%	1.364	70%	1.363
100%	1.358	75%	1.364	70%	1.364			75%	1.364
		80%	1.364	75%	1.363			80%	1.364
		85%	1.362	80%	1.363			85%	1.363
		90%	1.361	85%	1.362			90%	1.3615
								100%	1.358

3.5
Table and graphs showing the concentrations and the matching refractive indices for the different experiments.



Graph showing the refractive indices for different experiments. The dots stand for each solution used in the given experiment.



Graph showing the refractive indices for the same experiment but at the begnning and at the end, to show the change in concentration after time has passed, as acetone evaporates fast. The indexes plottet show that approx. 5% of the acetone has evaporated after 1,5h.

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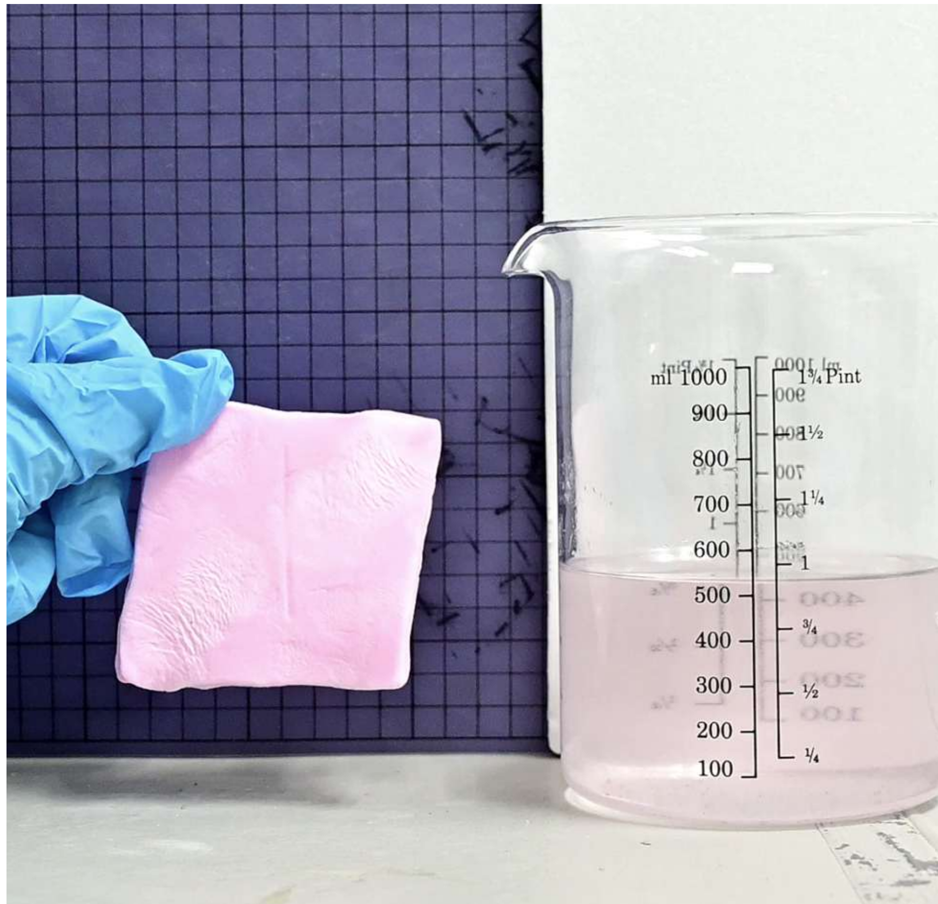

3.6
Snapshot of deformation of a 10 mm sample in the experiment at 80% acetone after 10 min submersion.

3.3 Time – Concentration

This experiment is designed to examine how different proportions of acetone and water affects XPS to find the most optimal ratio for softening the extruded polystyrene without causing it to break down. With the understanding that a higher concentration will cause more damage, it is worth exploring whether the duration of the submersion of a sheet of XPS affects the malleability of the material. If a longer duration of submission in a lower concentration can give the material similar malleability, but with less damage to its structure, it expands the opportunities for applications as well as reusability.

The experiment tests acetone-water solutions with the following acetone concentrations: 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, and 90%. Data from previous gained knowledge shows that concentrations below 50% does not affect and soften the extruded polystyrene to the desired extent, so these were excluded from the experiment. Similarly, upon conducting the experiment with an acetone concentration of 90%, a following test of a concentration of 95% is excluded, as the breakdown of the extruded polystyrene is too severe.

The different measurements of duration of submersion tested are the following: 30 s, 1 min, 2 min, 3 min, 5 min, 7 min, 10 min, 15 min, 20 min, and 30 min. These 10 different time measurements are repeated for all 9 concentrations, leading to 90 experiments conducted to test the relation between acetone-water ratios and duration of submersion.

The XPS samples are identical in these experiments. Their dimensions are 100 x 100 x 10 mm.

The results show that the effect of the acetone-water ratios below 70% did manage to soften up the material, but not to the desired extent, while the material was almost completely broken down at a concentration of 90%. The optimal ratio for the malleability and stretchability for the extended polystyrene lies within a range of 75% and 85%. This is the range that will be used in further experiments.

The duration of the submission of a sheet of extruded polystyrene into an acetone-water solution definitely has a clear effect on the malleability and stretchability of the material. Logically speaking, the longer the XPS is submerged, the softer it gets. Between the shorter submersion durations, the change in softness and malleability is notably bigger. Once a sample is submerged for longer than 15 minutes, it continues to soften, however the difference is insignificant in com-

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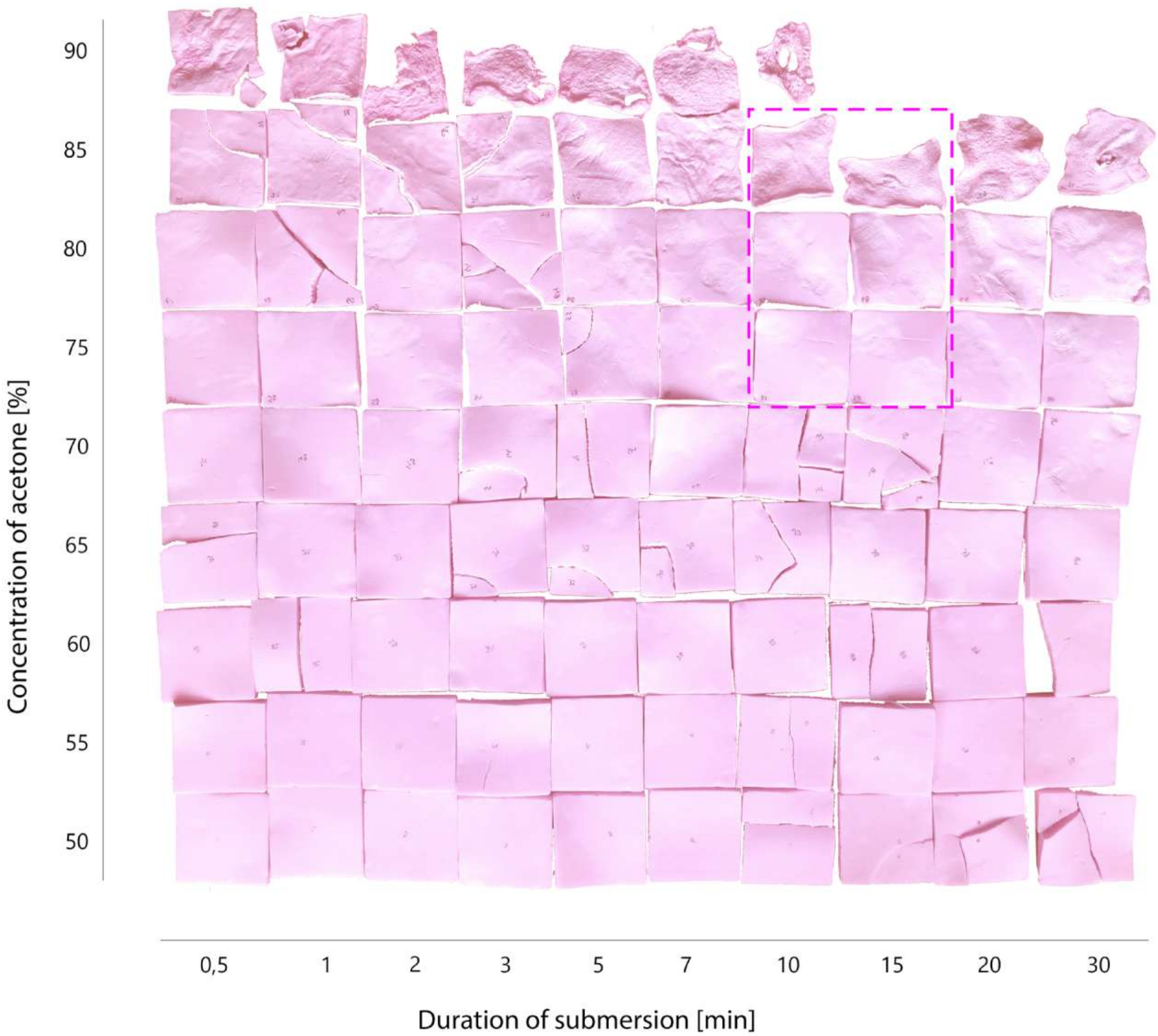
parison to the length of time. This means that the difference in the softness and malleability between 30 s, 1 min, 2 min, 3 min, 5 min, 7 min, and 10 min is quite big and it has a significant impact. However, the difference between 15 min, 20 min, and 30 min is relatively small in terms of the softness and malleability of the XPS samples.

Furthermore, the duration of the submersion should not be seen as an isolated variable from the concentration. At the lower concentrations under 65%, 30s of submersion barely has any effect on the XPS. In these cases, the very long durations are preferable to have a visible effect on the softness of the sample. Similarly, the lowest durations are preferable for the concentration of 90%, as a duration lasting any longer than a couple of minutes, breaks the material down entirely.

Consequently, for further testing, it appears a duration of 10 or 15 minutes of submersion at the above-mentioned 75%-85% is optimal.

Interestingly, comparing the results concerning the optimal concentration of softening the extruded polystyrene to the results of the refractive index measurements, these concentrations also seem to have the highest index measurements before the curve and values sink again with the highest concentration of acetone and pure acetone. Whether this correlation shows that these properties are linked in any way, or this correlation is just a coincidence, is an interesting topic for future research, but will not be investigated within this research.

3.7
Image of early tests that lay the foundation for the material experiments.



3.8
Image of all samples from the time-concentration material experiments.
They are lined up accorning to concentration and duration. The dashed pink outline shows the optimal concentration and time.

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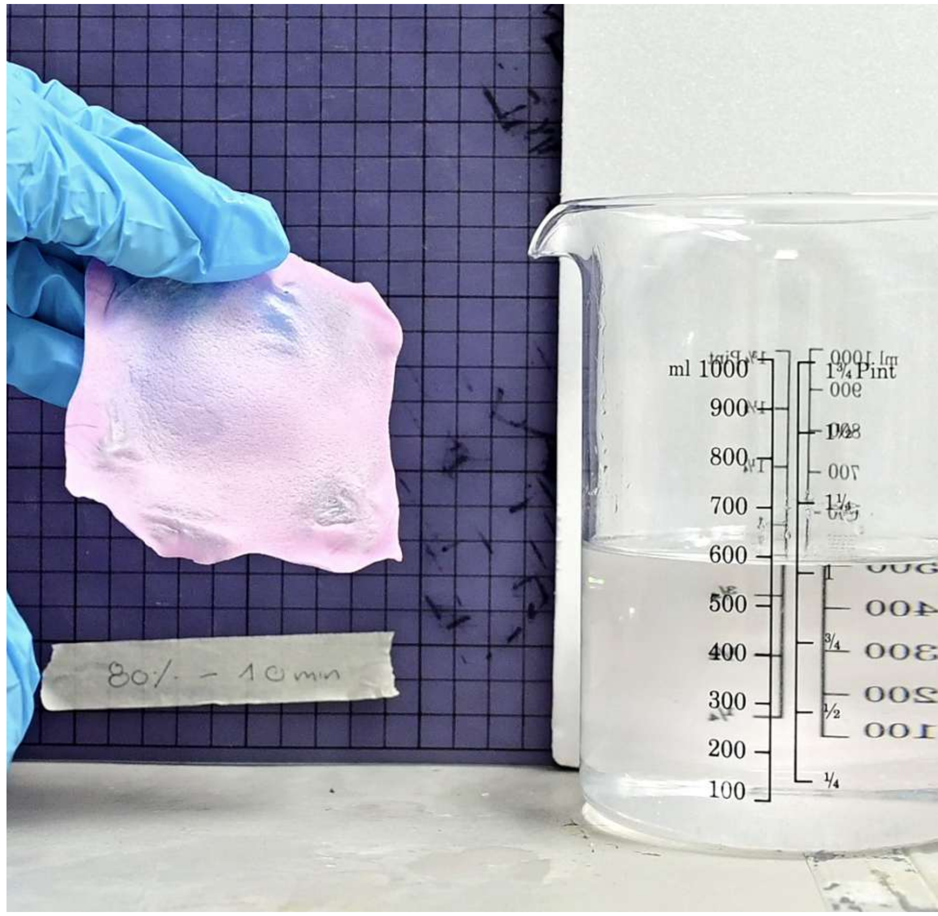

3.9
Snapshot of deformation of a 2 mm sample in the experiment at 80% acetone after 10 min submersion.

3.4 Thickness – Concentration

This series of experiments are designed to understand how the thickness of the sheet of extruded polystyrene plays into the process of softening and shaping it. It also examines whether there is a limit to how thick a piece can be, before the water-acetone solution does not have an effect any longer. The second set of experiments uses results from the first set of experiments by keeping the duration of submersion constant and varying the concentration of acetone and water.

The submerged samples of extruded polystyrene all have the same dimensions yet vary in thickness. The results of this experiment should give a better idea of the behaviour and limitations of the material, and thus the scalability. This further helps determine potential applications of this method as well.

The concentrations of acetone in the liquid used for this set of experiments are 75%, 80%, and 85%, since these were the optimal proportions in the previous set of experiments. The duration of each submersion is kept constant at 10 minutes.

As previously stated, the dimensions of the XPS samples are 100 x 100 mm. The thicknesses of the samples are as follows: 2 mm, 3 mm, 4 mm, 5 mm and 7 mm, 15 mm, 20 mm, 30 mm, and 40 mm.

During the previous series of experiments, the 75% concentration shows a weaker effect on the 10 mm thick samples, so the samples thicker than 10 mm are excluded from this set of experiments, since it is likely that they will respond even less to the solution. This leaves the samples of 2 mm, 3 mm, 4 mm, 5 mm, and 7 mm samples for testing at 75%.

For the experiments with an 80% acetone concentration, all the varying thicknesses are tested. For the acetone concentration of 85%, the samples with a thickness below 10 mm are excluded, due to small signs of material breakdown in the previous experiments with the sample of 10 mm. Thinner pieces are likely to break down more severely. This leaves the 15 mm, 20 mm, 30 mm, and 40 mm piece for testing at 85%.

The results of the experiments show that the thinner the piece, the more malleable and stretchable it is after submersion. Upon drying, the thinner pieces are more friable. The same can be said for the concentrations, the higher the concentration, the more stretchable and malleable it is, but the material is left more fragile upon drying.

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The samples of 20 mm and above do not soak in the liquid completely after 10min, which leaves a soft layer of extruded polystyrene around a hard and brittle core of dry extruded polystyrene. These samples cannot be deformed but stay straight, with indentations and irregularities in the soft outer layer when pressed and pulled.

Another small test is conducted to test whether leaving a thicker piece of XPS in a solution longer than 10min allows it to soak up more liquid. For this, a sample of 100 x 100 x 40 mm is submerged at 80% in a closed container to prevent too severe evaporation of the acetone. The sample is regularly checked upon every 30min for 6 hours. The results show that the sample was much softer than after 30 min and was indeed more stretchable. However, upon pressing into the sample, the sample still seems to have a small core that is less flexible, which leads to the assumption that the solution after 6 hours did not complexly soak into the sample.

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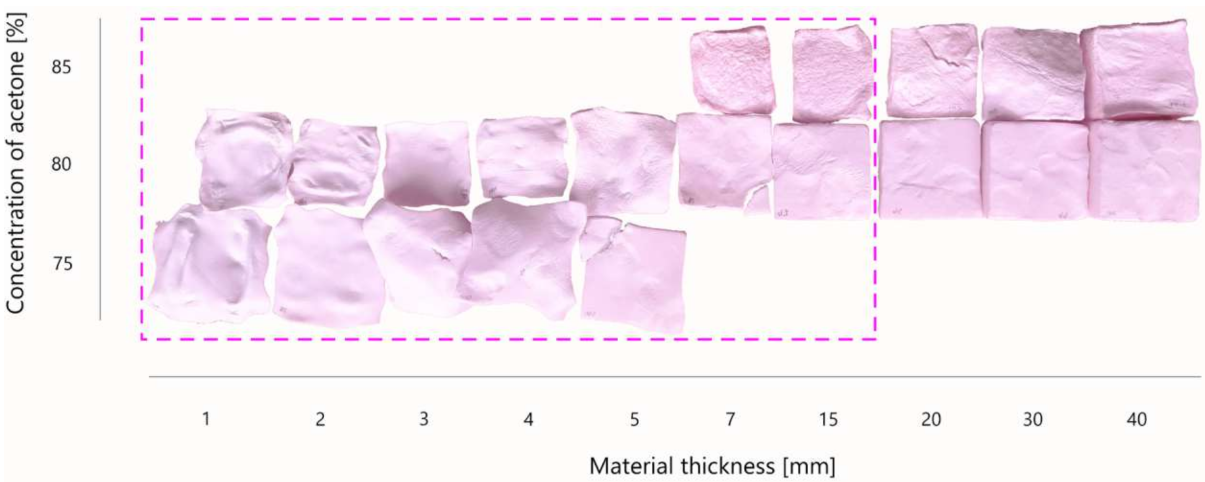

3.10
Image of all qualitative results from the thickness-concentration material experiments.
The dashed pink outline shows the thicknesses that showed positive outcome after 10 min submersion.

3.11
Comparison of 40 mm sample submerged for 10 min and 40 mm sample submerged for 6 h at 80%.

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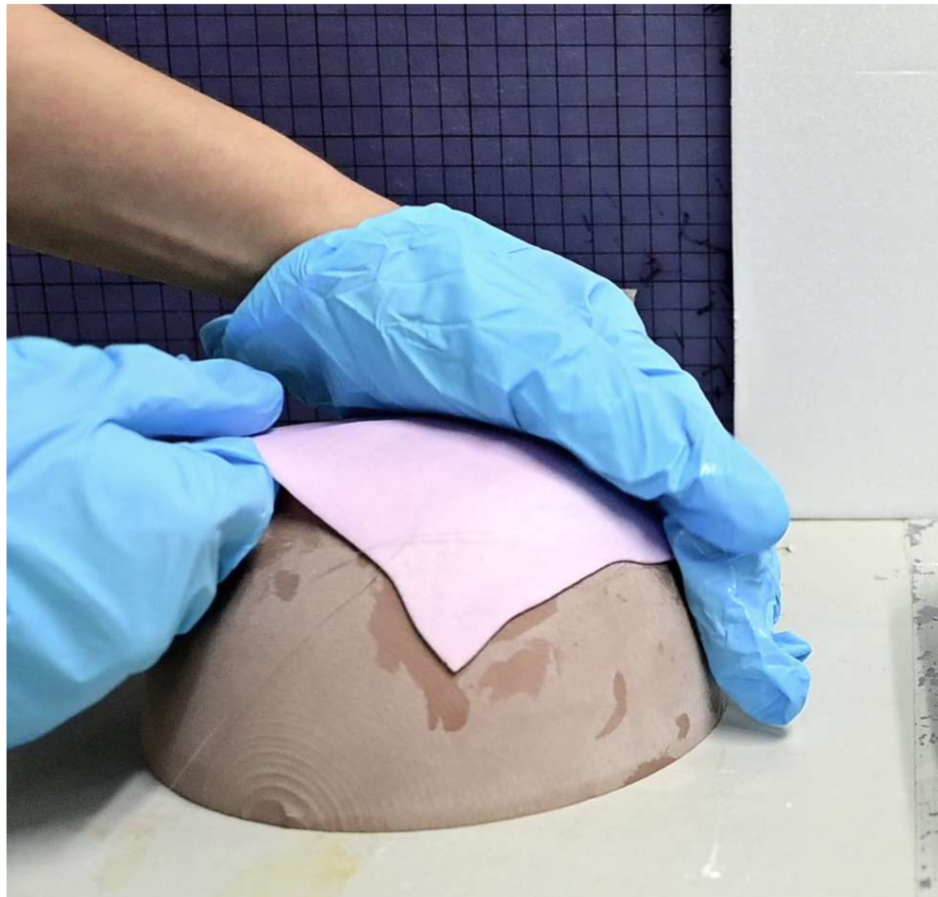

3.12
Snapshot of deformation of a 2mm sample in the experiment at 80% acetone after 10min submersion over a semi sphere.

3.5 Double-Curve Experiments

The third series of experiments are designed to test whether the material is capable of being shaped into a double-curved surface. For a material to allow a double-curved surface, it needs to be stretchable to a certain extent. The goal is to understand the limitations of the malleability and stretchability of the extruded polystyrene once softened.

Using the results from previous experiments, a series of experiments are conducted with the 2 optimal concentrations across 3 different thicknesses of extruded polystyrene sheets at a fixed duration of time.

The duration of each submersion for these experiments, similar to the thickness varying experiments, is set at 10 min.

The XPS samples have the same dimensions of 100 x 100 mm, however vary in thickness as follows: 2 mm, 5 mm, and 7 mm.

The two concentrations tested are 75% and 80% for the 3 thicknesses respectively. 85% was excluded in this testing, since the previous experiments showed that thin pieces of XPS, such as 2 mm and 5 mm, become very fragile and friable at this level of concentration.

Additionally, for these tests a half-sphere with a diameter of 150 mm is milled from ureol. The dimensions for the half-sphere are chosen to be close to the dimension of the samples, so that the curvature is visible, but still bigger, to give the samples space enough to stretch. Before the experiments, the material is also tested to ensure that it itself does not dissolve or soften with the acetone mix as well. The samples are then pulled over the surface of the halfsphere, in an attempt to shape the XPS after the object.

The samples submerged at 75% have some rigidity and stiffness. All three samples were pulled into a double-curved shape. However, the process worked best for the 2 mm sample. The thicker the piece, the more difficult it is to bend into the desired shape.

The samples submerged in the 80% solution are softer and more flexible than the previous ones in the 75% solution. The process worked for all thicknesses, however the 2 mm becomes more fragile and overall. This proportion worked better for the 5 mm and 7 mm pieces.

A challenge with this tested method of forming the samples is control of the deformation. During the experiment, each sample stretches unevenly and unpre-

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dictably, and the double-curved shape is non-uniform. While the samples stay in the uniform shape while on the sphere, the moment they are removed they arrange themselves in the irregular shape dictated by the uneven stretching of the sample. Some samples are left to dry completely on the sphere before they are removed. These samples show improvement; however, this does not correct the shape irregularity. Another challenge is the fact that the samples, once removed from the solution, only stay flexible for a limited amount of time. As the liquid starts evaporating and the sample dries up, the sample gradually stiffens, which shortens the shaping process.
In summary, all samples have taken on a double-curved shape, showing that this material allows a large freedom in shape.

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3.13
Top: XPS sample after submersion at 75%.

Bottom: XPS sample after submersion at 80%.
Both have a thickness of 2mm, duration of submersion 10min, and both are stretched over a semisphere.


Top: XPS sample after submersion at 75%.

Bottom: XPS sample after submersion at 80%.
Both have a thickness of 5mm, duration of submersion 10min, and both are stretched over a semisphere.


Top: XPS sample after submersion at 75%.

Bottom: XPS sample after submersion at 80%.
Both have a thickness of 7mm, duration of submersion 10min, and both are stretched over a semisphere.

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3.6 Surface comparisons

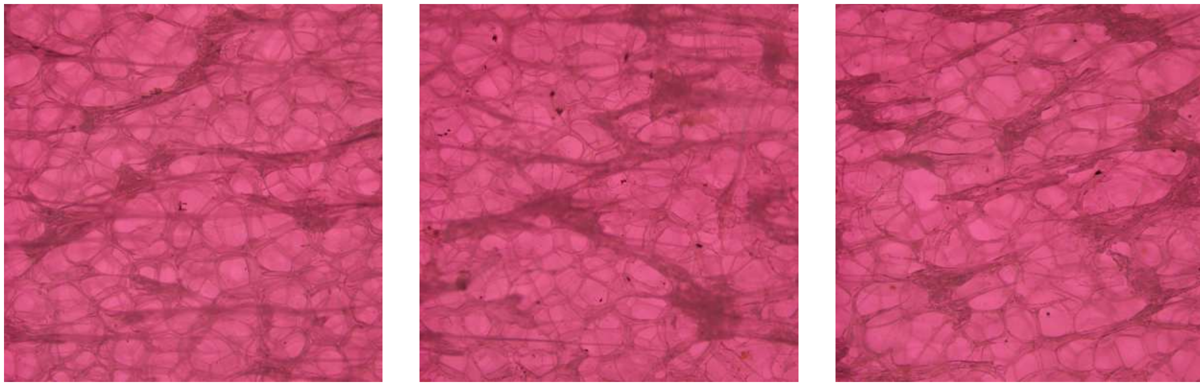
The material experiments very clearly demonstrate the behaviour of different sheets of extruded polystyrene after being submerged in different solutions of water and acetone for different periods of time. With the conclusion of the material experiments, the question arises as to what extend the process of submersion in an acetone-water solution impacts the physical structure of the extruded polystyrene. Extruded polystyrene foam has a closed cell structure, with many small air pockets, which can be observed under a microscope.

To see the physical impact that the different acetone-water solutions have on the samples of extruded polystyrene, the samples are put under a microscope along with pieces of XPS that have not been in any contact with an acetone-water solution. Any small physical changes to the material structure should become visible at a smaller scale.

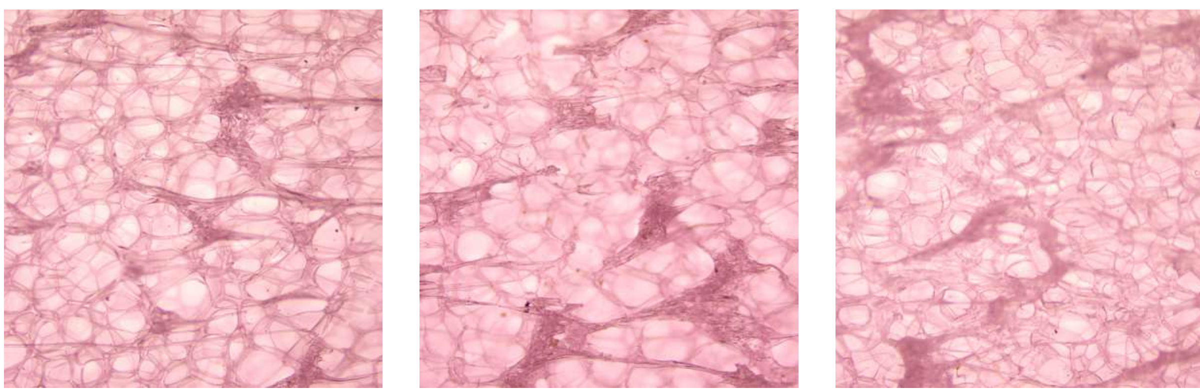
The microscope needed for this purpose is a metallurgical microscope, which shines light through the objective lens rather than under the magnified sample. This enables a closer look at objects which do not allow light to pass through. In this case, a metallurgical microscope is necessary, as some samples are too thick for light to pass through properly. In this case the microscope is also equipped with a camera that allows samples to be photographed. An image is taken of the surface of each sample that is put under the microscope, so that they can later be placed side by side and be compared.

The samples are magnified 50x and photographed. Interestingly, the images show that the structure of the XPS foam remains largely unchanged for the samples submerged up until 75% acetone concentration. For the samples submerged at a concentration of 75% for a longer duration, the swelling of the material becomes somewhat visible. At 85% acetone concentration, the samples show swelling at short durations and breaking down of the structures at longer durations.

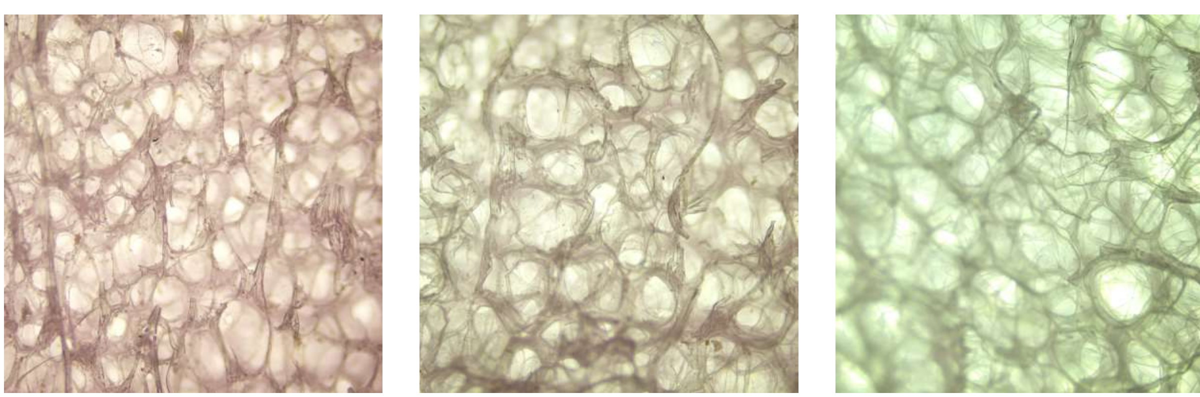
Samples of the experiments at 90% acetone concentration show significant break down of the structure.



3.14
Surface close up of XPS samples of 10 mm thickness submerged for 10 min.
From left to right: 75%, 80%, and 85%



Surface close up of XPS samples of 5 mm thickness submerged for 10 min.
From left to right: 75%, 80%, and 85%



Surface close up of XPS samples of 2 mm thickness submerged for 10 min.
The thinner a sample, the greener it appears, due to the light from the microscope.
From left to right: 75%, 80%, and 85%

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3.15
Photo of the heat transfer analyser measuring the thermal conductivity of a sample of extruded polystyrene.

3.7 Thermal Conductivity

Extruded polystyrene is widely used as insulation in the building industry. This is due to its very high heat resistance and thus very low heat conductivity. The heat conductivity of extruded polystyrene generally lies between 0,03 - 0,04 Wm−1K−1, which makes is one of the best and cheapest insulators we have readily available.

For this reason, it is interesting to examine whether the process of submerging will weaken the heat resistance of the extruded polystyrene, and if so, by how much.

Once the material experiments are completed, some samples are prepared for the testing and measuring of the heat conductivity of extruded polystyrene samples after they have been treated with a water-acetone solution, as well as a control sample which has not been in contact with the solution.

For this, 6 new XPS samples are cut in the dimensions of 80 x 120 mm. 3 of them with a thickness of 5 mm and 3 with the thickness of 10mm. One sample of 5mm and one of 10 mm are submerged into the solution with 75%, 80%, and 85% respectively for 10 min.

The measurements are carried out with a portable heat transfer analyser the Isomet 2114 from Applied Precision. The instrument is connected to a probe, which is placed on the sample of extruded polystyrene. This then measures the conductivity by sending heat through the material.

According to the values, none of the samples show any significant difference in heat conductivity compared to the control sample. The differences measured by the instrument are at a decimal level and negligible. This aligns with the results from the surface images showing that the closed cell structure of the material remains largely intact after its submersion and drying. This creates a possibility of using this technique to manipulate the shape of insulation of various products across industries.

However, for the specific measuring instrument used in this project, the surface needed to be flat and straight, which means that the samples measured are only submerged in the acetone water solutions before being left to dry. They are not deformed in its malleable state. It is possible, especially when looking at the images of the surface structure, that deforming the extruded polystyrene could cause the closed cell structure to change and pull apart, thus potentially weakening the insulating properties of the material. This would require further testing, which will not be conducted within the scope of this thesis.

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4 Form-finding Experiments

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4.1
Items used for the experiments. Glass measuring cups for mixing acetone and water and a baking tray is used as the container for the submersion process.

4.1 Setup

The material experiments have shown that, once the extruded polystyrene is submerged into a solution of water and acetone, it becomes malleable and can be stretched and shaped into asymmetrical shapes, double-curved shapes, and more. They have also shown that, upon drying, the sheet of XPS maintains the shape it has been deformed into. This process can be repeated, submerging and reshaping the object multiple times.

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However, to deform a sheet of extruded polystyrene, it is not enough to only submerge it in acetone and water. It requires a force acting upon the sheet to shape it. In the previous material experiments, the force used to test the malleability of the extruded polystyrene comes from a person pulling the sheet with their hands.

While this works for the material experiments, which is a qualitative experiment, it is difficult to reproduce or control the deformation in the same way each time.

The next series of experiments explore ways of systemizing the deformation and generating the shape of the extruded polystyrene. These experiments focus on using gravity as the force that shapes the malleable XPS rather than manual deformation. Based upon results from previous experiments, gravity alone is not enough to deform a sheet XPS, unless the sheet has been submerged in a high concentration of acetone where the internal structure of the material has started to break down. In these cases, the material is left fragile and friable.

To deform extruded polystyrene, which is merely softened, these experiments use a variety of different weights to cause the deformation. These include simple calibration weights, gypsum, and concrete. To enable this, 3 wooden frames are built, on which the sheets of extruded polystyrene can be placed to suspend them and allow them to deform downwards once the weight is added.

The results of previous experiments show that the thinner the sheet of extruded polystyrene is, the more it stretches. Logically speaking, it follows that this could be a possible way of controlling the shape of the soft XPS by controlling which areas of the sheet will stretch more and which will stretch less under the added weight. To test this theory, 3 different simple freeform patterns are created. These patterns are milled into the surface of a sheet of XPS with varying thicknesses across the surface.

Similar to the material experiments, these tests will also be conducted with the

different acetone concentrations within the optimal range, but at a fixed duration. The same tools and items are used for these experiments as for the previous ones, except that the samples will not be submerged in the solution directly in the beaker. Instead, the solution will be transferred to a deep baking tray, as the sheets of extruded polystyrene are larger in these experiments.
Due to the bigger surface area, it is expected that much more of the acetone will evaporate during the experiments. To test this, samples of the solutions are taken before and after the experiments to measure and compare the refractive indices. For each experiment, a camera is set up to record and document the outcomes.

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4.2
Top: 3 different freeform patterns.
Bottom: Milling of the patterns into extruded polystyrene to control the shape of the deformation.

4.2 Patterns & CNC-Milling process

As these tests are using gravity to shape the suspended material, this relates to catenary shapes. A uniform sheet of extruded polystyrene, once it has been softened by the solution and suspended, should deform uniformly in a catenary shape once weight has been added. The idea behind these tests is to see if it is possible to control the deformation in such a way that the XPS does not deform in a catenary shape, but into a different one determined by the pattern in varying thicknesses within the XPS.

The idea behind the patterns is simple: to shift the centre of the weight from the middle of the XPS. As shown in previous experiments, thinner samples of extruded polystyrene have deformed more, so by making the pattern thinner away from the centre, rather than in the centre, the sheet should deform in an asymmetrical way. These thin areas should create new centre points for the biggest deformation. Another thing that is tested is the possibility for both positive and negatively curved shapes.

The first pattern has a circular shape with a centre point, on which the weight will be placed. The second pattern has 2 centre points for the weight distribution, and the third pattern has 3. The 2nd and 3rd pattern also attempt to create negative curvature. They are both kept thicker in the middle of the sheet to test whether the weight can be distributed out to the centre points of the patterns, away from the centre of a catenary shape.

The patterns are created with control point curves in Rhinoceros 7 and by then creating surfaces from the planar curves. The surfaces are then adjusted to different heights from the null point in Rhinoceros 3D. The patterns consist of 3 surfaces, which will be milled into the extruded polystyrene, leaving it with a thickness of 2 mm, 5 mm, 7 mm, and 10 mm.

For these tests, it is decided that the pattern will be milled into the extruded polystyrene for a more precise result. The milling process came with some obstacles. The areas of the sheet that are milled down to a thickness of 2 mm were fragile and prone to breaking. This creates a challenge for dismounting the extruded polystyrene from the machine. To fix this problem, the pattern is changed, so that the thinnest areas are set to 3 mm rather than 2 mm.

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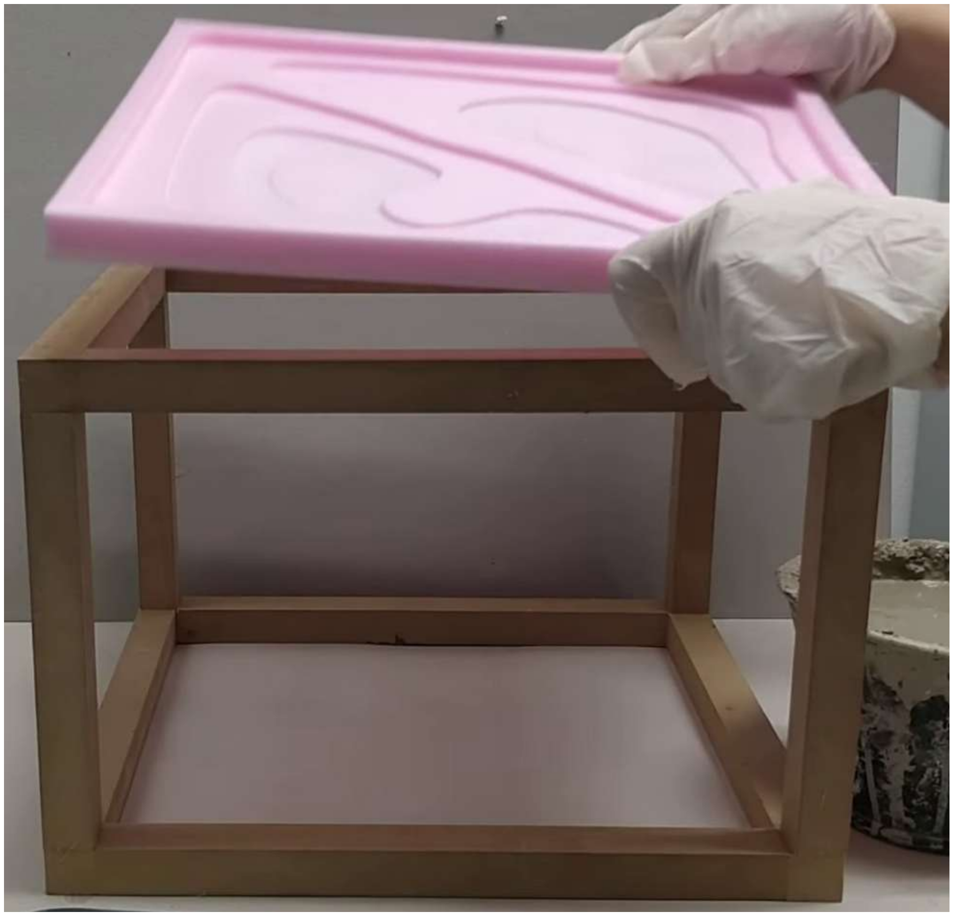

4.3
Preperations for the experiments.

4.3 Weight and Concentration tests

The geometry experiments are conducted using different types of weights, to determine how to best deform extruded polystyrene. The tests are conducted using calibration weights, gypsum and concrete. The tests also vary in acetone concentration in the solutions used to soften the XPS.

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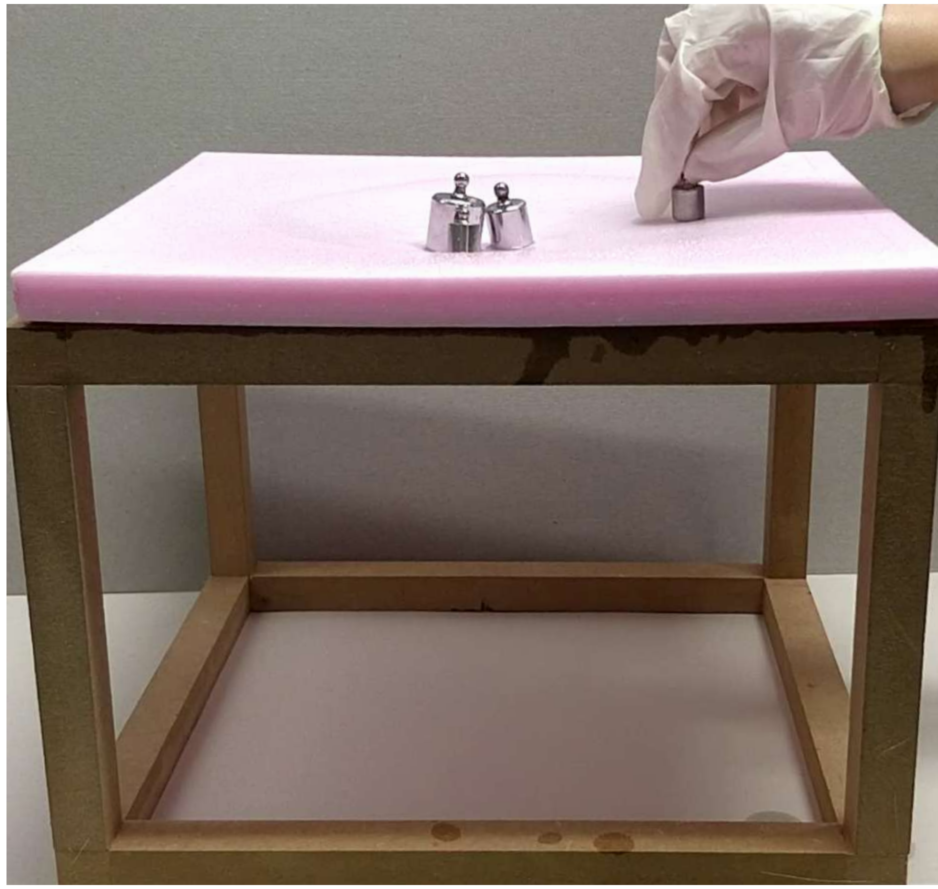

4.4
Weight experiment using calibration weights.

4.3.1 Calibration weights

For the first tests, calibration weights are used varying from 10g to 100g pieces, in total adding up to 200 g. For the tests, the duration of submersion of XPS in the water-acetone solution is set to 10min. The concentrations used are 75%, 80%, and 85%. There are 3 patterns per concentration tested, making the total of tests conducted with calibration weights 9. In the first pattern with 1 centre point, all weights are placed at the centre point of the pattern. In the second pattern, the weights are distributed with 100 g at each point, and in the third pattern, the weight are distributed with 100g at one point and 50g at each of the other points. Once the sheet of XPS has been submerged, it is removed from the liquid and suspended on the wooden frame before the weights are placed.

Across all concentrations, the tests are unsuccessful. The weights used are not heavy enough to create more than a smaller indentation, regardless of the thickness of the XPS and the concentrations. The force that is supposed to pull the XPS into shape is simply not large enough. Furthermore, the weight distribution is localised around the points of placement of the calibration weights. This means the little visible deformation is concentrated in the vicinity of the calibration weights, while the remaining area of the XPS sheet remains largely unaffected by the weight.

The results of the tests with calibration weights do display a curved deformation, however this is not due to the weights, but rather due to an uneven submersion and drying process, which seems to cause the material to deform while the liquid evaporates from the polystyrene. Overall, this method of adding selective weight to deform is not favourable, and better results are achieved when weight is distributed throughout the sheet of extruded polystyrene.

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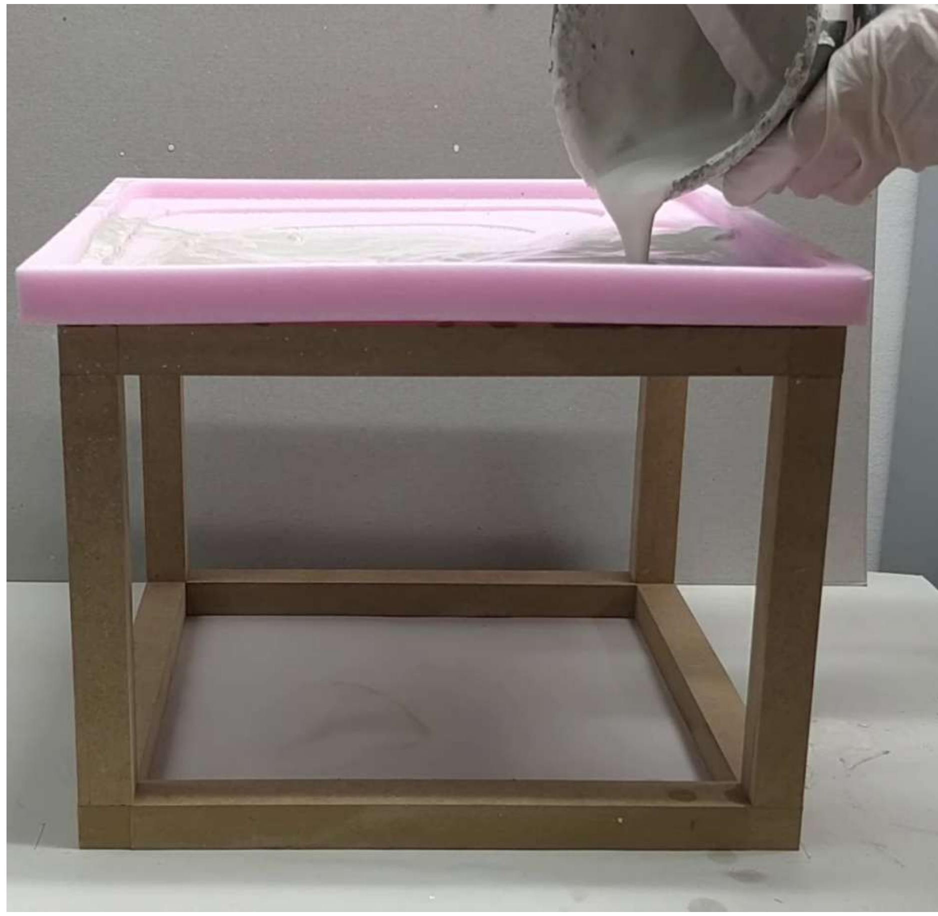

4.5
Weight experiment using gypsum as weight for deformation.

4.3.2 Gypsum as weight

The next round of tests is conducted with gypsum as the weight, under which the polystyrene should deform. Similar to the previous weight tests, the duration of these is set to 10 min. The concentrations are 75%, 80%, and 85%, and there are 3 patterns per concentration.

While the sheet of XPS is submerged, the gypsum is mixed up with water. Once the 10 min pass, the sheet is removed from the liquid and placed on the frame, and the gypsum is then poured onto the sheet. The gypsum is then left to dry overnight.

These tests display some challenges. Gypsum dries out quickly, making the pouring, and thus deforming of the sheet, difficult. Throughout the experiment, the technique of mixing and pouring the gypsum has been improved. The gypsum works best when mixed max. 2-3 minutes before pouring it, so this is timed in relation to the submersion process. The physical distances between where gypsum is mixed, where the XPS sheets are submerged and where the formwork is suspended, is reduced so that the process can be conducted as fast as possible, thus minimalizing the risk of the gypsum drying out.

The results show that the sheets deformed as expected. The sheets submerged at 75% have a weaker deformation compared to 80% and 85%, where the deformation was at its greatest at 85%. The tests produced non-uniform shapes. The results also demonstrate the challenges with the texture and the timing of pouring the gypsum.

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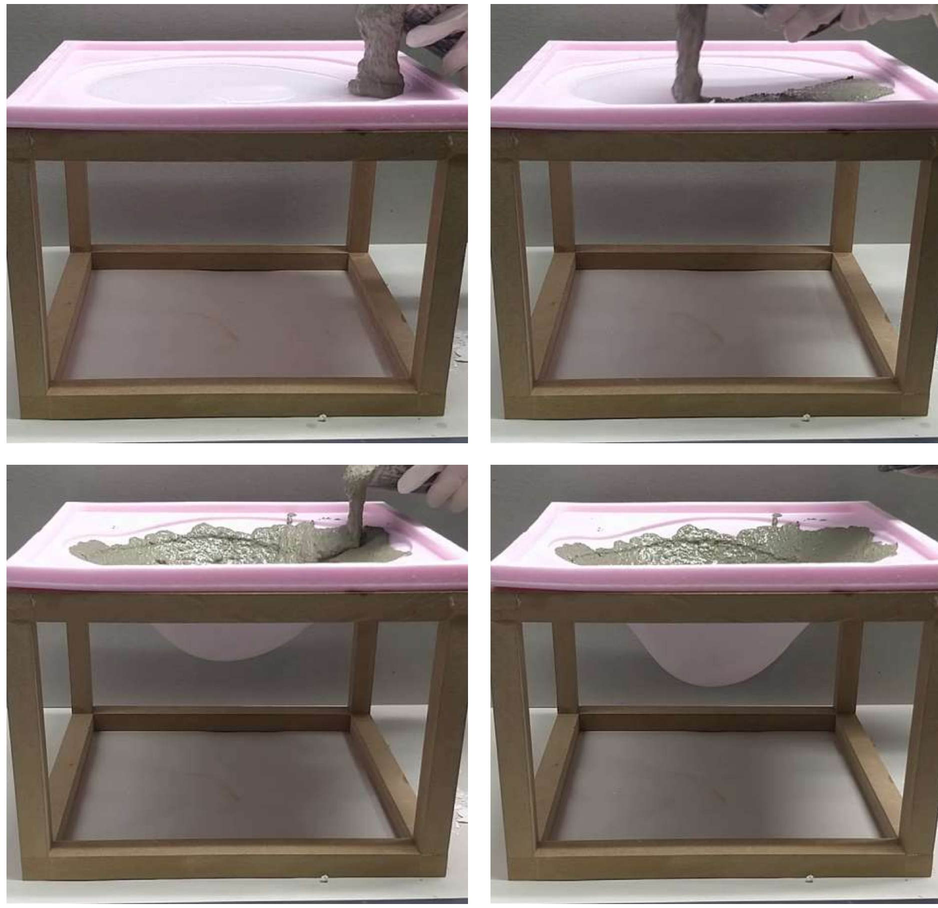

4.6
Process of the experiments using concrete as the weight.

4.4.3 Concrete as weight

The last round of tests is conducted using concrete as the weight. As with the previous experiments, the duration of the submersion is set to 10 min and the solutions used for the submersion have an acetone concentration of 75%, 80%, and 85%. For each concentration, 3 sheets with the different patterns are processed.

As with the gypsum tests, the XPS sheet is submerged. In the meantime, the

concrete is mixed. After the submersion, the XPS is taken out and suspended on the wooden frame and the concrete is then poured onto the sheet.
The concrete is more difficult to mix and does not dry out as fast, so for these tests, the concrete mixing should start at least 5 min before the end of the submersion of the XPS. Otherwise, the concrete would not be mixed properly by the time the duration of the submersion is over. Due to this, some of the first tests are kept in the liquid slightly longer than the previous experiments. Some of the tests are taken out of the liquid on time and then left on the frame, while the concrete is prepared. This also proved to be problematic, as it seems that the extruded polystyrene dries up and rapidly loses its flexibility.
Overall, these tests show similar results as the gypsum experiments. The sheets of XPS deform in a way that is dictated by the pattern milled into its surface under the weight of the concrete. The tests were successful in all concentrations. While the strongest deformation occurs through submerging the XPS at 85% acetone, this also damages the material significantly more. At 75% the deformation is much weaker; however, the material shows less damage.

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4.7
Weight experiment trying to create a shell.

4.4 Shell experiments

Looking at the results from the geometric experiments, it appears that this method of deforming the XPS using the weight from gypsum or concrete is successful. However, both the concrete and gypsum in the previous experiments fall towards the centre of the XPS sheet and pools there, which makes the cast object massive and quite heavy. It begs the question whether it is possible to create a shell of gypsum or concrete in the pattern with a non-uniform shape, rather than

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a massive object. This is what is explored in the next series of tests.

These tests are conducted in the same way as the previous experiments, i.e. a submersion duration of 10 min and a submersion in acetone concentrations of 75%, 80%, and 85%. For these tests, both gypsum and concrete are tested. The casting material is mixed while the XPS is submerged. In both the case of gypsum and concrete, the mixing ratio includes less water to make the consistency thicker and thus preventing pooling of the casting material in the centre of the sheet. After the 10 min, the sheets are removed from the solution and are suspended on the wooden frame before the casting material is poured onto the sheet.

These tests proved unsuccessful. The casting material is too thick to distribute equally and properly throughout the surface of the XPS sheet. This is particularly true for the gypsum, as the gypsum also dries out very fast. The concrete also did not spread properly on its own. In both cases, it is necessary to spread it manually, which defeats the purpose of the self-forming object. Once on the sheet, the gypsum is almost entirely solid. Furthermore, the concrete, which remained somewhat liquid much longer, started to pool towards the middle even after it was manually spread out. These tests do not show particularly promising results just yet. Considering the results of the experiments conducted, as well as a deeper understanding of how these materials work, it is believed that creating a shell rather than a massive object could be possible with some tweaking and refining of the method and possibly with the use of other materials. However, this will not be further explored within the scope of this thesis.

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4.8
Demoulding of concrete experiment.

4.5 Demoulding/remoulding

Before the demoulding, some of the objects have torn in the process of moving them around while photographed for documentation or even while moved for the demoulding process. This shows that this process, in some instances, weakens the XPS.

To demould the objects, the XPS sheets with the cured gypsum or concrete are placed back into the solution, softening the material and allowing it to be re-

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moved more easily. The concentrations of 75%, 80%, and 85% are tested to establish which concentration is optimal for the demoulding process. These tests are conducted more intuitively, depending on how each individual object reacts to the solution. Some of the gypsum and concrete objects are released from the sheets after a fairly short submersion and without too much work, while other ones take a much longer submersion and require careful pulling and tugging at the XPS to slowly release the cast object.

In the demoulding process, it is important that the XPS sheets remain as close to intact as possible. This would open the door to possible reuse of the material. The objects that are less deformed in the process are the simplest to remove from the XPS mould. It seems the more that the casting material stretches and shapes the XPS, the more fragile the XPS sheet becomes, making it more difficult to remove.

Similar conclusions can be drawn for the various concentrations. The objects that are cast in XPS submerged in lower concentrations demould easier than those cast in sheets that are submerged in higher concentrations, as the XPS mould is generally less damaged from the solution.

Testing the demoulding process in different concentrations shows that the demoulding process should be done at 75% concentrations. It is very clear that the demoulding attempts carried out at 85% acetone concentrations in particular leaves the XPS completely friable, which makes the demoulding process more challenging.

Another challenge appears to be the big steps between the different thicknesses of the pattern in the surface of the extruded polystyrene. These big height differences create sharp edges in the geometric shape of casting material, making the demoulding difficult.

It also appears that even with complete submersion of the object, the acetone-water solution does not manage to soak in and reach areas beneath the casting material. During the demoulding process, it is discovered that some areas of the XPS mould remain largely dry, which in turn also makes the demoulding more challenging. While demoulding, it is necessary to pour the solution over the entire object and then manually and slowly separate the XPS from the cast object. Bit by bit, as the XPS is removed, the space created between the object and the XPS should continuously be filled with more of the solution to help release the XPS from the object.

Furthermore, the surfaces of both the gypsum and the concrete object sticks to the XPS very well, which also causes the XPS sheet to tear during demoulding. In some cases, the XPS leaves residue on the surface of the gypsum and concrete even after it has been demoulded. This seems to mostly happen in the cases where the XPS was submerged in a stronger solution prior to casting.

Generally, none of the XPS sheets are intact with no tears after the conclusion of the demoulding process. Many of the sheets even broke off pieces during demoulding. Only one sheet seems less affected, with only a smaller tear in one corner, and this sheet is successfully reused.

The reuse of the sheets should be possible, so this aspect will be further tested in the next phase of this research. From the conclusions drawn above, the demoulding process can be optimized. Furthermore, some of the challenges can also be attributed to human error, which can also be addressed.

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4.9
Demoulding of concrete experiment.

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4.10
Formwork containing cast concrete.

4.6 Conclusion of experiments

The tests show that the method of deforming the extruded polystyrene works best when the weight is distributed throughout the whole sheet, rather than selective points as with the calibration weight. This means, for this specific case, that the pouring of a casting material to deform extruded polystyrene is the preferred method. This is also the direction for the continuation of this research.

Overall, the experiments which used a casting material successfully show that

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4.11
Result of demoulded concrete from figure 4.10.

the shape of the extruded polystyrene, after it has been submerged into the water and acetone solution, can be controlled by varying the thickness of the extruded polystyrene. All 3 patterns have predictably caused the extruded polystyrene to stretch more where the pattern has less material thickness and stretch less where the pattern has a higher material thickness. In this way, the pattern controls the shape of the outcome. All 3 patterns have produced non-uniform objects under the weight of the casting material.

Furthermore, the concrete tests show the best results, with a larger deformation than gypsum. This is likely due to concrete having a higher density and mass, which leads to a stronger force to pull the extruded polystyrene into shape. The concrete also has the advantage that the drying process is longer, and it is easier to regulate its consistency before pouring in contrast to the gypsum. In extension, the density of the concrete is calculated by measuring the weight of the mixed concrete, the diameter of the container, and the height at which the container is filled. The density of this concrete is approximately 460kg/m^{3}.

Another part of the process that turns out to be crucial in this method is how long the sheet of extruded polystyrene is suspended in the air before pouring the casting material. Acetone is a very volatile compound, and it evaporates quickly from the surface of the extruded polystyrene once it is taken out of the liquid. The sheet of polystyrene seems to dry out quite fast, which means that the window of time in which the material is malleable is quite short. A few of the tests show very little deformation, simply because the sheet of XPS becomes less flexible in the time the casting material is mixed and poured. Therefore, the time between the sheet being removed and the casting material being poured needs to be kept at short as possible.

Considering the results of these tests, it becomes apparent that this method lends itself to the possibility of using the malleable extruded polystyrene as flexible formwork for casting concrete with a possibility of reusing the formwork material.

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4.12
Top: Concrete in XPS formwork.
Bottom: Demoulded concrete object.

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5 Case study: concrete panels

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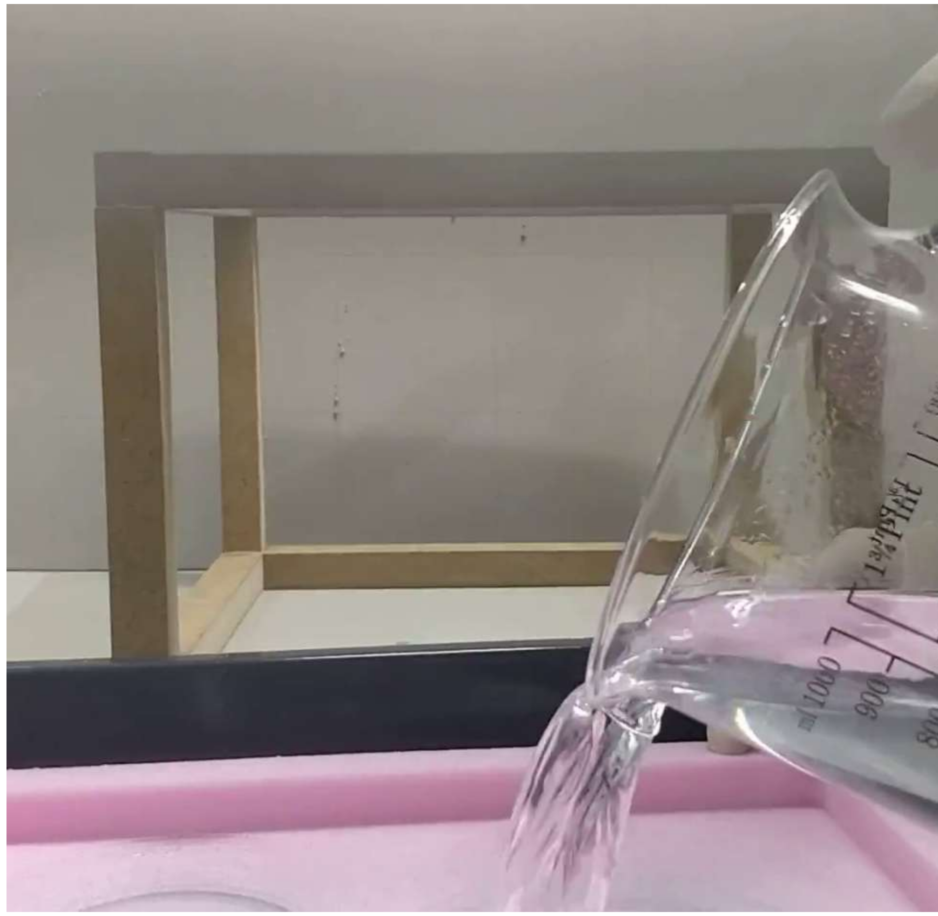

5.1
Submersion of polystyrene formwork for the fabrication.

5.1 Setup

To demonstrate the application of the technique developed and proposed in this thesis, 9 panels are cast in concrete using flexible extruded polystyrene as formwork. The dimensions of the panels will be 280 x 280 x 10 mm (base of the tile excluding the deformation) and the corresponding dimensions of the overall of the formwork is 320 x 320 x 30 mm, this gives the formwork a 20 x 30 mm edge that remains mostly rigid even after submersion and prevents possible unwanted deformation. A geometric pattern is designed for the overall shape of the tiles. However, the 9 tiles will be fabricated varying two parameters in each fabrication, resulting in 9 tiles with varying deformation.

Firstly, 3 different formworks are created with identical patterns, milled at 3 different depths into the formwork, creating 3 formwork-types of different thickness. 3 of each type is produced, resulting in 9 moulds. The pattern milled into the surface, is more finely tunes in for the fabrication, with 1 mm steps the different material thicknesses within the pattern, to produce a smoother surface and ease the demoulding process. Moreover, the moulds will be sanded slightly, to further smoothen the surface.

Secondly, the fabrication of the tiles will differ by using 3 different acetone concentrations for the solution used to soften the extruded polystyrene mould. The three concentrations are 75%, 80%, and 85%. This creates a matrix showcasing variation in deformation of each concentration paired with each thickness, and ties in nicely with the general focus of the research. (sketch of matrix)

The setup of the fabrication is similar to the geometric experiments. For the fabrication, only concrete will be used, as this is what produces the best results. Glass measuring beakers are used to mix the solution, which will be transferred to a baking tray for the submersion. The wooden frames built for the geometric experiments are also used for the fabrication process to suspend the formwork during the concrete casting. A camera is set up to document the process.

For the fabrication of the tiles, a few things are added to the setup to improve the fabrication method. To ease the demoulding process, a coating agent is introduced in the form of a vegetable oil poured into a spray bottle for a fast application between the submersion and the casting of the concrete.

A timer is used to control the timing of each step in the process in an attempt to fabricate each tile as controlled as possible.

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A station for mixing the concrete is moved as close to the submersion area as possible. Additionally, assistance is acquired for the experiments both to reduce the time between the submersion of the formwork and the casting of the concrete and to smooth out the process.

Furthermore, a display wall is designed to showcase the tiles. To enable the mounting of the tiles onto the wall, dowels will be embedded into the tiles during the fabrication process. To control the placement of the dowels across all tiles, a sheet of XPS with the same dimensions as the formwork, 320x 320 mm and a thickness of 20 mm (simulating the thickness of the display wall), is prepared as a guide that can be placed on top of the formwork after the concrete has been cast. 4 holes are drilled into the XPS sheet at the placement where the dowels will be embedded. The placement is determined by looking at the pattern and embedding the dowels in the locations where the tile is expected to deform the most. Screws that match the dowels are pushed through the XPS and the dowels are screwed on.

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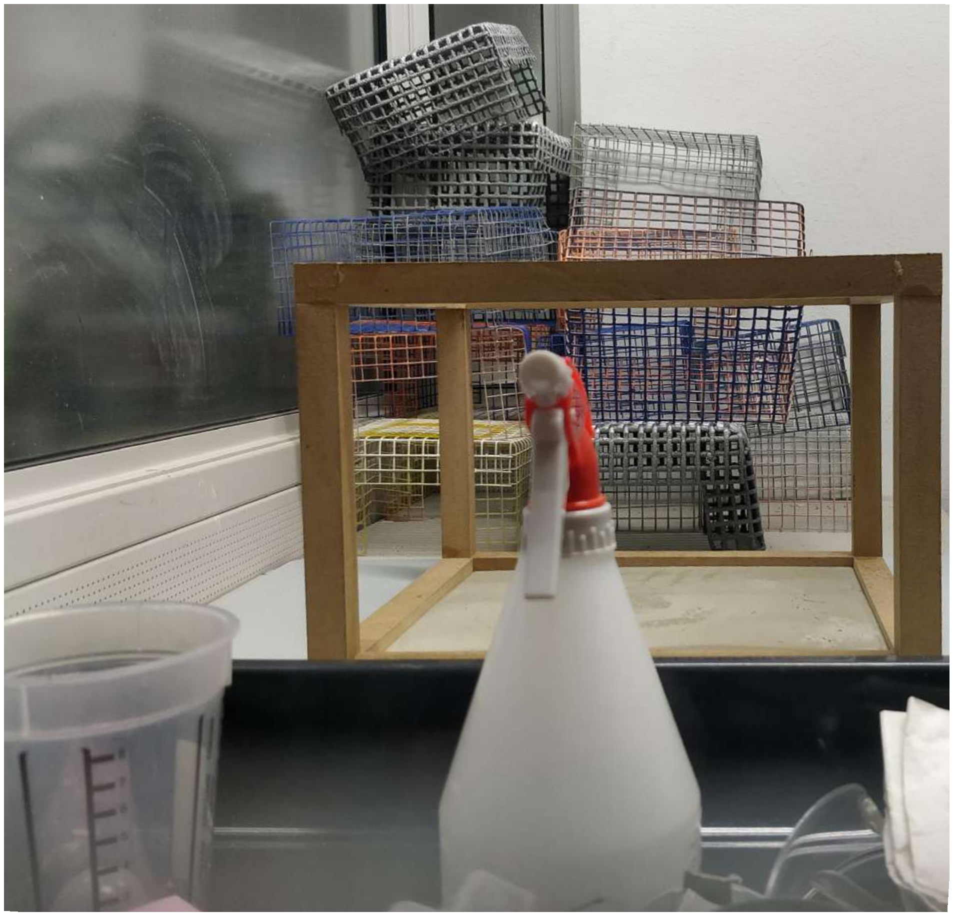

5.2
Behind the scenes of the experiments and fabrication.

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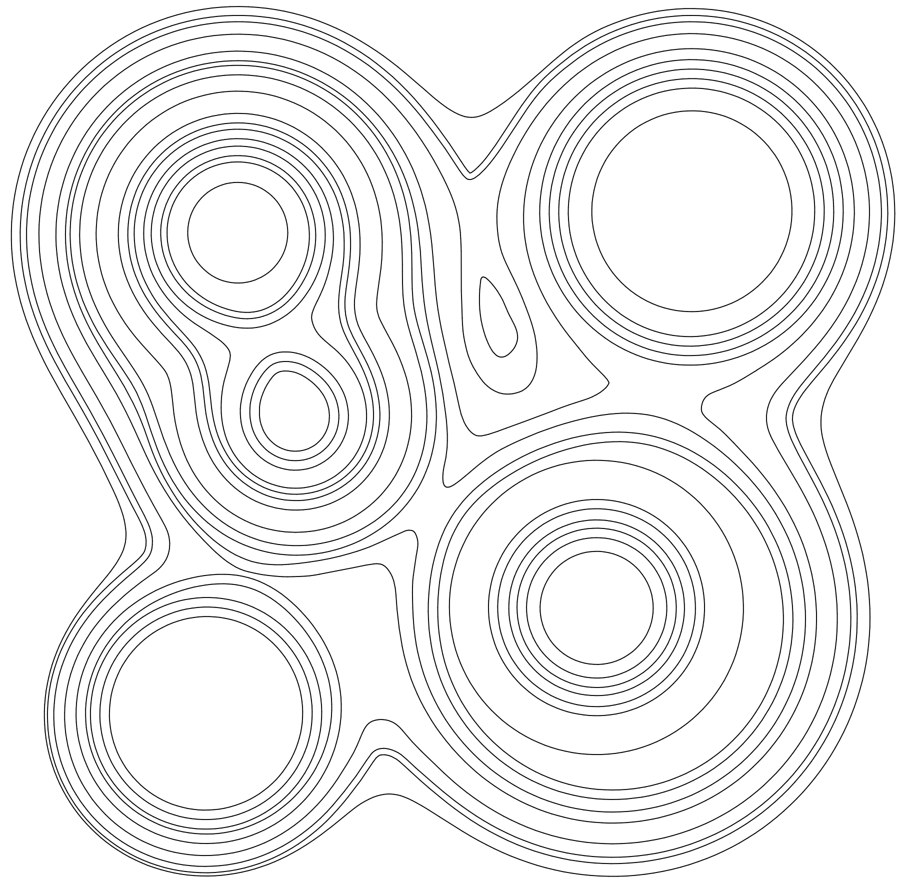

5.3
The geometric pattern for the concrete panels inspired by gravity force fields.

5.2 Design of geometric patterns

Gravity plays a large role in the concrete casting technique which this thesis is built up around. For this reason, gravity and forcefields are the inspiration for the design of the tiles. The design of the tiles consists of a circular pattern and aims to display the possibilities of this method by demonstrating a both positive and negative curved topology.
The pattern is generated with Grasshopper within Rhinoceros 7. To start off with,

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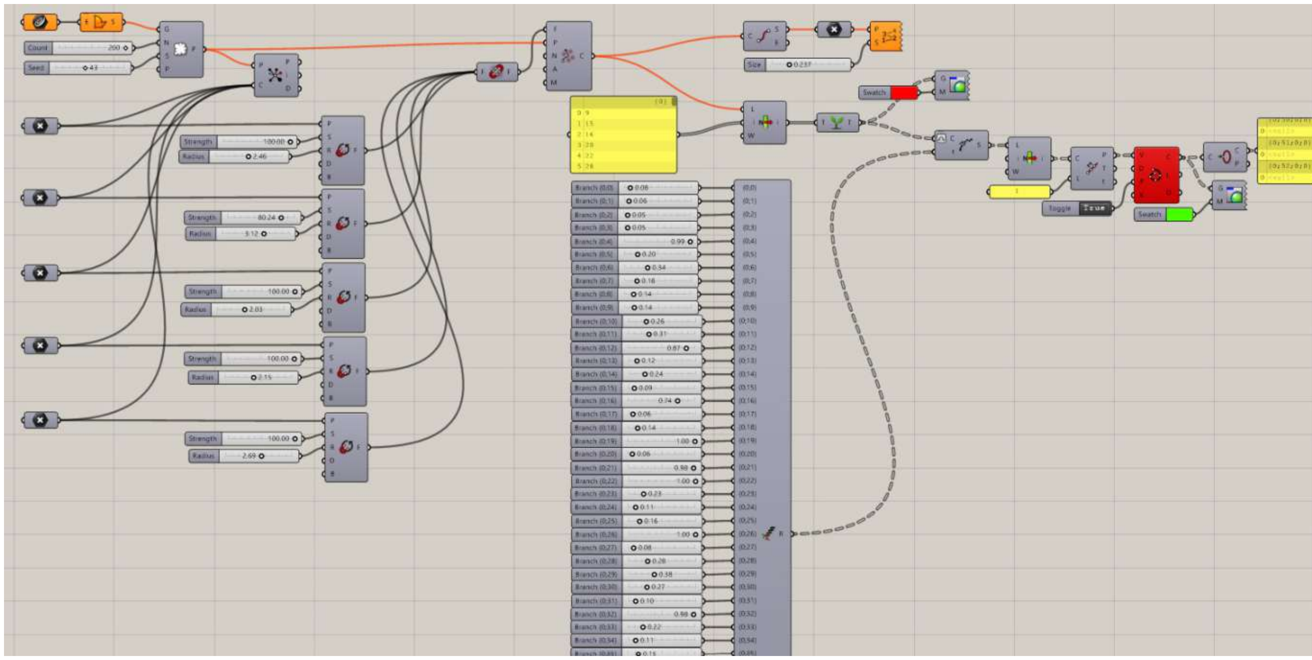

5.4
Grasshopper definition of the pattern.

a curve is used to set a boundary of 300 x 300 mm, from which a surface is generated. From here, various points with a random distribution are added within the boundary, using the geometry population function. Sliders are added for the number of points generated and for seeds, which allows for control of the randomization process. These points will be used to define field-lines.
Furthermore 5 other individual points are created, which are used as the centre points of forcefields. The output of the population and the 5 points are connected to the component closest points as points and cloud respectively. Additionally, the outputs of the 5 points are connected to individual spin force components to generate 5 force fields and sliders are added for radius and strength. These 5 forcefields are then merged with a merge field component and fed into the field input of a field line component, while the population points are connected as

input for starting points of field lines. This then generates a circular pattern, that connotes an expression of forces.

Through the manual movement of the 5 points of force field and by adjusting different sliders, the randomized pattern, size, and strength of the forcefield can be manipulated. Several patterns are generated, and one is chosen for the design of the concrete tile.

The pattern is baked into Rhinoceros to continue with the next steps and immediately an issue is found. The curves produced by the field lines are open curves wrapped multiple times around the forcefield, giving the illusion of a closed curve. However, this does not allow for the generation of surfaces, which are needed for the next step. The issue is solved by adding another step to the equation in grasshopper to process the curves.

A list is created of all field lines that are selected to be used in the pattern. The list is fed into a tree graft, which adds data branches for each item on the list. It is then connected as a curve input to a shatter component, which shatters the field lines into segments, while an entwine component is added as the parameter for splitting up each individual curve. The segment output is connected to another list component, which is used as input for division each of the field line curves. The curves are then interpolated and connected to a close curve component.

The pattern is once again baked and now the field lines behave as closed curves, from which surfaces can be generated.

At this point, all surfaces in rhino are at the same height, forming a 2-dimensional pattern. However, for the CNC-milling machine to mill the pattern into the surface to create a mould which varies in thickness, the surfaces of the pattern need to be placed in the correct heights. The next step is identifying which surfaces represent which thickness in the mould, as there are 10 thicknesses. It is vital that the height difference between neighbouring surfaces is always 1mm

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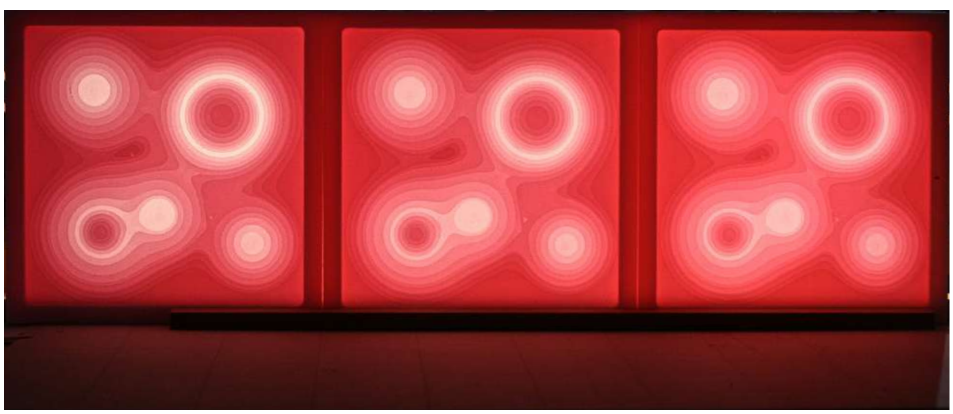
and this adds up to a total of 10 mm between the thinnest and thickest part of the mould. As mentioned previously, the 9 tiles will be cast in 3 different moulds with an identical pattern, but a different minimum thickness. 3 tiles will be cast in moulds, where the thinnest part is 3 mm and the thickest part is 13 mm. Similarly, the 3 moulds with a 4 mm minimum thickness and the 3 moulds with a 5 mm thickness will be 14 mm and 15 mm at its thickest, respectively. To visualise the thicknesses of the pattern, each surface is colour-coded depending on their height displacement from the null point.
The data from the pattern is fed into the application of the CNC-milling machine, a milling path is generated, and then the moulds can be milled.



5.5
Milled formworks.
Picture taken in darkness with a lightsource behind to showcase pattern and thicknesses.

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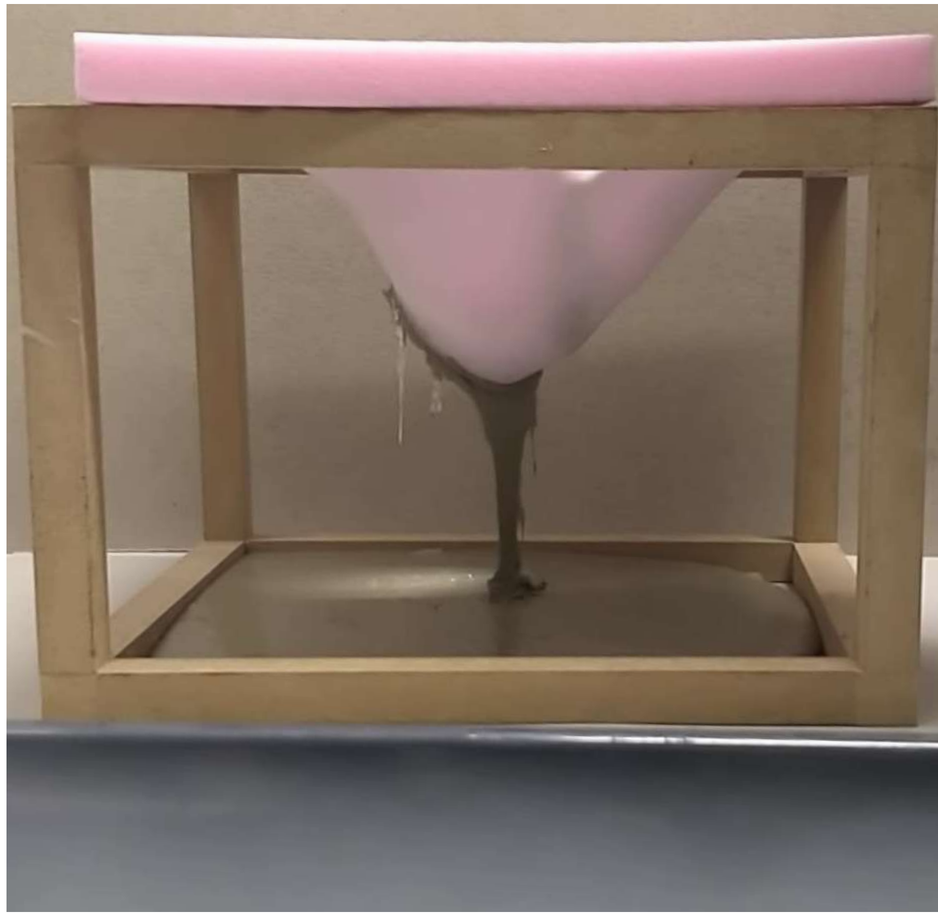

5.6
Torn formwork from testing of the fabrication patterns.

5.3 Testing and challenges

Before casting the final product, a few trials runs are done, casting several tiles and adjusting different aspects of the fabrication process. This is done to test the geometric pattern, test 2 different types of concrete, test whether the vegetable oil works as a coating agent, and test whether the system for embedding dowels into the tile works.

For each test run, 3 moulds are prepared with varying thickness and are submerged in a solution with 80% acetone concentration. The formwork is submerged for 10 min after the XPS is removed from the solution and vegetable oil is sprayed on. The sheet is placed on a wooden frame and concrete is poured. Then the guide with the screws and dowels is placed onto the formwork with the dowels sinking into the fresh concrete. The test tiles are left to cure and are demoulded the following day.

The results of the first test tiles firstly show that the deformation is minimal. This is likely due to the milled pattern having a large surface area where the material thickness is high, and a smaller surface area with thinner material thickness. As previously mentioned in this paper, the thinner the material, the greater the deformation. Furthermore, the pattern has a very gradual change in thickness, as each of the heights between the two extremes also have quite a large surface area. This is also reduced, making the graduation between the maximal and minimal thickness steeper.

The pattern is revised in Rhinoceros 7, by using the offset command to alter the sizes of individual pattern curves. New surfaces are generated from these, and heights from the null point are adjusted anew.

3 new moulds of varying thickness are milled, and the process is repeated. Another reason for the low deformation could be attributed the period of time between the mould being removed from the acetone solution and to the casting of the concrete. Time was taken to properly dab off access liquid with paper and to evenly spread the vegetable oil. However, as it has already been concluded after the geometric experiments, the liquid that softens the formwork evaporates quickly and becomes less flexible as the mould dries. For the second test run, attempts are made to reduce this time by quickly shaking the mould to reduce the access solution, and the oil is sprayed on generously, but quickly.

During a second casting of the revised tiles, the thinnest mould tears under the

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pressure of the concrete poured, while the other two tiles produced have a large deformation.

The pattern of the second trial run likely has a surface area of low material thickness that is too large in comparison to the thicker areas. Once again, the pattern is revised in the same way as previously to better distribute the different thicknesses. Apart from just revising the pattern, changes in the methods of casting are also made. Until now, the concrete is poured straight into the middle of the mould without much thought being given to the speed of pouring, or where the concrete is poured into the mould. For the fabrication of the final tiles, this is considered.

The process is repeated a third time with the pattern and process adjustments and is successful, however a stronger deformation would be preferable. To address this, the submersion duration for the final fabrication of the tiles is extended to 15 minutes.

Up until this point, only one type of concrete has been used, namely the concrete "Bastelbeton" from the company Ultrament. A decision is made to also test whether another type of concrete, which is also a more economical solution, could give similar or even better results. The concrete tested is the "hobbybeton" produced by the company Baumit.

Testing shows that the "bastelbeton" from ultrament is the preferable concrete for the fabrication of the thesis tiles. Compared to the "hobbybeton" from Baumit, the viscosity and texture proved better for pouring at this smaller scale, and the texture of the concrete upon drying has a much smoother finish, while the other is very rough.

The vegetable oil as a coating agent proves successful. The demoulding process is significantly easier in comparison to the demoulding process of the geometric experiments and will be incorporated in the fabrication process. Some

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5.7
Vegetable oil as coating agent.
The oil is applied by spraying.

of the test tiles come out with a very interesting surface texture reminding of bubbles. It is not yet understood how some tiles have this surface texture and some don't, as this bubbled surface seems to appear in these tiles, while not appearing in the geometric experiments. Since the vegetable oil is new variable, the bubbled surface is attributed to the use of the oil.

The dowels seem to be successfully embedded into the tile with the correct placement. The removal of the screw and guide is done prior to demoulding and is somewhat resistant to the removal but does not pose a significant issue.

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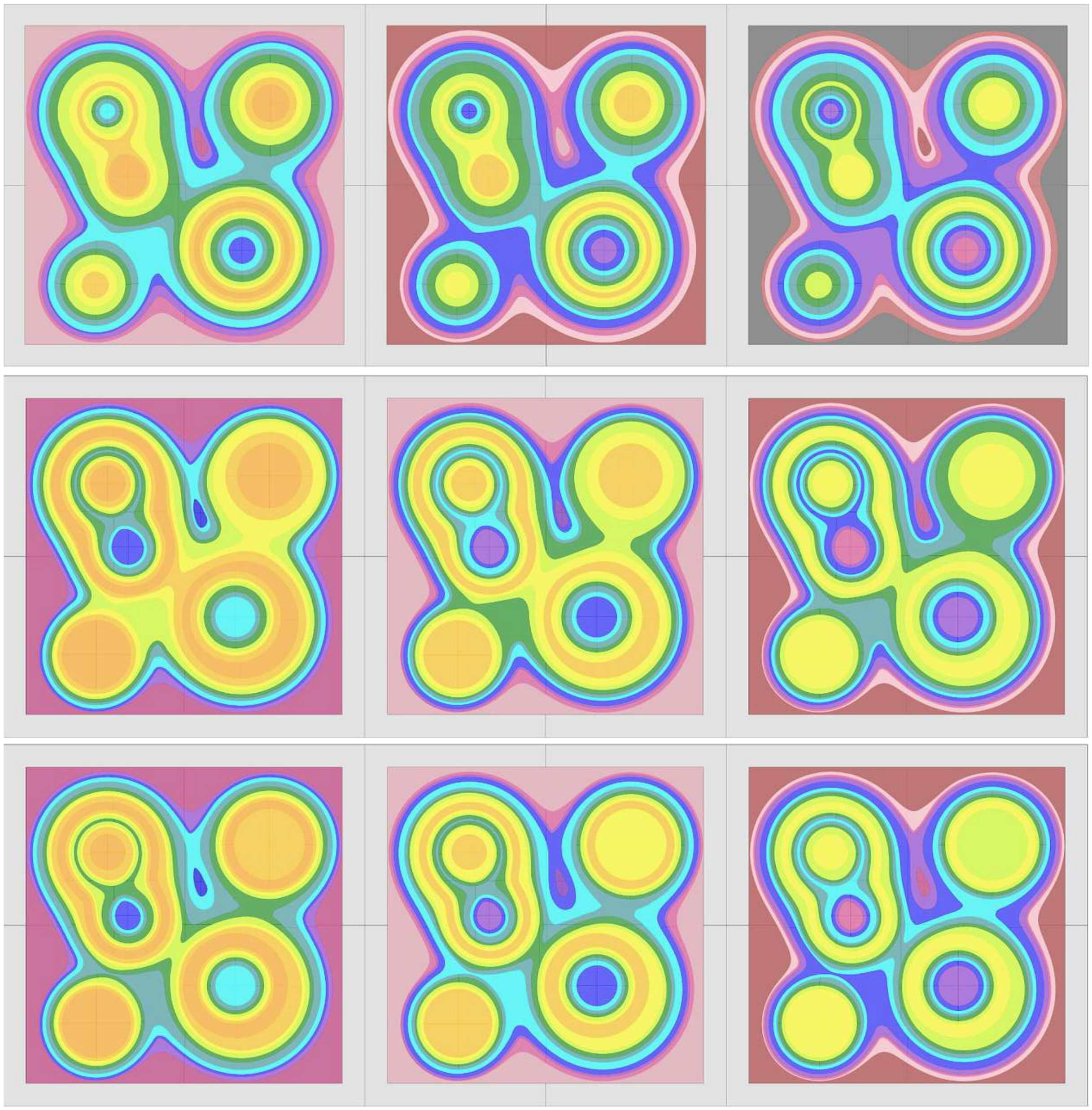

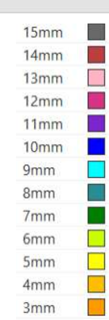

5.8
Comparison of the 3 variations of the same pattern, the top being the first pattern tested, the bottom being the pattern used for the formwork of the final panels fabricated.
The variation in the distribution and ratio of the material thicknesses is visible.

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A challenge does appear during the test of screwing the screws back into the dowels in the concrete tiles. If the screw is screwed too far in, the dowel will expand. This causes the tile to break. For future mounting of the tiles, this issue needs to be considered, and it is of great importance that the tiles are mounted with caution to prevent breaking.

Due to the change in pattern, the placement of the embedded dowels is also revised. At the first and second trials, the dowels are offset 50 mm inwards from the edges of the tiles. With the final pattern, the dowels embedded are moved inwards and placed at 65 mm from the edges.

Some of the test tiles have some defects that are attributed to human error in the handing of them, this is noted and improved for the fabrication phase.

Notably, it is worth noting that the tearing of the formwork in the second trial run demonstrates the elasticity of the mould, as it starts pulling back and dries in a position that is significantly less deformed immediately after tearing from extreme deformation. A layer of concrete is also left coating the torn formwork as a thin shell. It could be worth exploring whether these findings could lead to developing method of casting concrete shell elements. However, this will not be explored within the scope of this thesis.

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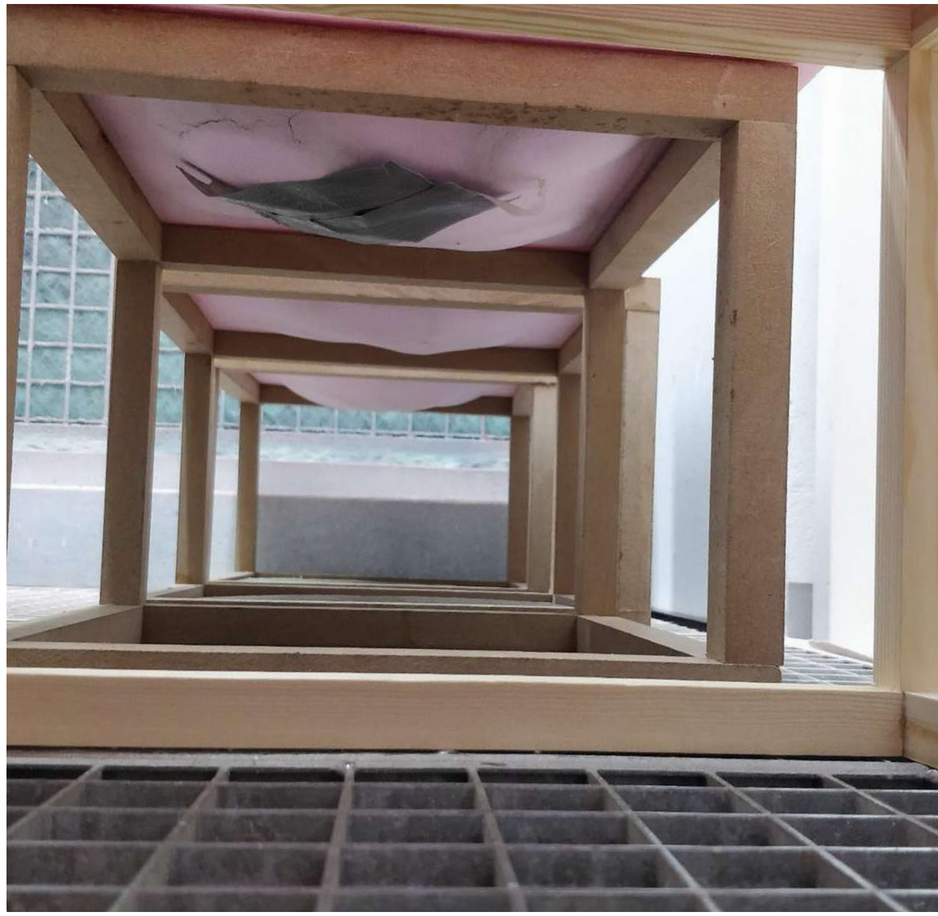

5.9
Suspended cast formwork viewed from below.

5.4 Fabrication

The fabrication process builds on the geometric experiments and uses the outcomes to improve the overall fabrication method.

The duration of submersion in the fabrication process is set to 15 min for each formwork, regardless of thickness or concentration. This is an increase from the geometric experiments and is done to further amply the results. In the second half of the submersion time, concrete is mixed. For the fabrication of tiles at 75%

and 80% concentration, 3,5 kg of concrete powder is mixed with 630 ml of water. This is sufficient, as the formwork deforms less. The fabrication of the tiles at 75% does not require the full mass of concrete, so some concrete material is left over upon the conclusion of this process. For the fabrication of the tiles at 85%, 4 kg of concrete powder are mixed with 720 ml of water, as these tiles have a greater deformation and require more casting material.

After submersion, the formwork is removed from the liquid, gently shaken to let some of the excess liquid drip off, and then the vegetable oil is sprayed generously onto the surface before being placed on the wooden frame. It is strived for to keep the duration of this process under 15 s, meaning that it should take no longer from the moment the formwork is removed from the liquid and until the concrete it starting to be poured, as the extruded polystyrene does not stay malleable for long.

The concrete is slowly poured exclusively from the corners and edges of the formwork, letting it flow towards the middle as gravity slowly pulls it in and the sheet deforms according to the pattern of thicknesses. This is done to prevent the mould from tearing, as mentioned previously in the testing phase. The pouring of the concrete is aimed to take 30 s for the fabrication at 75% and 80%, while the fabrication at 85% is aimed at a duration 45 s.

The fabrication of the tiles at 75% and 80% exhibit no challenges or issues, and the casting runs smoothly. The fabrication of the thinnest mould at 85% tears during the pouring of the concrete, presumably due to the concrete being poured too fast. The fabrication is repeated and runs smoothly the second time. Once the concrete is poured, a guide piece with screws and dowels are placed on top of the formwork, enabling the dowels to sink into the concrete. In this way, the dowels will be embedded.

5.10
Cast formwork with the dowel guides viewed from above.

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5.11
Intact formwork after demoulding.
This was submerged at 75% for fabrication.

5.6 Demoulding

The curing time of the concrete tiles is approximately 24 hrs, so the tiles are demoulded the day after they are cast. Before the tiles are demoulded from their formwork, the screws are removed from the dowels in the tiles and the guiding sheet is removed as well. Upon removal, the concrete still seems somewhat wet and is quite warm, so they are left for 2-3 hrs to cool down and dry.

The demoulding of the concrete tiles is done in a lower concentrated acetone-solution at 75%, in an attempt to preserve the material as much as possible. The process of demoulding the 9 concrete tiles show similar results as in the geometric experiments.

The largest difference between the experiments and the fabrication is the application of vegetable oil on the surface of the extruded polystyrene as a coating agent after the submersion in the solution. This proved to be successful. Most notably, some tiles can be removed from their formwork even without resubmerging them into any acetone solution. This mostly proved to be the case with the tiles that are fabricated using the acetone-water solution of 75%. It also proved possible for the one tile fabricated at 80% with the thickest formwork of min. 5mm. In these cases, the formwork is left entirely intact and can likely be reused. It is worth exploring whether the vegetable oil leaves residue on the XPS mould and whether this has any consequences for future remoulding, e.g. by changing the materials ability to soak in the solution evenly. However, this will not be included within the scope of this research.

For the tiles cast in a higher concentration, the oil significantly eased the demoulding process and decreased the time needed to demould. However, it does not have much impact on preserving the moulds, particularly the ones cast after a submersion at 85%. Regardless of the oil coating, the submersion in the solution still leaves the extruded polystyrene friable. During the demoulding, these moulds tear up at the weakest points of the mould, i.e. the thinnest surfaces, which are further stretched out during the casting process. Even if a demoulding

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5.12
Formwork containing cast concrete.
This was cast at 85% and the compromise in the formwork is visible.

left the formwork intact, it is uncertain whether these moulds could be reused successfully without tearing in the process. Additionally, tiles cast in formwork which is submerged in the higher concentrations appear to have XPS residue embedded in their surface, particularly in the areas with the highest deformation, meaning that these areas are cast in the thinnest and weakest parts of the formwork.

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5.13
Demoulded concrete from 5.12.

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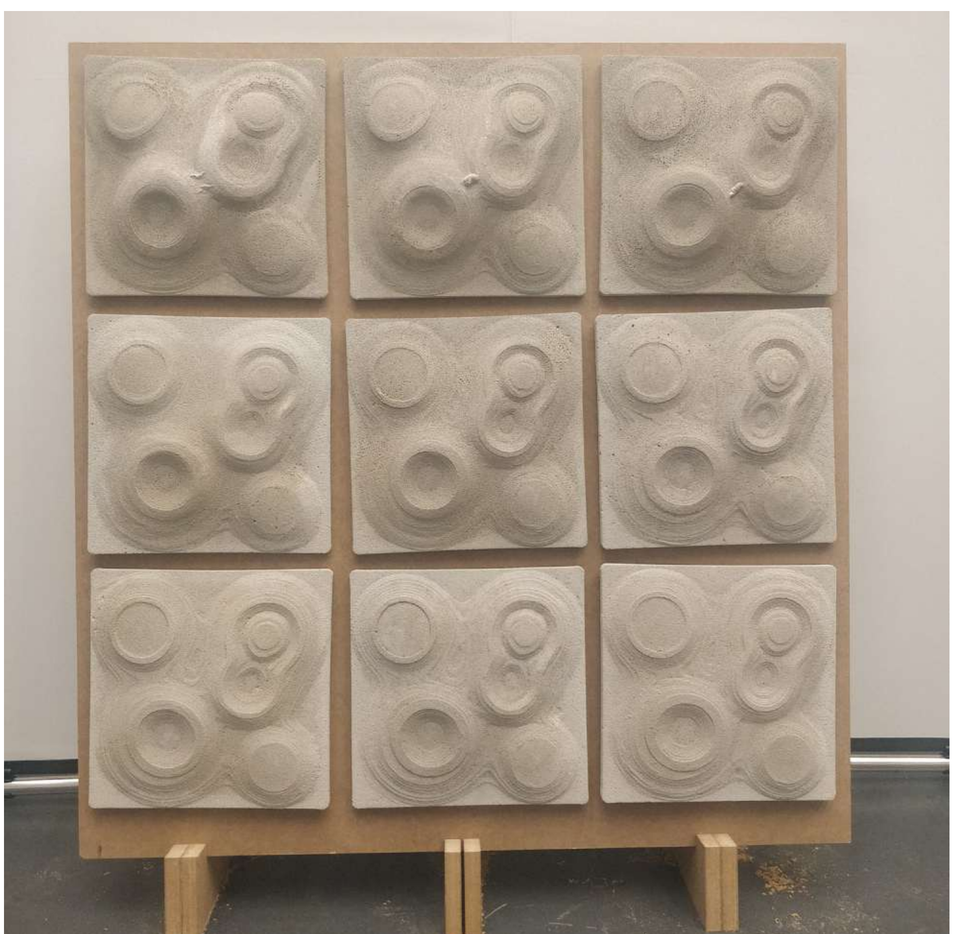
5.14
Left: Display wall seen from the back and front.
Right: Mounting system with embedded dowel.

5.6 Display and mounting system

As mentioned, during the fabrication process of the tiles, 4 dowels are embedded into the concrete of each tile while the concrete is setting. This will allow the tiles to be mounted on a wooden board for display. The dowels used are made of metal and match screws with a diameter of 4mm.

The mounting system developed for the display of the tiles is a simple one. It consists of a 920 x 960 x 19 mm MDF board, on which the tiles are mounted with 10mm gap between the tiles. 36 holes with a 4 mm diameter are drilled into the board with a placement that matches the dowels embedded in the concrete tiles. The idea is to insert 4 screws into each of the tiles through the backside of the MDF board to secure them to the board. Tests show that this has to be done slowly and carefully, as the concrete will shatter if the dowel starts extending.

The board is places on 3 identical feet made from MDF as well. The feet are designed in a way that the board can slide into the feet and lie on them securely, without the need for fastening them, enabling an easier transportation of the entire system.



5.15
Image of the finished display wall with the 9 finished panels mounted.

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5.16
The finished 9 concrete panels viewed from the side.
From left to right, thinnest to thickest formwork,
From up to down, highest to lowest concentration.

5.7 Results

The finished tiles overall showcase the expected graduation in deformation according to the parameters of the fabrication method. To clarify, the tile fabricated in the thickest formwork at 75% acetone concentration shows the smallest deformation, while the tile fabricated in the thinnest mould at 85% acetone concentration shows the largest deformation, while the rest of the tiles arrange within the expected order in between according to their deformation.

There are some irregularities and inconsistencies exhibited on the tiles. Apart from the difference in the amount of deformation, the tiles seem to have some differentiation in the shape as well, which can be noticed by focusing on the pattern. It seems that the pattern does have some minimal difference in the overall shape of the tiles when comparing them to one another. This could presumably be due to the concrete being poured from the corners and edges and the concrete then flowing in an unpredictable way and that the pouring is done manually, which means it cannot be completely controlled and replicated identically between the fabrications of the individual tiles. Generally, this difference in shape is not significantly noticeable.

All 3 of the tiles fabricated using an 85% acetone solution also exhibit some

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irregularity on the surface. This is likely caused by a small tear in the formwork during the setting of the concrete. The concrete has likely at this stage probably been liquid enough to be forced into the tear, but viscous enough that it didn't spill out through, simultaneously with the formwork being dry enough that the tear hasn't extended. The irregularity is sanded down so that is does not distract from the overall shape of the tile when displayed.
Additionally, they clearly display both negativly and positivly curved double-curved shapes.

5.17
Comparison of the thickest panel cast in the thinnest mould at 85% acetone and the thinnest panel cast in the thickest mould cast at 75% acetone.

5.18
The finished 9 concrete panels viewed from the front.
From left to right, thinnest to thickest formwork,
From up to down, highest to lowest concentration.

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6 Conclusion

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6.1
Detail showcasing positive and negative curvature.

6.1 Conclusion

This research successfully offers a novel approach to fabrication of double curved concrete elements, which demonstrate both positive and negative curvature. The use of extruded polystyrene and acetone as the formwork material makes this technique a more economic approach in comparison to traditional formwork. Although the fabrication in this paper does make use of a CNC-Milling machine, this technique does not inherently require expensive infrastructure to be applied. Theoretically, similar results could also be achieved by carving out a pattern to control the shape of the deformation. This makes this method more cost-effective compared to techniques like 3D-printing or adaptable moulds, which require high-tech machinery. This fabrication method also offers more freedom of design, allowing for non-uniform shapes, which are difficult to achieve with rigid or fabric formworks. Lastly, due to the property of the extruded polystyrene to deform itself from a planar sheet into a double-curved mould, large quantities of material are not required, as with other subtractive fabrication methods, which also shortens the overall production time of the formwork. This means that the material waste is greatly reduced, as it is limited to the material removed to control the shape of the deformation.

This research is built around qualitative experimentation and small-scale fabrication. There have been some restrictions in this research, namely the facilities and tools used, which has an impact of the scale of the fabrication, as well as possible inaccuracies and discrepancies. However, overall, the outcome of the experiments and fabrication is largely positive.

Overall, this fabrication method can be adjusted and altered, depending on the desired outcome. If the objective of the fabrication is to create concrete elements with larger deformations and more complex shapes, a higher acetone-solution can be applied to achieve this, however at the cost of the formwork material. On the other hand, more simple and slightly deformed elements can be produced in a lower acetone concentration, which greatly reduces the damage done to the formwork and allows reuse of the moulds.

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6.2 Further research

Throughout the research, several topics worthy of further exploration have emerged but could not be covered within the scope of this project.

As the main material proposed in this study is extruded polystyrene, which is known for its insulation properties, it is worth exploring whether this technique could be used to deform thermal insulation for complex-shaped building s, or even to produce insulation for other industries, such as the automotive industry. The thermal conductivity of XPS samples that had been submerged in the acetone-water solution were measured in this study and didn't show any significant change. It was, however, not possible to measure samples that were deformed; therefore, it is unknown whether the deformation of the extruded polystyrene causes some changes in the material structure, thereby weakening the heat resistance.

Furthermore, this method could also lend itself to production of concrete elements, where the extruded polystyrene functions as a mould while the concrete is setting and then, instead of demoulding, the polystyrene is left on the object to function as insulation.

In this project, the direction taken was focussing on this method as a subtractive formwork fabrication, but it would be interesting to explore whether it is possible to only soften and deforming some specific areas of the XPS sheet while the rest remains rigid, rather than submerging the entire sheet. By controlling which areas are softened and how much, this formwork would become truly versatile and adaptable. It would also completely eliminate material waste.

The biggest culprit in this study is that the materials and their production it not exactly environmentally friendly. Finding a way in which the XPS moulds can be reused to cast several times is an important topic to consider. It is believed that some tweaking and adjusting of this process, and further studying the materials and their interaction, could lead to the moulds being completely reusable.

One of the challenges in the fabrication process is the fast-drying extruded polystyrene. Once it is removed from the solution, the sheet does not stay flexible

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and stretchable for long. Finding a way to keep the extruded polystyrene flexible longer would make the manipulation of the material easier.

The tiles cast in this project are all solid and massive. This makes them heavy, and the fabrication of these has its limitations. Finding a method with which concrete elements can be cast hollow, or as shells, would open up many more opportunities for the application of this fabrication method.

The materials used for this project, both the extruded polystyrene and the acetone, were the same product throughout the entirety of the research. This was a conscious choice made in order to keep the material constant and to explore other parameters. It would be worth exploring whether there are other products, or even other materials, that could improve this fabrication technique. Another approach could be to develop a foam, or a solvent, specifically for this application.

Similarly, different types of casting material could also be explored for this purpose. In this project, ready-made gypsum and concrete mixtures are used for the various applications, but there could be casting materials that are better suited for this fabrication method. This could potentially also help solve the problem with casting shells rather than solid elements.

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3 Material Experiments

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4 Form-finding Experiments

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5 Case study of concrete façade tiles

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6 Conclusion

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