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Foam and solvent: a low-tech self-forming casting technique for the production of double-curved asymmetrical concrete panels

Ivana SUSIC*, Efilena BASETA

*TU Wien, Institute of Art and Design, Karlsplatz 13, 1040 Vienna, Austria
ivana_susic@hotmail.com
efstathia.baseta@tuwien.ac.at

Abstract

Considerable current research in the construction industry focuses on developing concrete elements in complex shapes. Traditional methods to achieve that are wooden or steel formworks, which are costly and constrained in shape. Novel methods such as fabric, 3D printed, and CNC milled formworks allow more formal possibilities. However, they come with design limitations, expensive infrastructure, and material waste. This paper introduces a novel low-tech and cost-efficient adaptable casting technique for the production of double-curved, asymmetrical concrete panels. The technique relies on extruded polystyrene foam (XPS), as a self-forming formwork. In particular, the research explores how XPS becomes malleable and stretchable when submerged in a solution of acetone and water. The formability of the XPS is controlled through three parameters: the concentration of the acetone solution, the thicknesses of XPS and the duration of the submersion. A case study of the production of 9 concrete panels with various thicknesses is presented in this paper. The weight of the cast concrete deforms the impregnated XPS formwork. This process allows the formation of both negative and positive curvature, which is controlled by the variable thickness of the formwork. In comparison to other adaptable formworks, the discussed low-tech technique is more accessible; while, in comparison to non-adaptable formworks, it reduces the material waste.

Keywords: Concrete casting, Flexible Mold, Double-Curved Surfaces, Formwork, Extruded Polystyrene, Self-forming, 3D scanning.

1. Introduction

Extruded polystyrene is a common material among architects since it is frequently utilized for prototyping during early design stages. In the construction industry, it is widely used as insulation material due to its efficient thermal properties, and it is often used as formwork for casting concrete. This research, however, takes a novel and experimental approach to this well-known material. Within the context of a material experimentation university course, the interaction between extruded polystyrene (XPS) and acetone was examined. This led to the finding that a water-acetone solution merely softens XPS, rather than dissolving it. To gain a deeper understanding of the interplay of extruded polystyrene and acetone-water solutions, an extensive series of different experiments have been conducted in which the impact of acetone concentration, the thickness of XPS and the duration of the submersion of the XPS in the solution were tested. Finally, the results and knowledge are utilized to develop a concrete casting technique for the production of double-curved concrete panels. The research presented is in its early stages and focuses on, qualitative and perceptive understanding of the developed material system as well as the potential for possible application.

2. State of the art

Various techniques are currently used for the production of complex concrete elements. The most common production method is subtractive formwork fabrication. This method includes robotic CNC milling, hotwire cutting, and abrasive wire cutting. The company Odico is one of the leading companies when it comes to the production of machines needed for large-scale industrial fabrication of subtractive formworks [1]. An example of recent research of subtractive formwork, is the development of a concrete casting formwork using abrasive wire cutting [2]. The advantage of subtractive fabrication technique is the high accuracy; whereas, the disadvantages are the expensive infrastructure and expertise needed, the inherent material waste, as well as the long production time.

Another fabrication technique for formworks is additive fabrication, i.e. 3D printing, which is still a relatively new concrete casting method. The technique can be applied both for 3D-printing wet concrete layer by layer, as well as the printing of formworks for concrete casting. The later has been explored for printing flexible formwork [3]. 3D-printing wet concrete requires a supporting structure, while it cures. To make these structures more versatile, adaptive formwork solutions have been developed to be used alongside 3D-printing concrete [4]. Adaptive formworks are a novel technology that uses a computer-controlled mechanism to deform a flexible sheet, onto which concrete can be cast. Adaptable formworks are available on an industrial scale by various companies such as Adapa [5]. The advantages of both additive and adaptable formworks are the large freedom that they offer for complex shape and their reusability. However, similar to the case of subtractive formwork fabrication, expensive infrastructure and expertise is required. Apart from this, both techniques carry challenges with scalability and additionally, 3D printing inherently has a longer production time.

As far as textile formwork is concerned, it has been explored as a concrete casting technique since the beginning of the 20th century. Different processes such as suspending it on an external structure, using a pneumatic system or changing the structure of the textile itself [6] have been demonstrated. Recently, a collaboration of Aachen university with the company Stanecker and Penn textile has resulted in the production of double-curved façade concrete panels for commercial use [7]. The advantage of fabric formworks, compared to the previously mentioned methods, is the low production cost, as well as their accessibility. However, fabric formworks come with a constrain in terms of shape, as it is limited to uniform, symmetrical shapes due to their activation by gravitational forces.

In summary, many fabrication techniques allow for double-curved concrete casting. The high-tech methods are associated with a high production cost, while the low-tech methods are often constrained in formal freedom. The discussed novel casting technique aims to offer an accessible, cost-efficient system that supports design freedom.

3. Material system

This research focuses on the interaction of two main materials: XPS and acetone. Extruded polystyrene foam (XPS) is usually rigid and is widely known and used for its insulation properties. Throughout this research the extruded polystyrene used, was the XPS TOP 30 SF insulation board, produced by Austrotherm. The specifics of this product in terms of foaming agent and other additives are unknown.

The second material used is acetone, which is an organic solvent. It is highly volatile, and quick to evaporate. Both the vapor and liquid are highly flammable. Additionally, acetone can be an irritant, but generally not considered toxic to humans. However, appropriate measures should be taken while working with this substance. The product used throughout the research is the acetone produced by Meffert AG Farbwerke.

When extruded polystyrene comes into contact with pure acetone, it swells and then immediately breaks down. What is left over after this process is polystyrene in the form of a viscous gel along with colorants and possibly other additives.

Diluting the acetone with even small amounts of water, immediately changes the effect that the liquid has on extruded polystyrene. Adding low amounts of water, slows down the process of the material breaking down. In the right amount, the solution softens the extruded polystyrene, making it malleable, without breaking down the closed cell structure of the foam or significantly weakening it; thus, the first part of the research focuses on finding the right ratio of water to acetone. Furthermore, a deformed piece of extruded polystyrene will harden and remain in the given shape upon drying. The process of softening and shaping the material can be repeated several times, without significantly compromising the material.

3.1. Time-Concentration experiments

The first series of qualitative material experiments were conducted to observe and test the effect of different acetone and water solutions on XPS. The first aspect of these experiments focuses on finding a solution with the optimal water to acetone ratio, in order to soften and deform samples of extruded polystyrene. The different acetone concentrations tested were as follows: 50, 55, 60, 65, 70, 75, 80, 85, and 90% of acetone in water.

The second aspect tested in these experiments was the duration of submersion of the extruded polystyrene in the water and acetone solution. This was done to understand whether a longer duration of submersion has any influence on the outcome. For each of the 9 concentrations tested several submersions were done at different durations. The time durations tested were as follows; 30seconds, 1, 2, 3, 5, 7, 10, 15, 20 and 30 minutes. This adds up to 90 tests of time and concentrations.

For the abovementioned tests, 90 identical square samples of extruded polystyrene of the dimensions 100 mm x 100 mm x 10 mm were used. Each polystyrene sample was submerged in a water and acetone solution for a given amount of time. Once the sample was removed from the liquid, they were manually pulled from the corners and bent to stretch and deform the polystyrene sample. The observations were noted and evaluated (Figure 1).

From these qualitative experiments of deforming extruded polystyrene, it is concluded that concentrations below 75 % did not have as much impact on the material, while the test of 90 % broke down the extruded polystyrene (Due to this, durations above 10 min were not conducted at this level of concentration). Thus, the optimal acetone concentration in water lies within the range of 75 % and 85 %, when it comes to deforming and stretching XPS. At 75 % the deformation was smaller, and the XPS more difficult to deform. However, the material at 75 % acetone concentration did not appear damaged. Whereas, at 85 %, the XPS had a significantly greater deformation and stretchability, but did appear to compromise the material. In further experimentation and fabrication, the concentrations of 75 %, 80 % and 85 % are used.

When it comes to the duration of submersion, the difference in outcome between the submersion durations 30seconds, 1, 2, 3, 5, 7, 10, and 15 minutes, was remarkably noticeable. The durations of 20 and 30 minutes did soften the material more, but not significantly, compared to the amount of time required. For further experimentation durations of 10 and 15 minutes will be used. The optimal acetone concentration and submersion times for deforming XPS are highlighted in figure 1.

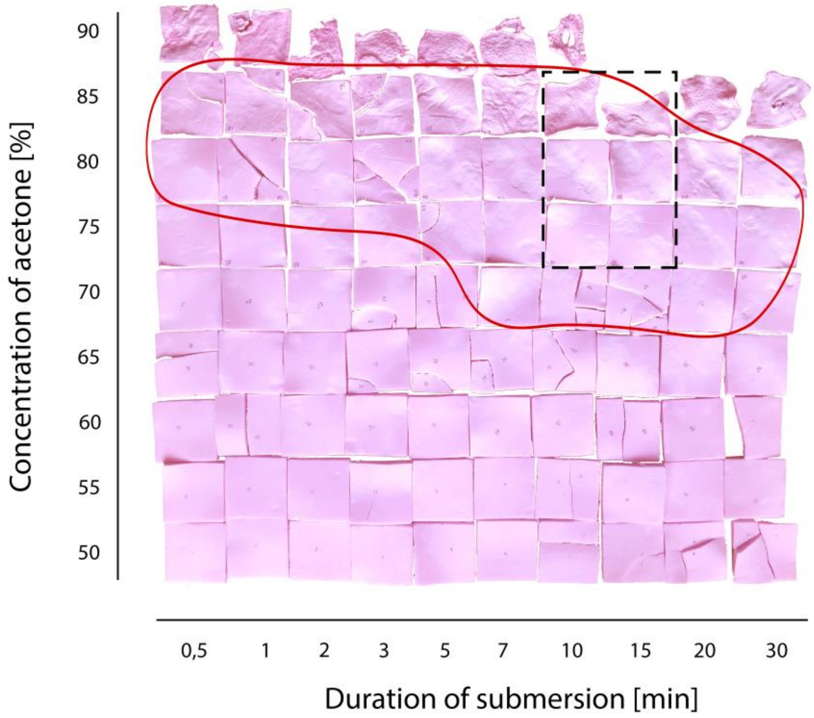

Figure1: Qualitative results of the different submersion durations on the x-axis and the acetone concentration in water on the y-axis. All samples' dimensions are 100x100 mm. The samples within the red-outlined area are malleable at the XPS thickness of 10 mm and vary in rigidity. Outside the red area, the samples are either too rigid or too damaged from the acetone. The samples within the dashed line are the optimal outcomes for deforming XPS and are used in further research.

3.2. Thickness-Concentration experiments

Given that the material thickness could have an impact on the overall scalability of this process, the next series of experiments focus on understanding how the thickness of extruded polystyrene affects its malleability and defining an applicable range for the deformation of extruded polystyrene.

The extruded polystyrene samples used in these experiments measure 100 x 100 mm and vary in thicknesses. The thicknesses tested were as follows: 1, 2, 3, 4, 5, 7, 15, 20, 30, and 40 mm. The duration of submersion was 10 minutes across all experiments. The acetone to water concentrations used were within the previously suggested range (see 3.1): namely 75%, 80%, and 85%. Based on the outcomes of the previous experiments, the thicknesses above 10 mm are excluded from the testing of 75% concentration, as it was unlikely to have an impact on the thicker pieces. For the tests of 80%, all thicknesses were tested, and for the experiments conducted at the concentration of 85%, the samples with a material thickness under 10 mm are excluded, due to the strong impact of the high concentration of acetone on the structure of the material.

The experiments were conducted in the same manner as the previous ones. A solution of water and acetone was mixed, a sample of extruded polystyrene was subsequently submerged for 10 minutes. Once the sample was removed from the liquid it was deformed and stretched by pulling and bending the sample manually.

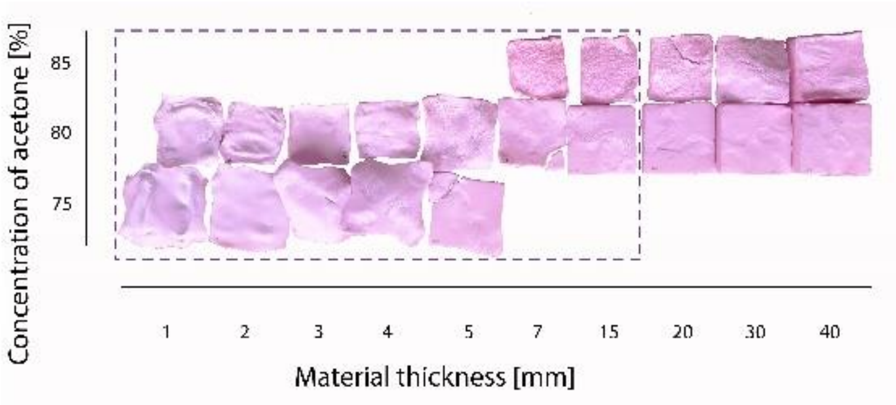

Figure 2: Outcomes of the qualitative experiment of concentration of acetone and material thickness for submersion duration of 10 minutes of samples of 100 x100 mm. Variable parameters are the thickness of the individual sample, which are noted on the x-axis and the variation of the concentration on the y-axis. The dashed line shows the range of malleable pieces, while the ones outside the border did not allow to be stretched or deformed completely.

The results of this series of experiments, graphically presented in Figure 2, showed that thinner sheets exhibited greater malleability and stretchability but became more fragile upon drying. Thicker samples retained a rigid core despite the surface softening. Above the sample thickness of 20 mm, the solution did not soak into the extruded polystyrene. The samples had an “outer layer” which was soft and malleable, but with a harder “core”, that remained rigid. To further test whether the impact of longer submersion duration on the malleability of thicker samples, another test was conducted with a 100 x 100 x40 mm sample. This was submerged at 80% acetone concentration for 6 hours, with a regular check after every 30 minutes. The outcome showed a significantly softer sample of extruded polystyrene. However, it still exhibited a layering of a softer, malleable layer on the outside and a more rigid core.

In summary, the material experiments show that extruded polystyrene becomes malleable and stretchable after submersion in an acetone-water solution and that the concentration and duration play a significant role. Furthermore, the results show that the thinner the material, the more it allows to be stretched and deformed. Additionally, it was demonstrated that double-curved and freeform surfaces are possible to achieve and that, upon drying, the extruded polystyrene holds the given shape.

4. Casting technique

Given that a sheet of extruded polystyrene after being submerged, does not deform on its own but requires external forces, the findings of the above experiments show great potential in utilizing the discussed material system for the development of a flexible formwork for concrete casting. In this case, the gravitational forces of the cast concrete are employed to deform a sheet of extruded polystyrene. The shape and curvature of the deformation are controlled by the varying thicknesses of the formwork, which can be produced by subtractive techniques.

At the respective experiment, shown in Figure 3, an extruded polystyrene formwork is deformed under the weight of concrete, proving the potential of this casting process. The concrete used, has a density of 460 kg/m^3.

Figure 3: Process of concrete casting in a flexible XPS formwork. The formwork used in this test had a simple, circular pattern with varying thicknesses. The thinnest area was 3 mm and the thickest 10 mm. The formwork is suspended on the wooden frame after a submersion in an acetone and water solution and concrete is poured onto the formwork. As predicted, the thinnest area stretched the most under the weight of the concrete.

4.1. Case study set-up

As a case study of the aforementioned casting technique, concrete panels with variable depth were fabricated. To produce these panels, three formworks with a single pattern (see 4.2) and three different thicknesses have been produced with CNC milling. On top of the three different formworks, the three different concentrations used in the previous research, namely 75%, 80% and 85%, are also used for each one of the three formworks. By combining these two parameters, thickness and concentration, the deformation of the produced formwork to can be controlled, and thus the shape and depth of each panel.

In summary, this is expected to produce 9 panels that gradually increase in depth. The expected outcome is the thickest formwork submerged at 75% would have smallest deformation and thus produce the shallowest panel, while the thinnest formwork submerged at 85% concentration is expected to show the biggest deformation and thus the deepest panel. The duration of submersion was kept constant at 15 minutes for each submersion. Additionally, wooden frames were built, on which the formwork was placed after being removed from the water and acetone mixture. The concrete is then poured onto the formwork, as illustrated in figure 3.

4.2. Design and fabrication

The design of the pattern for the concrete panels is inspired by forcefields, as this relates to the core principle of the casting process, which is gravity. To show the possibilities of the discussed technique, the formwork is designed to produce panels with both positive and negative curvature.

The pattern is generated in grasshopper 3D, using field lines. Spin force is added to 5 main points of interest, which affect the field lines. Subsequently different heights have been given for the the production of the variable thickness formwork through CNC-milling. 2 of the 5 points are selected to form negative curvature, while the other 3 form a positive curvature on the final panels. The pattern is identical for all formworks. There is a 1 mm step between each consecutive change in thickness, and the total gradient on each formwork is 10 mm.

The thickness of the bottom layer of the formworks a), b) and c), shown in figure 4, is 3 mm, 4 mm, and 5 mm respectively resulting in total thickness of 13 mm, 14 mm, and 15 mm. The pattern controls the shape of the deformation through the varying material thicknesses. Considering the results of the material experiments, the thinner areas are expected to stretch more than the thicker areas.

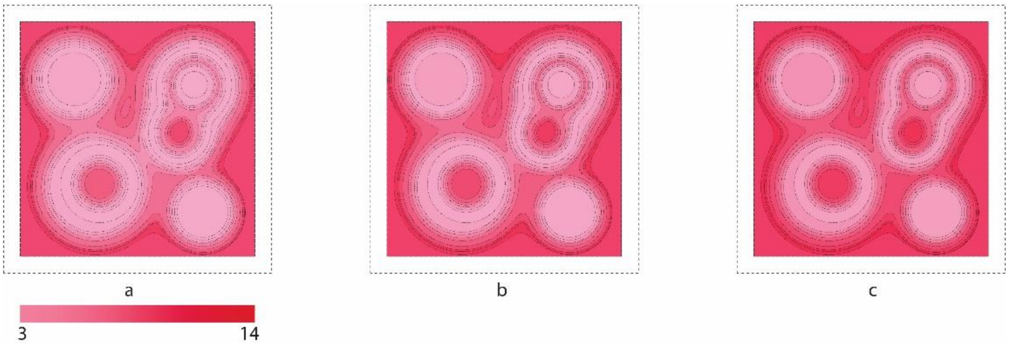

Figure 4: The single pattern used for the three formworks with the three different material thicknesses. Each formwork has the dimensions of 320 x 320 x 25 mm in total. The thickness of the pattern varies in the three shown formworks, where a) shows the thinnest formwork spanning from 3 to 13 mm, the formwork in b) spanning from 4 to 14 mm and the one in c) being the thickest and ranging from 5 to 15mm in thickness. The change of intensity of the color represents the thickness variation of the formworks.

The above patterns were CNC milled into the surface of a sheet of extruded polystyrene. The formwork has the dimensions of 320 x 320 x 25 mm (including the border for the casting) with casting area of 280 mm x 280 mm. The XPS formwork is sanded slightly to smooth out the surface and to make the demolding process easier.

As far as the casting process is concerned, it was challenging, as it must be conducted at the same pace for each panel to have comparable results. More specifically, given that the acetone/water solution is volatile, and the formwork dries up very quickly, the casting of the formwork must happen as soon as the formwork is removed from the solution. This has a large impact on the deformation of the formwork. Moreover, if the concrete is poured too fast, the formwork tears; whereas if poured too slowly, the formwork deforms slower, and thus less, as the formwork material dries in the process of casting. By conducting the casting process very carefully the human error was minimized.

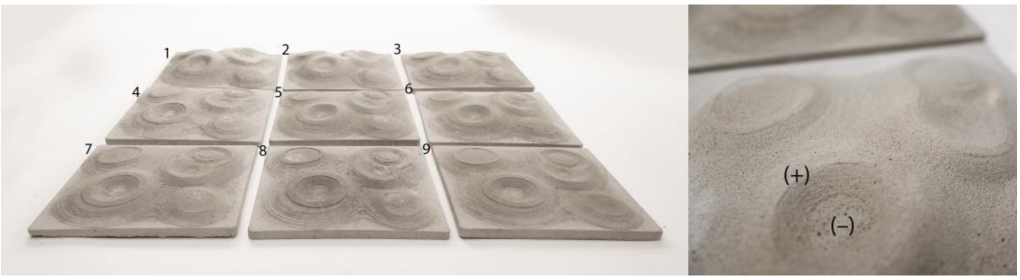

Figure 5: Left; The 9 concrete panels, where formwork thickness increases from left to right from 13 mm to 15 mm and the concentration increases from the bottom to the top from 75 % acetone concentration to 85 % acetone concentration. This results in panel 1 being the deepest panel, while panel 9 is the shallowest. The numbers and panels correspond to the 3D scans in figure 6. Right; Detail of negative (-) and positive (+) curvature of concrete panel 1.

These 9 produced panels indicate a clear difference in the depth of their shape, which is caused by the above-mentioned parameter variations. The panel at the number 9 was cast in a thicker formwork, at 75 % acetone concentration and the panel number 1 was cast in the thinnest formwork at 85 % concentration.

Finally, the demolding proved much easier for the formwork used in the fabrication at 75% and 80% acetone in comparison to the formwork submerged at 85% of acetone concentration, as the damage from extensive stretching of the material in combination with high concentration of acetone, makes the extruded polystyrene very friable.

4.3. Evaluation

The 9 fabricated concrete panels indicate visible variability in their form. To accurately evaluate their shape and their relation to the XPS formworks parameters, each panel has been measured by means of a 3D laser scanning.

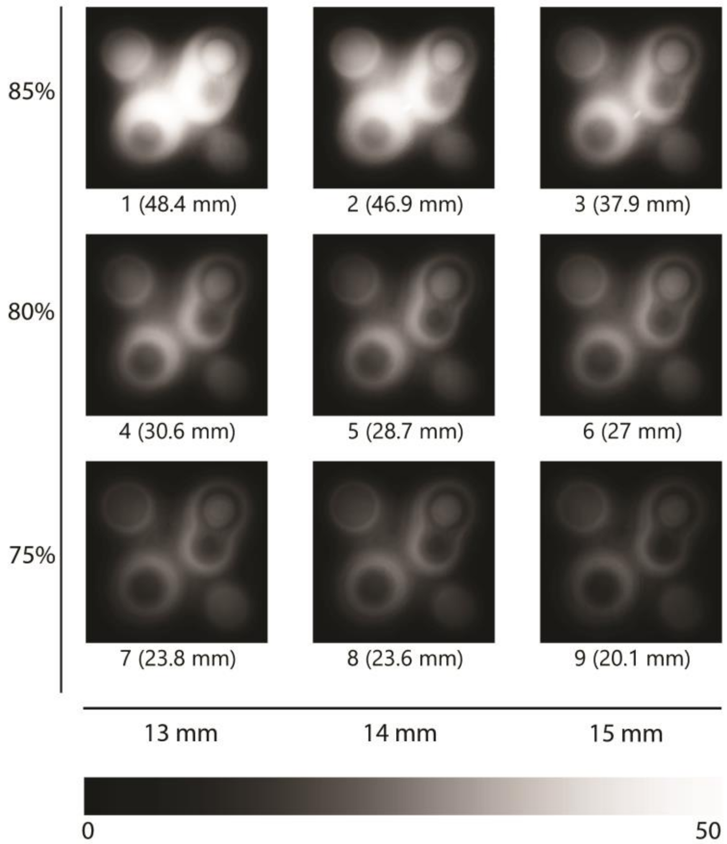

Figure 6: Results of the 3D laser scan of the 9 fabricated concrete panels, where the thinner parts are indicated with black, while the thicker with white. The black circles in the middle of the circular pattern show the negative curvature of the tiles and correspond to the inversed thickness of the formworks shown in figure 4. The X-axis shows the overall material thickness of the formwork, while the Y-axis shows the different acetone concentrations of the solution used to soften the formwork.

From this figure it is evident that the combination of material thickness of the formwork (Figure 4 a, b and c) and concentration of each casting process caused a constantly decreasing depth from panel 1 to 9. In addition, the thickness variation within each formwork allowed both positive and negative curvature, and thus asymmetrical forms.

By plotting the maximum depth of each panel (blue graph in Figure 7) it becomes apparent that by varying the concentration of the solvent and the thickness of the formwork, the depth of the panel is controlled. The increase of the concentration had a bigger impact, to the deformation of the formworks, in comparison to the thickness of the formworks (steepness of blue graph in Figure 7).

In order to evaluate the cost-efficiency of the discussed fabrication method, the total XPS volume used for the 9 panels of this case study was calculated and equals to 0.023 m^3. Considering the data from the 3D scans, additional calculations were made to evaluate the material usage for the 9 formworks, for the scenario of not using shape-adaptable formworks, but standard CNC-milled foam formworks. The calculations showed that in the latter case 0.044 m^3 of foam would have been needed. This concludes to the material reduction of 48% with the use of the discussed technique. The respective material volumes needed per panel are illustrated in figure 8 and numerical data are shown in figure 7 with orange.

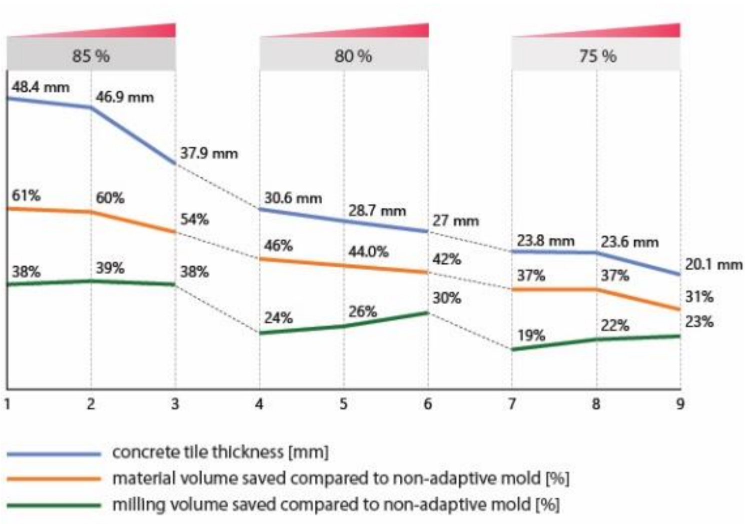

Figure 7: The measured differences in the depths of the 9 concrete panels is illustrated by the blue graph, while the orange graph shows the formwork material saved by using this planar formwork and softening it, rather than subtracting the full depth of the panel from a larger block of XPS. Subsequently the green graph visualizes the milled volume difference associated with both techniques. The numbers on the x-axis corresponding to the panels shown in figures 5 and 6.

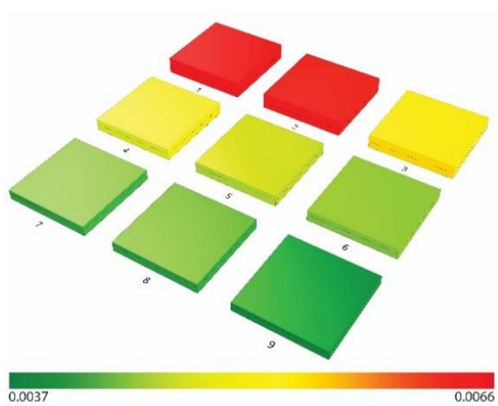

Figure 8: Visualization of the formwork material that would have been used for the production of each of the 9 concrete panels with traditional non-adaptable milled formworks. Red indicates a higher volume of material saved given the used adaptable formwork had the minimum height.

A second calculation was conducted for the CNC milled volume needed in both scenarios. This resulted to a total of 30% less milling needed with the discussed adaptable formworks, in comparison to the milling needed for the standard formworks. Numerical results per panel of these results are shown in Figure 7 indicated with green graph. From this diagram, it is evident that the thicker the panel the more resources can be saved with the discussed technique.

5. Conclusion

The case study of the 9 concrete panels successfully showed controlled variability in their form, defined by the combination of two parameters, namely concentration of acetone in the water solution and material thickness of the XPS formwork. Additionally, it demonstrates the possibility of creating both positive and negatively double-curved shapes. The square concrete panels produced are of the size of 280 mm with the possibility of scaling up. In conclusion, the discussed fabrication method shows great potential as a low-tech casting technique that could be applied broadly in industry. This is based on the fact that it relies on widely available and cost-efficient materials, such as extruded polystyrene and acetone. In addition, it depends on a commonly accessible industrial fabrication method such as CNC-milling. Finally, it can save up to 50% of formwork material, in comparison to non-adaptable formworks and can reduce the milling volume, and thus the material waste, by 30%.

Currently the data presented is mainly qualitative and based on haptic exploration of the interaction between extruded polystyrene and acetone. Steps need to be taken in future research to gather quantitative data of the change in properties of the extruded polystyrene. Furthermore, there are some challenges to the presented fabrication method as well. The main one is the fast speed necessary to fulfill the casting. This could be mitigated when handled by a machine. Another challenge is that the difficulty of the demolding process for the formworks submerged at high concentrations. This is an important aspect to be explored further in order to make the XPS formwork reusable.

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