Saimaa University of Applied Sciences
Technology, Lappeenranta
Mechanical Engineering and Production Technology

Junjie He

Concrete casting moulds with 3D-printing technology

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Abstract

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Instructor: Mikko Ruotsalainen, Saimaa University of Applied Sciences

This thesis aims to test the feasibility of adopting 3D printing technology in concrete moulds manufacturing and formulate the advantages and limitations of 3D printing technology in casting mould making.

This study was carried out in the laboratory of Saimaa University of Applied Sciences by conducting an experimental project. The background information was gathered from the Internet and the literatures in Lappeenranta Academic Library. In this study, the different additive manufacturing techniques and the testing equipment were introduced, then the procedure and results of the experimental project were elaborated and discussed, finally the conclusions of this study and the niche market of 3D printing casting moulds were summarized.

This study is just a preliminary research to explore the possibilities of adopting 3D-printing technology in the manufacturing innovation. Further study is required to exploit the full potential of this technology.

Keywords: 3D printing technology, concrete casting moulds, feasibility

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Terminologies

AM	Additive Manufacturing
CAD	Computer-Aided Design
SLA	Stereolithography Apparatus
ASTM	American Society for Testing and Materials
STL	Surface Tessellation Language
DED	Directed Energy Deposition
FDM	Fuse Deposition Modelling
PBF	Powder Bed Fusion
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
SHS	Selective Heat Sintering
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
LOM	Laminated Object Manufacturing
UAM	Ultrasonic Additive Manufacturing
UV	Ultraviolet

1 Introduction

Concrete casting is an effective way to duplicate a tangible object by solidifying the concrete in its mould. Due to the good adaptive property of concrete, the duplicates can preserve excellent surface details. Concrete casting has been extensively used to replicate architectural elements like concrete form liners, stone veneers, concrete countertops, concrete barriers, etc. It can also be applied in reproduction and restoration of concrete medallions, decors and sculptures.

The traditional process to create a concrete casting mould is by pouring, brushing or spraying the liquid rubber against a well-sealed object, nowadays the 3D printing technology brings the possibility to create concrete casting moulds with less effort. 3D printing is an emerging technology to achieve the rapid creation of tangible 3D parts from digital prototypes. The synonymous term additive manufacturing (AM) is preferably used in scientific context. As opposite to traditional subtractive and formative manufacturing methodologies, additive manufacturing creates the 3D objects incrementally through deposition of the material layer by layer.

In this thesis, the feasibility and limitations of concrete casting mould fabrication with the 3D printer will be tested. The testing printer is Stratasys Objet30 Prime. The digital prototypes will be built with the help of the lithophane creating software and Solidworks. Upon completion of this study, we will conclude the advantages and disadvantages of the 3D printing concrete casting mould compared to the traditional method and find the niche of this method.

2 Literature review

2.1 Research background

For millennia, concrete has been acknowledged as one of the most important construction materials. Along with the modernization trends, the construction industry was booming and thriving during the last few decades, the market demand for mass production of concrete elements with complex features and exceptional surface quality has been increasing tremendously. Therefore, the traditional methods of concrete casting have been facing an unprecedented challenge to cater to the rapid market growth.

To improve productivity and efficiency, the concrete casting elements must be massively manufactured off-site. To this end, the casting moulds must be of good reusability and nice flexibility (various materials, dimensions, shapes or textures might be needed), moreover, the casting mould needs to be created without the original part and put into use within a very short lead time. Obviously, the traditional way to create the mould is too limited to satisfy all the requirements.

However, 3D printing technology is not constrained by a single homogeneous material and stereotypical design thinking. Even though 3D printing concrete casting mould technology is still at its nascent stage, yet the 3D printing technology is relatively robust. With the vision that AM technology will spur a manufacturing renaissance, the productivity boost in concrete casting industry might be realized if put this topic into further study. (Joan Horvath, 2014)

2.2 Additive manufacturing technology

3D printing technology has been around us more than thirty years since the first stereolithography 3D printer was developed by American engineer Charles W. Hull in 1984. In 2005, the RepRap movement encouraged the participation of people on the Internet to improve the design of 3D printer and made 3D printing technology an open-source concept, which accelerated the process of evolving

and diversifying of 3D printers and made this high-tech product easily accessible and very user-friendly. (Joan Horvath, 2014)

The versatility of this technology not only brought innumerable conveniences to one's daily life but also materialized a vast variety of novel ideas. For instance, the life-size 3D-printed mammoth skeleton accurate reconstruction project, which indicates that AM technology also has great potential in the palaeontology field. Nowadays AM technology is proven more than a novelty or fad, 3D printing has been integrating into every aspect of our life, it can be seen in manufacturing, medical, industrial and even domestic applications. As shown in *Figure 1* below, we can see all the AM technology application areas and the percentage of shares. (Gertjan Brienen, 2018)

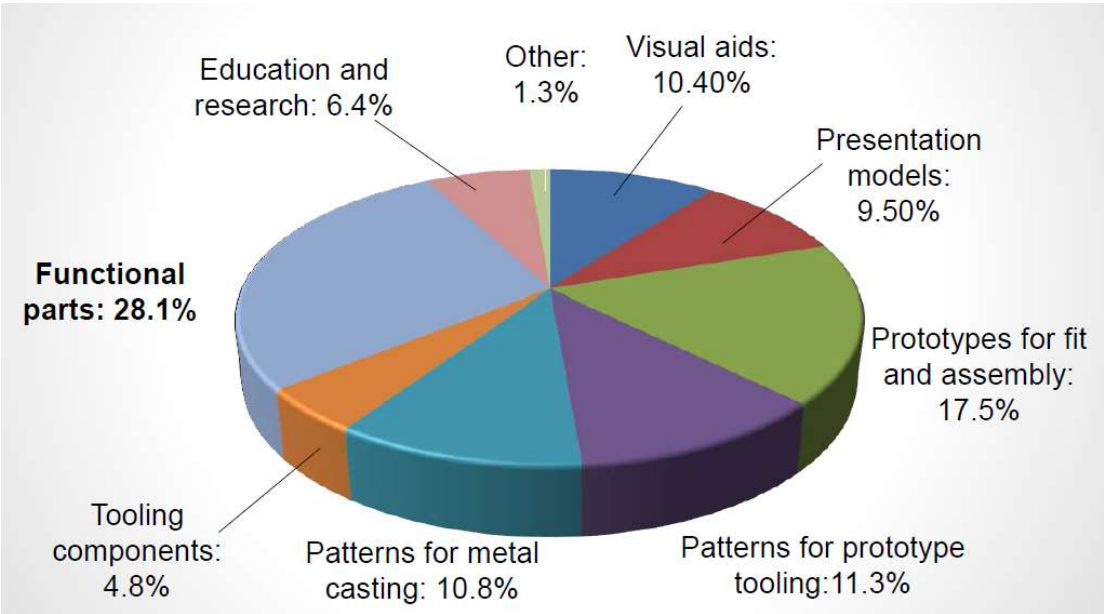

Figure 1. AM technology applications (Wohlers Report, 2013)

Due to the extensive applications, the wide range of materials has been used in 3D printing technology and the suitable additive manufacturing techniques are selected accordingly. The materials include plenty of polymers, metals and ceramics. Referring to ASTM F2792-12a standard terminology for additive manufacturing technologies, the AM techniques can be divided into seven main categories based on the different types of building platform and binding methods of each layer:

1) **binder jetting –** The powder material is spread over the gradually descending build platform with the help of a roller; the liquid binder is selectively deposited through the printhead nozzle to bond powder material layer by layer. The schematic is shown in *Figure 2*.

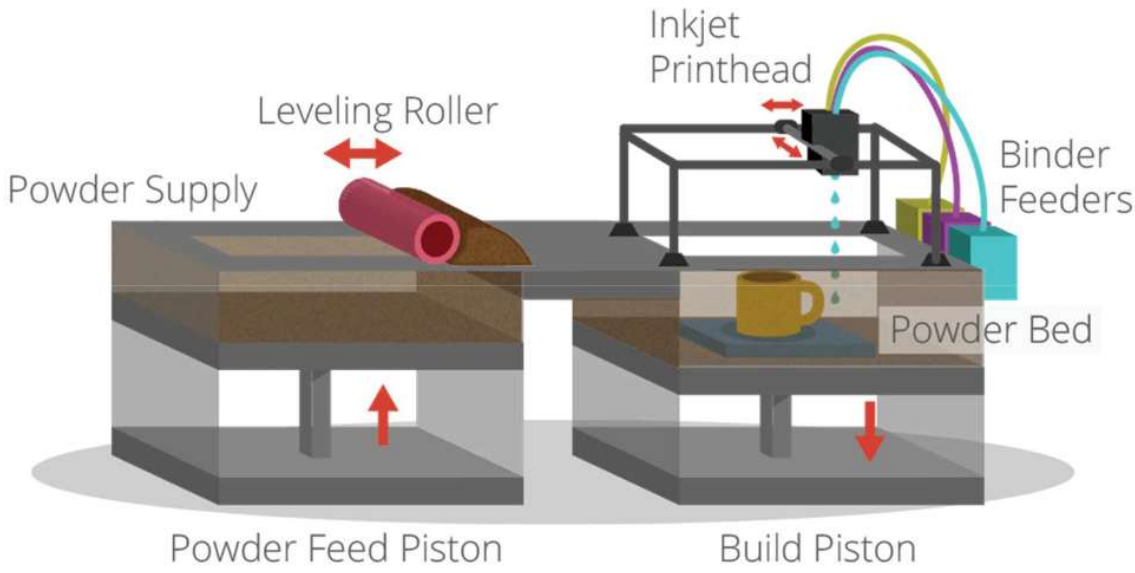

Figure 2. Binder jetting schematic (Source: Threeding.com)

2) **direct energy deposition (DED) –** Focused thermal energy is used to fuse materials as they are deposited onto the existing layer surface to solidify and join together. Typically, the build platform is fixed, and a nozzle can move along multiple axes and directions. The schematic is shown in *Figure 3*.

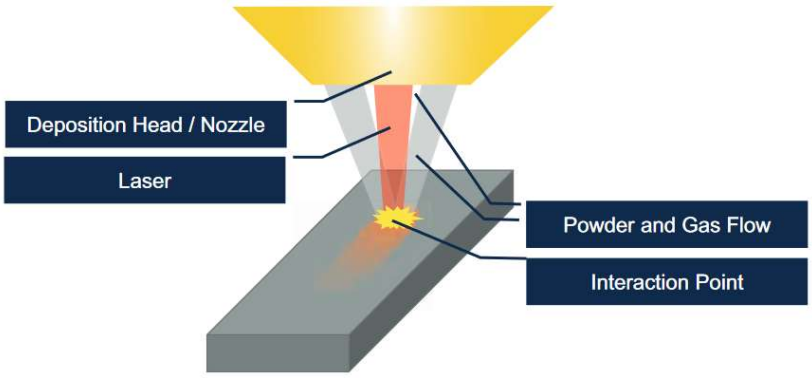

Figure 3. Direct energy deposition schematic (ABS, 2017)

3) **material extrusion –** The most common material extrusion process is Fuse deposition modelling (FDM), in which thermoplastic material is drawn through a nozzle to be heated and selectively dispensed layer by layer. The build platform will be descending one-layer thickness once a layer is completed, as shown in *Figure 4*.

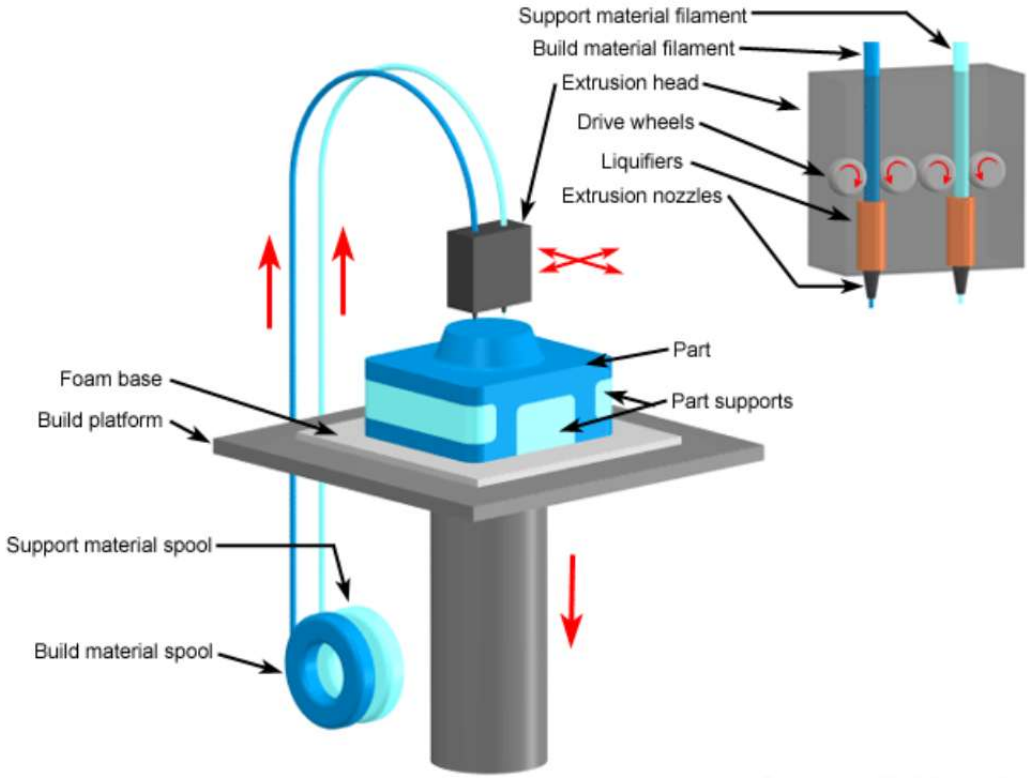

Figure 4. Material extrusion schematic (source: custompartnet.com)

4) **material jetting –** Similar to the 2D inkjet printing, typically the droplets of photosensitive material are selectively deposited layer by layer on the gradually descending build platform, then the material layer will be cured and hardened by ultraviolet (UV) light, the layers will be joining together during photopolymerization process to form an object. Material jetting allows multiple printheads to work at the same time, so multi-material printing and colourful printing is possible. However,the post process is required to remove the coating and support materials. The schematic of material jetting is shown in *Figure 5*. (Alkaios, 2018)

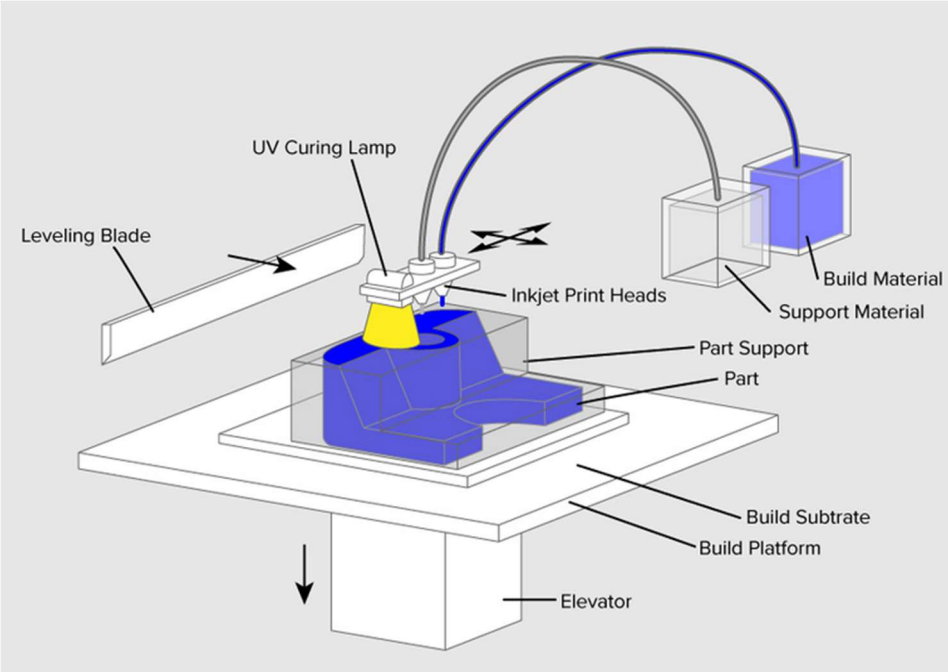

Figure 5. Material jetting schematic (source: custompartnet.com)

5) **powder bed fusion (PBF) –** The most common PBF methods include Direct metal laser sintering (DMLS), Electron beam melting (EBM), Selective heat sintering (SHS), Selective laser melting (SLM) and Selective laser sintering (SLS). Typically, powder of material is spread over build platform to be selectively fused and melted together by the laser or electron beam, once a layer is completed, build platform will descend one-layer thickness and the roller will spread a new layer of powder, as shown in *Figure 6*.

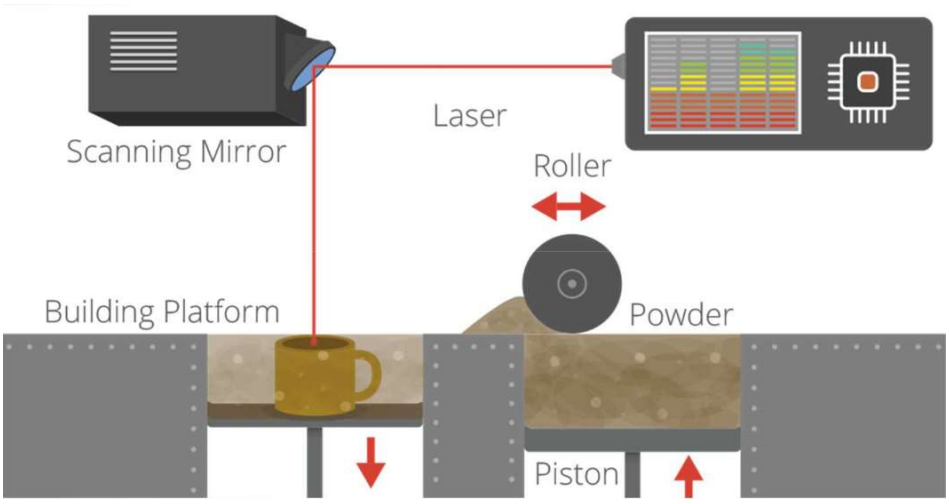

Figure 6. Powder bed fusion schematic (source: 3dprintingindustry.com)

6) **sheet lamination –** The sheet lamination 3D printing material can be either printing paper (LOM) or sheet metal (UAM). For the first one, printing paper will be cut into correct contours by the blade before bonding with the former layer using an adhesive. For the metal sheet lamination printing process, the metal sheet will be cut by laser and bound using ultrasonic welding. The sheet lamination 3D printing products are of high aesthetic value but not suitable for functional use. The working principle of sheet lamination is illustrated in *Figure 7.*

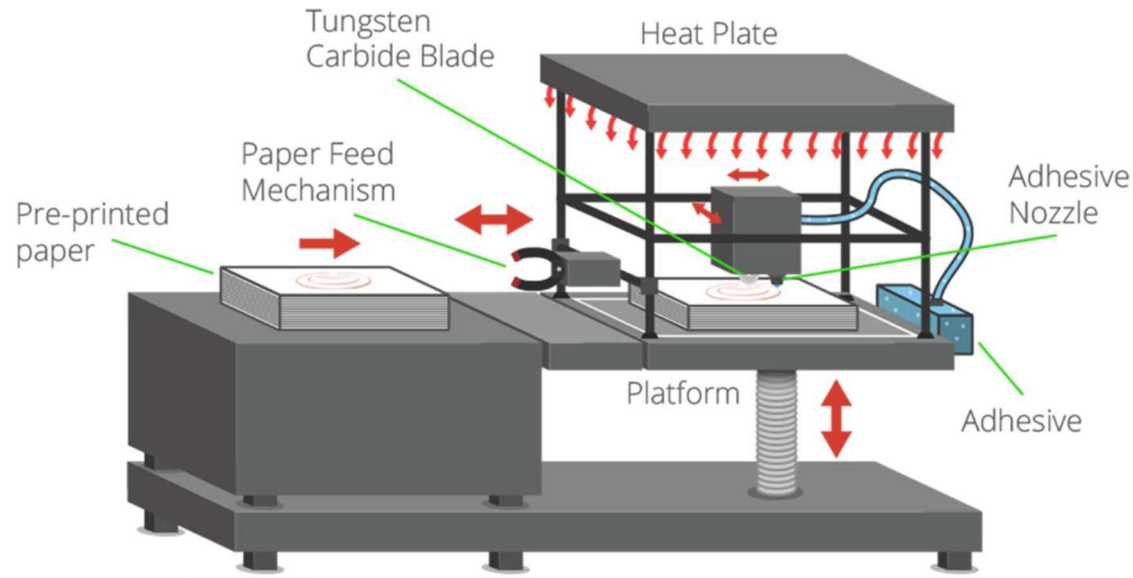

Figure 7. Sheet lamination schematic (source: 3dprintingindustry.com)

7) **vat photopolymerization –** The liquid photopolymer resin in a vat is selectively cured through photopolymerization layer by layer, the ultraviolet (UV) light is used and directed by a lens while the build platform continues moving vertically during the whole process, once the entire process is completed the vat will be drained. Stereolithography (SL) method belongs to this 3D printing category. The working principle of vat photopolymerization is illustrated in *Figure 8*.

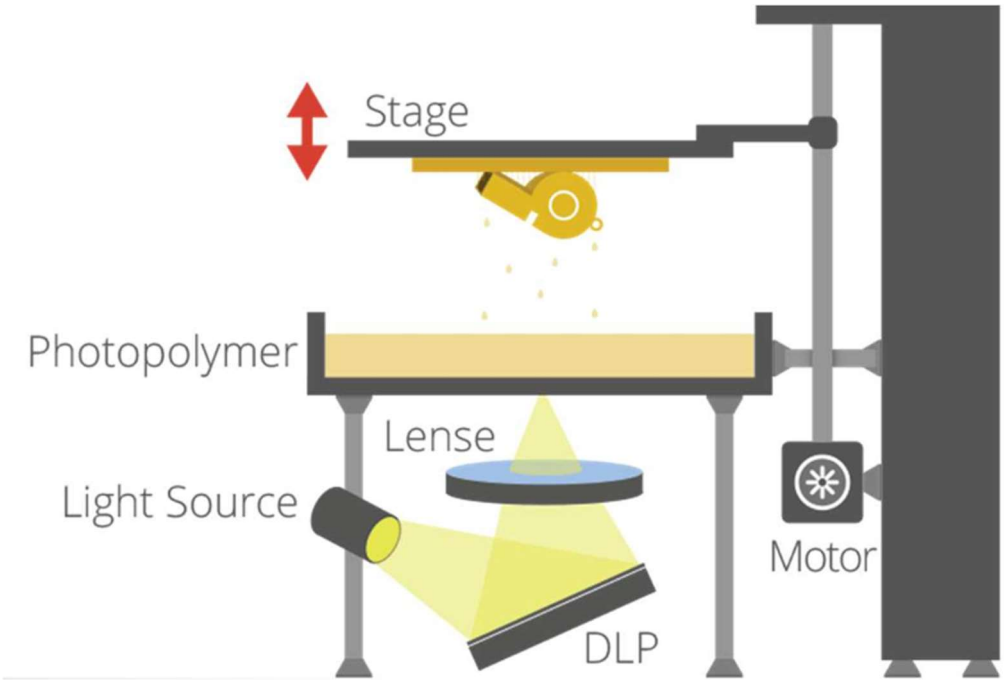

Figure 8. vat photopolymerization (source: 3dprintingindustry.com)

Generally speaking, the main working principle of all AM techniques listed above is to build a physical object by successively adding layers of the material until completion of the object, each layer is the corresponding thin cross-section derived from CAD data of the digital prototype. (Gibson et al 2010)

Prior to execution of the printing process, some steps need to be done:

1. Define the geometry by building a CAD model or 3D-scanning an existing part
2. Convert the model into STL file format
3. Slice the STL file into printable thin layers
4. Select printing material and set up printer parameters

The purpose of STL format conversion is to create the meshed virtual model data to fully describe the geometry by approximating the surfaces of the model with a series of triangular facets, as shown in *Figure 9* below. Moreover, the STL format is also the basis for calculation of the slices. (Gibson et al 2010)

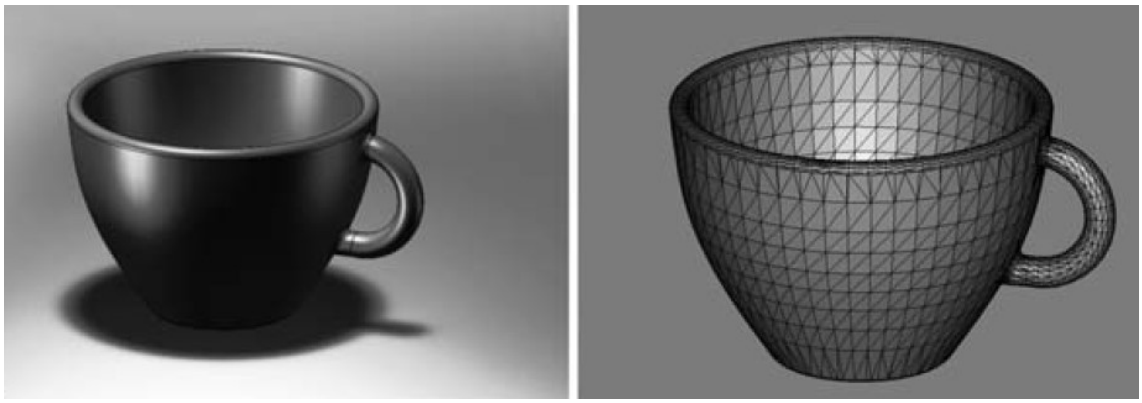

Figure 9. 3D CAD model (left) and its STL format (right) (Gibson et al 2010)

The 3D model can be additively fabricated without any process planning or human intervention, however, in most cases, post-printing treatment is necessary, namely the supporting or coating material needs to be removed from the printed part before putting it into use as shown in *Figure 10.*

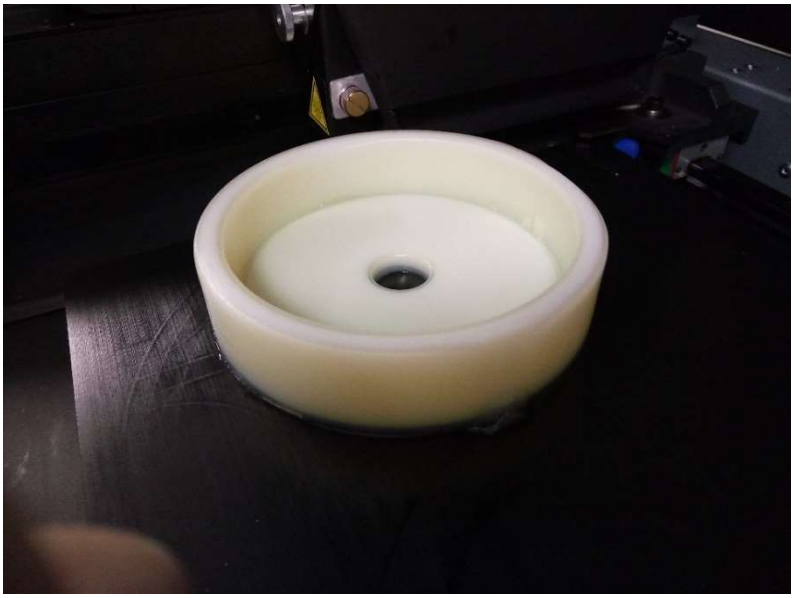

Figure 10 Printed part covered with the semi-liquid coating

The support materials are applied to uphold the overhangs of the printed object, which is indispensable for the layer-by-layer approach. They are normally gel-like and easily removed with a water jet, also there are some soluble support materials.

2.3 Preliminary research of testing equipment

Stratasys Objet30 Prime 3D printer is used in the laboratory of Saimaa University of Applied Sciences. This printer is an inject-technology based desktop 3D printer. Analogous to the inkjet printer, Objet30 Prime 3D printer uses a print head to jet ultra-thin layers of liquid state photopolymer onto the build tray and instantly cures the layers with UV light. (The 3D printing solution company, 2015)

Objet30 Prime 3D printer offers a wide range of printing materials options to meet the demands of different applications, including:

- Rigid opaque materials (Vero family)
- Transparent materials (RGD720 and VeroClear)
- High-temperature materials (RGD525)
- Simulated Polypropylene materials (RGD450 & RDG430)
- Rubber (Tango Gray or Tango Black)
- Bio-compatible (MED610)

Three printing modes can be selected for the printer:

1) HQ (high quality) mode: 16-micron layer thickness, suitable for printing fine details but time-consuming

2) HS (high speed) mode: 28-micron layer thickness, suitable for printing most of the models, much faster compared to HQ mode

3) Draft mode: 36-micron layer thickness, suitable for printing initial designs or large models, is the fastest and most economic mode

There are several very important specification values of this 3D desktop printer, as shown in *Table 1.*

Table 1. Stratasys Objet30 Prime 3D printer specifications

Maximum building size (XYZ)	294 x 192 x 148.6 mm
Accuracy	0.1 mm
Minimum layer thickness	28 microns for Tango materials 16 microns for other materials

Besides, this desktop 3D printer can print images or features with high resolution, and the printer must be working with Objet Studio intuitive 3D printing software.

3 Research methodology

In this chapter, the research methodology of the “concrete casting mould with AM technology” study will be elaborated. The procedures and results of the inquiry will be recorded to support the conclusions in the end. In order to prove the technical feasibility and gain credible insights of this topic, the research planning and process must be conducted thoroughly and rigorously. The reference data must be precise and validated.

3.1 Research objective

The main target of this research is exploring the possibilities to adopt AM technology in concrete casting mould fabrication to improve the productivity and flexibility, reduce the material waste without compromising the quality of the final product. The Stratasys Objet30 Prime printer will be used as the testing equipment.

3.2 Research approach and questions

The whole research process consists of an experimental project and discussion. The experiment will apply “Build-Measure-Learn” iterative loop to improve the quality of concrete casting moulds built by additive manufacturing technology. The polypropylene will be used to build the moulds. The final product quality of each iteration will be evaluated and analysed mainly based on intuitional observation of the specimens. The comparison between the AM technology and conventional concrete casting mould fabrication method will be conducted. Finally, the conclusion will be drawn on the premise of equal final product quality. This research aims at validating three hypotheses:

1) Concrete casting mould fabrication with AM technology will yield better productivity.
2) The adoption of AM technology can improve flexibility. (Customization design, a variety of materials)
3) Material waste will be reduced in mass production with 3D printing technology.

3.3 Experimental project

To validate the three hypotheses, the experimental project was carried out in Saimaa UAS laboratory, the testing equipment is Stratasys Objet30 Prime 3D printer. The approaches to implement the research were mainly qualitative, namely, the observation and analyses of the experiment results are based on non-numerical data, the experiment can be divided into four phases including designing the experiment procedure, collecting data of the samples, analyzing the results and interpreting the findings.

3.3.1 The first experiment

Concrete casting is a manufacturing process used to create concrete products for both architectural and decorative applications. Two primary parameters will affect the quality of the concrete casting products:

1) the nature of the casting material
2) the nature of the mould

Concrete mixture

As for the casting material in this experiment, the concrete is made by mixing:

- Cement
- Water
- Coarse and fine aggregates
- Plasticiser

To increase the quality of casting material, the main ingredients must be measurable and mixed in suitable proportion since the relative amount of each ingredient affects the properties of concrete.

1) Cement

The cement powder is very important in concrete forming, cement must be mixed with a suitable amount of water to form a cement paste, which acts like a glue and bonds the coarse and fine aggregates mixture together after curing for a certain period. In this experiment, the cement needed is 1.030 kg, as shown in *Figure 11*.

Figure 11. 1.030 kg Cement for the experiment

2) Water

Water has always played an extremely significant role in concrete making, it must be clean and pure. In this experiment, 540 mL recycled water is used. As shown in *Figure 12*.

Figure 12. 540 mL recycled water for the experiment

3) Aggregates

The aggregates can be divided into two basic types:

- Coarse: a mixture of crushed rock and gravel
- Fine: screened sand and crusher fines

The coarse and fine aggregates generally occupy 60% to 75% of the concrete volume and 70% to 85% by mass, the hardness and adaptive property of the concrete are strongly influenced by the proportions of the containing contents of different sizes. In this experiment, the constituents of an aggregate consist of five types, including:

- 120 grams of 63-micrometre fine aggregate
- 314 grams of 125-micrometre fine aggregate
- 482 grams of 250-micrometre fine aggregate
- 607 grams of 500-micrometre fine aggregate
- 683 grams of 1-millimetre fine aggregate

As shown in *Figure 13.* The different types of aggregates are separated by a screening device.

Figure 13. Different types of aggregates

4) Plasticizer

Also known as the water reducer. Plasticiser is a chemical admixture that can be added to concrete mixtures to improve workability. Since the strength of concrete is inversely proportional to the amount of water added, the plasticizer can reduce the water needed in the concrete forming so that to increase the strength. The plasticizer used in this experiment is shown in *Figure 14*. The amount of plasticizer used is 23 grams.

Figure 14. The plasticizer used in the experiment

After pouring every ingredient into one bucket, the mixture must be mixed well, so an agitator is used, as shown *in Figure 15.*

Figure 15. The agitator

Casting moulds

The concrete casting moulds comprise of three parts: the lithophane cylinder, the base-holder and the top-holder. The 3D model of Lithophane cylinder was built using Lithophane creating software PhotoToMesh and the base holder and the top holder were built by 3D modelling software Solidworks, and it must be converted to STL format.

Figure 16. Lithophane cylinder STL file for first concrete test

As shown in *Figure 16*. The dimensions and the parameter settings of the lithophane cylinder are shown in *Table 2* below:

Table 2. Dimensions and parameter settings of the first lithophane cylinder

Height	100 mm
Outer diameter	100 mm
Wall thickness	5 mm
Texture height (convex)	2 mm
Samples for both X and Y	717

As shown in *Table 2.* The samples for both X and Y directions represent the accuracy and resolution of the lithophane image, the bigger the value is, the more accurate and distinct the lithophane will be.

The top-holder and the base-holder are used to hold the top and bottom ends during the concrete casting process in case of collapsing. The inner diameter of both holders has to be consistent with the outer diameter of the cylinder so that they can fit perfectly. In this case, the inner diameter of both holders was defined as 100.02 mm. The base-holder and the top-holder are shown in *Figure 17.*

Figure 17. Top-holder (left) and base-holder (right)

Printing material

In this experiment, the printing material used to manufacture the concrete casting mould is Rigur (RGD 450), which is an advanced, simulated polypropylene material. This material is of high toughness and can provide excellent dimensional stability and surface quality. However, Rigur will leave relatively more residues on the print head. After the printing is completed, the support material must be removed, in this case, the support material is SUP706. The completed parts are shown in *Figure 18.*

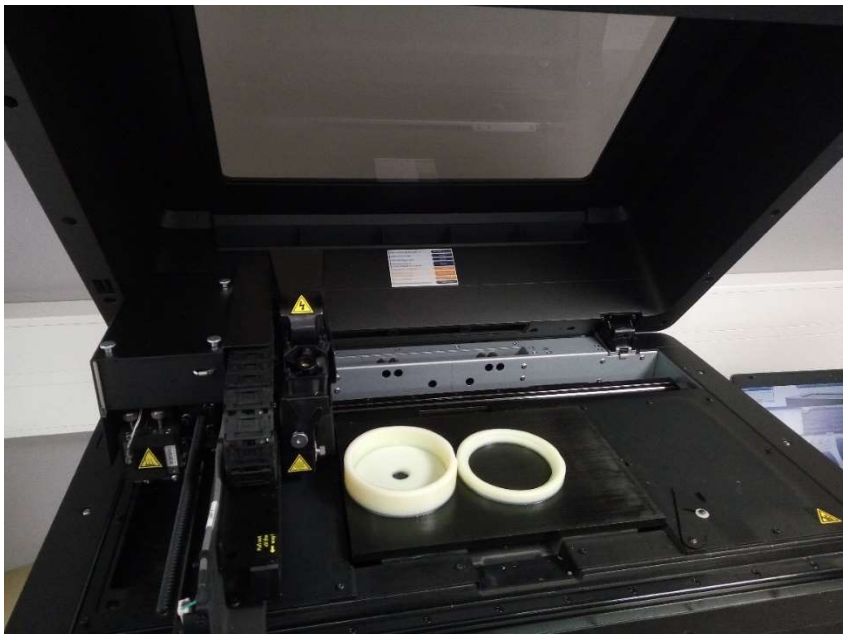

Figure 18. The printed parts

After the post-processing, namely washing off the support material and coating material of each part, they are ready to be assembled. The final assembly is as shown in *Figure 19*.

Figure 19. Final assembly of casting mould

Considering the difficulty of demoulding, we split the lithophane cylinder into two halves and painted a layer of oil as an isolating membrane, as shown in *Figure 20*.

Figure 20. Two halves of lithophane cylinder

After pouring the liquid concrete mixture into the casting moulds, put them on a vibrating table for five minutes to get rid of the bubbles inside the concrete mixture. When this step is done, the concrete casting products are ready for curing and hardening in a well-aired, clean and dry place, as shown in *Figure 21*.

Figure 21. Two halves of lithophane cylinder

Final products

After curing and hardening for one day, the concrete casting products are ready for demoulding. The two demoulded concrete casting products are shown in *Figure 22.*

Figure 22. The final products of the first experiment

Evaluation

The final concrete casting products were barely satisfactory since the surfaces were porous and the lithophane image on the surfaces was vague and broken to a certain extend.

Reflection

The reason for the porosity of the surface and the vagueness of the image might be:

1) The vibrating is not effective to get rid of all bubbles inside the concrete
2) The concrete mixture has a tendency to produce bubbles
3) The choice of lithophane image is inappropriate

3.3.2 The second experiment

This experiment was carried out based on the results of the first experiment, aiming to improve the quality of the final concrete casting products and minimize the imperfections. To this end, some modifications need to be made to the second experiment procedure according to the reflection of the last experiment.

1) To make the vibrating process more effective to get rid of all bubbles inside the casting concrete, the concrete casting mould must be well-sealed to prevent the air outside from entering the concrete during the vibrating and curing process, also prolong the vibration process. Therefore, the modifications we made for increasing the effectiveness of vibrating process are:

- Changing the vibrating process period from five minutes to ten minutes
- Using a cable tightener to make the moulds well-sealed, as shown in *Figure 23*.

Figure 23. Casting moulds with cable tighteners

2) To eliminate the bubbles inside the concrete mixture, we made some adjustments to the proportions of several concrete constituents.

- Adding 500 grams of 2 mm aggregate and 500 grams of 4 mm aggregate into the mixture
- Increasing the water content from 540 mL to 600 mL
- Decreasing the cement to 1 kg

3) To eliminate the vagueness of the lithophane image, we changed the image to a more distinct one, and changed the texture height (or cavity depth) from 2 mm to 3 mm so that it will be easier to observe. The new lithophane concrete casting moulds digital prototypes are shown in *Figure 24.*

Figure 24. Lithophane moulds for the second experiment

Upon completion of the printing process, the printed moulds are coated with a thick layer of semi liquid coating material and the support material. The printed lithophane cylinders are shown in *Figure 25.*

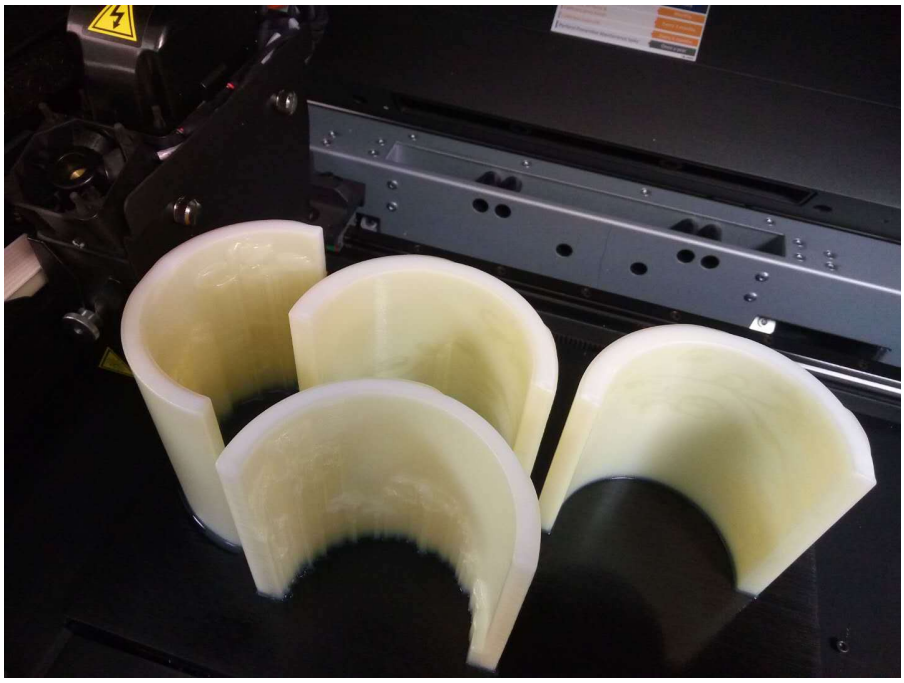

Figure 25. Printed lithophane cylinders with support material

After the post-processing, the printed lithophane moulds are as shown in *Figure 26*.

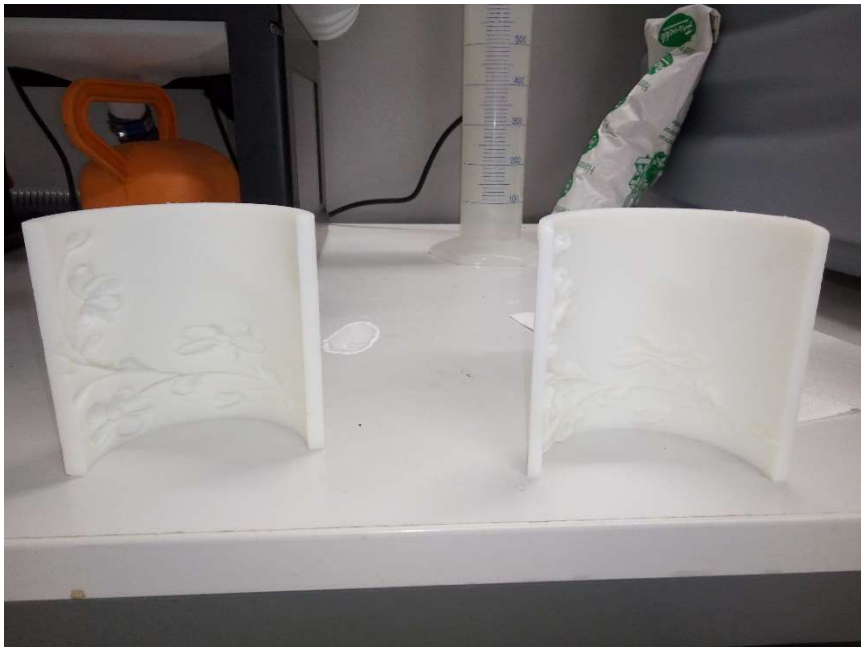

Figure 26. Printed lithophane cylinders for the second experiment

Final products

The final products of the second experiment are shown in *Figure 27*.

Figure 27. The final products of the second experiment

Evaluation

Compared to the first experiment, the second experiment was quite successful. As we can see, the surfaces are much smoother and barely porous. And the lithophane images are relatively distinctive.

Reflection

The prolongation of the vibrating process and adoption of well-sealed moulds will effectively eliminate bubbles and proper adjustment to the proportion of the concrete contents will yield the smoother casting surfaces, which means that the defects in the first experiment were not due to the adoption of AM technology. As a matter of fact, the reasons were the inexperience and the misconduct of the concrete casting process.

3.3.3 The third experiment

Through the previous two experiments, the feasibility of adopting AM technology in concrete casting mould fabrication has been tested and verified. For this experiment, the main target is to evaluate the spent time and material on the fabrication of concrete casting mould with AM technology.

The lithophane cylinder 3D models for the third experiment were the same as in the second experiment. And there were still some adjustments made to the concrete mixture contents, As shown in *Figure 28*.

- Increase the water content from 600 mL to 800 mL
- Add 3mm aggregate 60g
- Use bubble-free cement

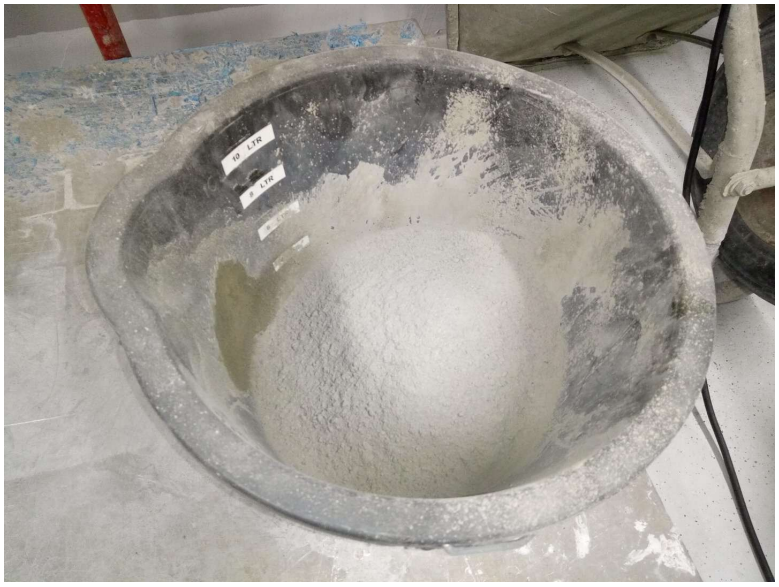

Figure 28. Bubble-free cement

The printing process was finished over one night without any human intervention. To clearly illustrate the time and material cost, the picture of the estimation of time and material needed was taken from the screenshot of Objet Studio intuitive 3D printing software interface, as shown in *Figure 29.*

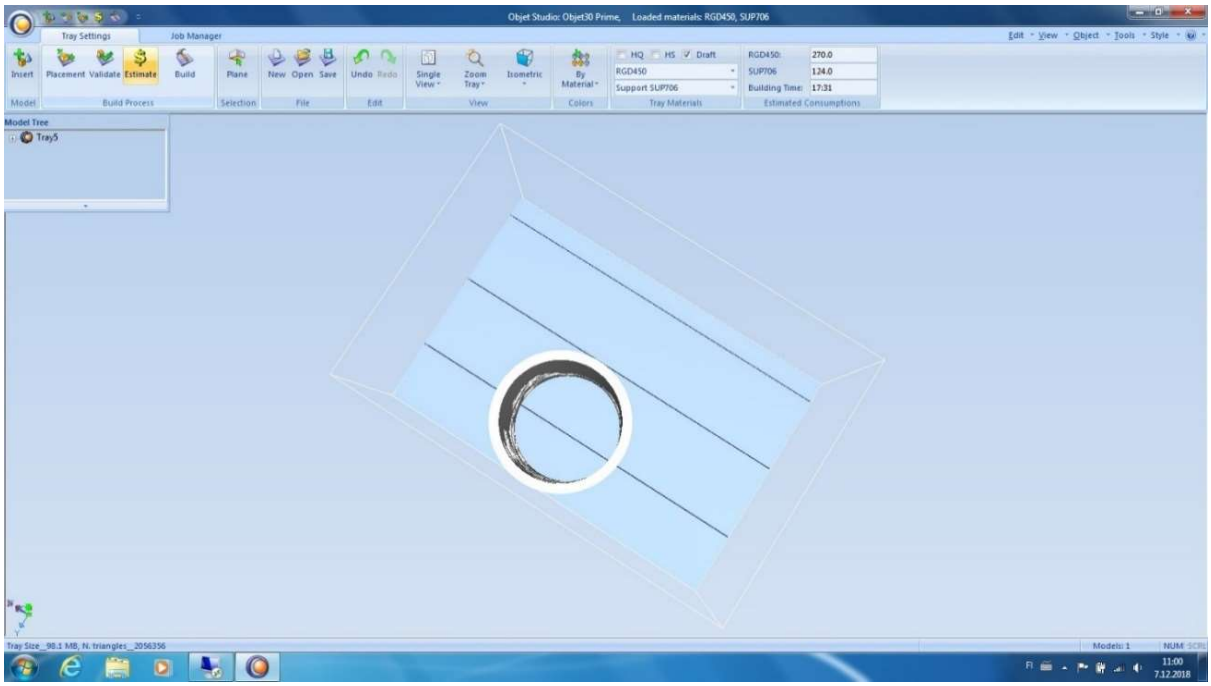

Figure 29. Objet Studio intuitive 3D printing software interface

As we can see from the software interface above, for printing one cylinder, the estimated consumption of building time is 17 hours and 31 minutes, the estimated consumption of building material RGD450 was 270 grams and support material SUP 706 was 124 grams.

After the printing process was finished, the printed moulds were assembled together as shown in *Figure 30.*

Figure 30. The assembled casting moulds for the third experiment

Final products

After the curing and hardening process, the final concrete casting products of the third experiment are shown in *Figure 31.*

Figure 31. The final products of the third experiment

Evaluation

As we can see in *Figure 31* above, the final products of the third experiment are not very good compared to the second experiment. The surface is still porous, but the lithophane texture is well-presented on the surface.

Reflection

1. The lithophane image is well-presented on the surface, which means the printed casting moulds were not responsible for the unsatisfactory result.

2. The evaluation of time consumption for one batch of concrete casting mould would be approximately 17 to 20 hours (Draft mode) depending on the batch size and the complexity of the mould. Note that the printing time is not increasing in proportion to the number of parts, normally the printing time of the second and the third part is much less than the first one, so for mass production

of the concrete casting moulds, the 3D printing technology will definitely yield better productivity.

3. The lithophane image can be changed to any picture including a selfie, which means the customization of concrete casting mould products can be realized; moreover, according to the preliminary research of the testing printer, there is a wide range of printing material options, so the flexibility in material selecting can be validated.

4. The estimation of the material consumption was 270 grams of polypropylene material for the lithopahne cylinder mould, which is almost equal to the actual mass of the printed object. The printing material is nearly zero wasted, however, the 124 grams of support material was inevitably wasted, but on the other hand, the support materials are applied to uphold the overhangs of the printed object, so it does not have to be solid. The topology design and crosshatching method can be applied to minimize the mass of the support material and make it easier to be removed.

3.4 Discussion

Through the whole experimental project, we have successfully achieved the feasibility test of making concrete casting moulds with 3D printing technology and validation of the three hypotheses. The results are presented below:

i. The procedure and results of the first experiment and the second experiment can prove that the adoption of 3D printing technology in concrete casting mould making is practically feasible.

ii. The procedure and the second reflection of the third experiment can validate that the hypothesis, that the concrete casting mould fabrication with AM technology will yield better productivity, is true.

iii. The procedure and the third reflection of the third experiment can validate that the hypothesis, that the adoption of AM technology can improve the flexibility, is true.

iv. The procedure and the fourth reflection of the third experiment can validate that the hypothesis, that material waste will be reduced in mass production with 3D printing technology, is true.

The limitations of 3D printing technology have been clearly exposed as well during the experimental project, including:

1. There is no effective way to recycle the support materials, so mass production with 3D printing technology may cause an environmental burden.

2. Mass production is not possible yet for most of the 3D printers.

3. The total cost of the equipment and maintenance will be very high.

4 Conclusion

The additive manufacturing technology fundamentally changes the way how the manufacturing process is done and has been gradually superseding the conventional fabrication methods of many industries.

In this thesis, the feasibility of adopting 3D printing technology in concrete casting mould making has been tested. The hypotheses of the advantages we should get by adopting 3D printing technology have been validated through the experimental project, and the limitations for 3D printing technology were formulated compared to the traditional methods.

For this study, the feasibility test was well planned and successfully conducted, however, the conclusions about advantages and limitations are still not convincing enough, further research could focus on optimizing the experiment procedure to get more data to support the conclusions of advantages and limitations.

Through analysis, 3D printing technology could be used in rapid customization of concrete casting mould manufacturing products.

List of figures

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