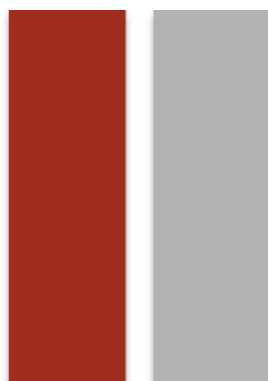


3D Printing of Urban Furniture with a Cement and Granite based material

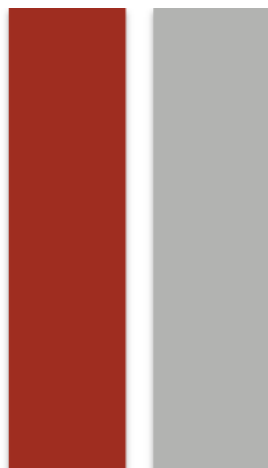
Master Thesis in Industrial and Product Design

Faculdade de Engenharia da Universidade do Porto
Faculdade de Belas Artes da Universidade do Porto

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Abstract

3D printing presents itself as a technologically viable alternative for several conventional manufacturing processes, which significantly helps reducing the amount of waste produced and the production time, due to the optimization on 3D printing process.

However, the most studied materials in 3D printing include Portland cement, which is one of the most pollutant construction materials, increasing the environmental burden due to its high emissions of CO₂. So, in order to reduce this environmental impact, granite dust was studied as a possibility of replacing a large amount of cement, with granite. Granite is a material which exists in large scale in the Portuguese territory, therefore it was a viable material to be considered in this investigation project.

This investigation was separated in three distinct parts, the research on 3D large scale printing methods, the advantages of introducing granite waste when printing with cement and then there was made an evaluation of the already existing urban furniture produced through 3D printing.

The study was based on cement and granite, and the experimental plan followed a theory of trial-and-error, leading to new opportunities to investigate the colors, textures, and viability of production in terms of the material's mechanical properties. For each mixture that was studied, the extrudability, buildability and workability was tested.

When the right mixture of cement and granite dust was reached, tests were performed, such as compression strength and hygrothermal performance (water absorption), and finally the product was designed with accordance to the materials and the environment in which it will be integrated.

It has also been demonstrated that the same developed material is suitable for 3D printing and can be used to print items with either a standard or customized design. As a result, it was determined that it is possible to replace natural waste in mixtures from construction and demolition waste.

Finally, taking into account all the learning, and proving the printability of the material, a new 3D printed bench prototype was made in a smaller scale and with a few alterations with the final product, because due to the small scale of the bench some features wouldn't be able to print. Compared to moulds, this type of manufacturing can produce more complex parts, with greater detail and at lower costs.

Keywords: Design, 3D printing, granite dust, furniture, urban furniture

Resumo

A impressão 3D apresenta-se como uma alternativa tecnologicamente viável para vários processos de fabrico convencionais, que ajudam a reduzir significativamente a quantidade de resíduos produzidos e o tempo de produção, devido à otimização do processo de impressão 3D.

No entanto, os materiais mais estudados na impressão 3D incluem o cimento Portland, que é um dos materiais de construção mais poluentes, aumentando a carga ambiental devido às suas elevadas emissões de CO₂. Assim, de forma a reduzir este impacto ambiental, foi estudada a possibilidade de substituir uma grande quantidade de cimento e areia, ambos materiais que na sua produção e extração produzem elevadas quantidades de dióxido de carbono, por granito em pó (resíduos de construção e extração de pedreiras). O granito é um material que existe em larga escala no território português, pelo que seria um material viável a ser considerado neste projeto de investigação.

Esta análise foi dividida em três secções distintas: o estudo das técnicas de impressão 3D em grande escala, os benefícios da adição de resíduos de granito durante a impressão com cimento e uma avaliação do mobiliário urbano já existente construído com recurso à impressão 3D.

No projeto experimental de tentativa e erro, o estudo foi baseado em cimento e granito. Isto proporcionou novas opções para investigar as cores, as texturas e a viabilidade de fabrico em termos das qualidades mecânicas do material.

Foram avaliadas a extrudabilidade, a construtibilidade e a trabalhabilidade de cada mistura em estudo.

Quando se chegou à mistura correta de cimento e pó de granito, procedeu-se a testes como a resistência à compressão e o desempenho higrotérmico (absorção de água) e, finalmente, o produto foi concebido de acordo com os materiais e o ambiente em que será integrado.

Também foi demonstrado que o mesmo material desenvolvido é adequado para impressão 3D e pode ser usado para imprimir itens com um design padrão ou personalizado. Como resultado, foi determinado que é possível substituir os resíduos naturais em misturas de resíduos de construção e demolição.

Por fim, tendo em conta todas as aprendizagens, e comprovando a capacidade de impressão do material, foi feito um novo protótipo de banco impresso a 3D numa escala mais pequena e com algumas alterações em relação ao produto final, pois devido à pequena escala do banco algumas características não poderiam ser impressas. Em comparação com os moldes, este tipo de fabrico pode produzir peças mais complexas, com maior detalhe e a custos mais baixos.

Palavras Chave: Design, impressão 3D, pó de granito, mobiliário urbano

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Abbreviations

3DP – Three Dimensional Printing

AM – Additive Manufacturing

CAD – Computer Aided Design

WASP – World's Advanced Saving Project

PPVC - Prefabricated Prefinished Volumetric Construction

Chapter 1- Introduction

The following dissertation was developed for the course of the Masters in Industrial and Product Design, in the Faculty of Engineering (FEUP) and the Faculty of Fine Arts (FBAUP) of the University of Porto. This chapter aims to present the work that was developed, with the following title “ 3D printing with cement-based material, for the development of designed urban furniture.”

The following chapter aims to explore about 3d printing with quarry stone waste and cement. So with this in mind, it's our duty to have and mindful usage and management of them. 3D printing streamlines simplifies and reduces the costs of designing furniture. It's possible to test multiple prototypes in a short amount of time and produce customized pieces that are not constrained by geometry.

Approximately 80% to 90% of the ornamental stone industry in the marble zone (Alentejo, South of Portugal) is wasted and disposed of in the numerous quarry waste rock piles across the Alentejo region. This numerous quarry waste is due to the material's low fracture toughness, so the probability of the ornamental stones breaking is high. If the block of stone doesn't have the necessary measurements to be extracted it is also considered waste, to the point where it has no more ornamental and monetary value. (Sá Caetano et al., 2020)

The need to reduce the amount of cement is urgent, due to its high CO₂ emissions, therefore it's necessary to search for new ways to reduce the consumption of cement. By adding quarry waste to the concrete, the percentages of cement can be lowered making it a more sustainable way of utilizing concrete. By using the conventional method for the use of concrete requires a framework, which adds to the amount of material needed to proceed with the normal constructions made of concrete. By combining the granite waste from the quarry piles and the functionalities of 3d printing with cement, the possibilities of creating numerous printable materials are optimal. (Matos et al., 2022)

3D printing is a rapidly growing technology that has revolutionized the way we think about manufacturing and construction. The ability to create complex and intricate designs with ease has led to a wide range of applications across many industries. In the recent years, researchers have been exploring the use of materials for 3D printing, including granite dust and cement.

The goal is to investigate the feasibility of using 3D printing with granite dust and cement as an alternative to the traditional building methods, in the meantime reducing the percentage of cement used, whilst also analyzing the aesthetic aspect of the final product such as the chromatic variation in the mortar and the creation of a ergonomic street furniture.

Compared to normal construction methods for outdoor furniture, 3D printing has many immediate advantages to offer, such as customization, since it allows for highly customizable designs, which could not be easily replicated with traditional construction methods. The cost-effectiveness of 3D printing is huge, since it does not require expensive molds or tooling, and consequently less waste is generated than traditional construction methods. It is also possible to reduce the production time since manual labor is only needed for the maintenance of the 3D printer, the printing can therefore be done 24/7, this rapidly increases the production time.

1.1.Objectives

General objectives

The main aim of this thesis is to deepen the knowledge of the use of stone waste in 3DP and understand the possibilities of its use in urban furniture focusing on the 3D printing of an outdoor furniture. It's necessary to research/ investigate cement-based materials and develop a mortar that is compatible with outdoor weather conditions.

Specific objectives

- Characteristics of materials that can be used in outdoor conditions (street furniture).
- Usage of ornamental rock residue, to try and reduce the use of sand in the concrete mix.
- Study of the customization for pre-fabrication modules.
- Design of a street furniture 3D printed with the granite and cement-based mortar.

1.2. Methodology and Structure of the dissertation

The methodology utilized throughout this master's thesis in industrial and product design contains three main chapters to investigate the use of 3D printing with granite dust and cement in the design of urban furniture. Each chapter written equals a distinct research phase and is important, in order to achieve the objectives defined in the objectives chapter.

Chapter 1:

This chapter conducts a thorough analysis of the current research on large-scale 3D printing with cement as well as cutting-edge technologies. The characteristics of granite, a potential additive material, are also thoroughly examined. This action provides the theoretical framework for further research and lays the groundwork for understanding the technical elements and difficulties of 3D printing as they relate to urban furniture.

Chapter 2:

The market study for initiatives including 3D-printed urban furniture is the main topic of the second chapter. Examining effective case studies, new trends, and the market's need for cutting-edge and sustainable materials are all part of this. By highlighting market insufficiencies and openings for the use of 3D-printed granite-cement composite materials in urban furniture projects, the insights gained from this research assist in the conceptualization and design process.

Chapter 3:

The research's experimental phase is covered in the third chapter. Granite dust and cement are combined in a variety of ways, and their physical, mechanical, and aesthetic qualities are put to the test. The purpose of this experiment is to identify the ideal blend ratios and printing settings for obtaining desired results. A bench for urban use is being constructed and designed as part of the research in order to put the newly created materials to use. This phase includes refinement, iterative testing, and prototyping as essential elements.

Chapter 4:

The findings from the literature research, market analysis, and experimental investigations are summarized in the last chapter. The findings of the study are assessed in light of their contribution to the field of industrial and product design, particularly in the area of 3D printing of urban furniture using granite dust and cement. The design of the urban bench serves as a real-world illustration of the viability and potential of the created materials. The consequences of this study, its shortcomings, and potential directions for further research in this cutting-edge design field are discussed in the concluding remarks.

This technique divides the research into separate phases in order to give a systematic and thorough investigation of 3D printing using cement and granite dust for urban furniture, ultimately advancing innovative and sustainable design.

Chapter 2 - State of the Art

This chapter contemplates the state of the art with and a market research with a few examples related to 3D printing with concrete and the reuse of ornamental rock waste, as well as other examples that use ornamental rock waste to understand how it's possible to insert waste into the manufacturing of design products.

With the use of the 3D printing method, it's possible to reduce up to 50% of final costs in any project, comparatively to the traditional building method used with concrete (Kumar Mehta, n.d.). Furthermore, it allows for various degrees of freedom when it comes to geometry.

The main advantage of 3d printing is its speed compared to traditional methods, in a matter of days, it's possible to build a house from zero. It's a significant 60% difference in the time saved on the job site and 80% saved in labor. (*3D Printing in Construction: Growth, Benefits, and Challenges*, n.d.)

In the construction industry, 3D printing has been primarily done with concrete, by creating a paste thick enough to support consecutive layers and liquid enough to be extrudable through a nozzle.

3D printing technology began in the 1980s with Dr. Hideo Kodama, who created the concept of polymerizing resin by UV light. (Chapman, 2022)

The recent history of 3DP in construction

Additive manufacturing is a constantly growing technology, it works by building up solid objects, layer by layer. (Gebhardt & Fateri Hochschule Aalen, 2013).

In the area of civil construction 3D printing has had its exponential growth, with studies continuing to largely improve the current knowledge on the matter. In 1943 Ernest Neufert idealized a house building machine “Hausbaumaschine”, which translated means it would be a big building machine, on train tracks, that would leave behind a 5 story high building. Keeping in mind that this was simply an idealized concept (Weinwiesmuth and Weinwiesmuth, 2018).

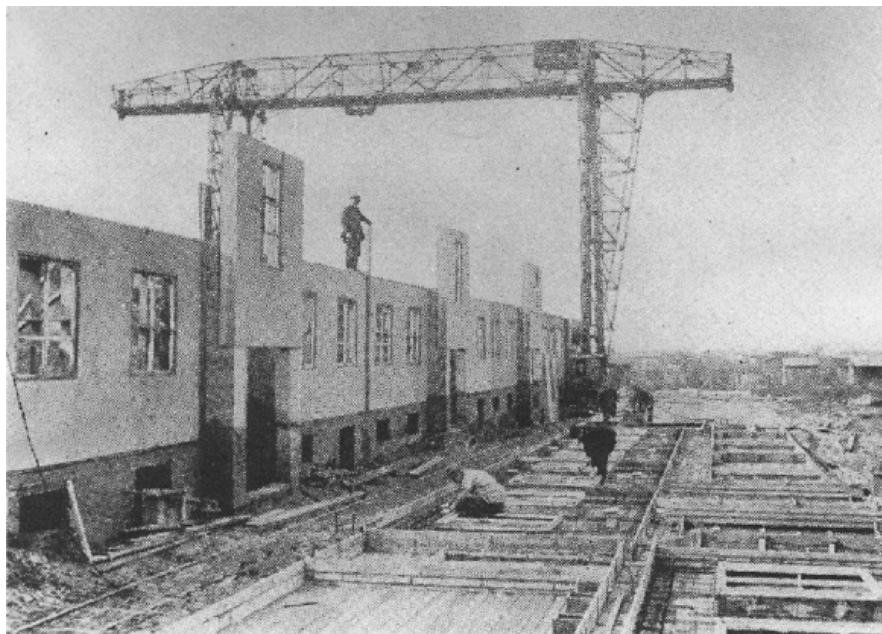


Figure 1. Martin Wagner: (1924-1925)-Construction with the Occident system using a gantry crane. (Martin Wagner: *Experimental Siedlung in Sewanstraße / Splanemannstraße...* | Download Scientific Diagram, n.d.)

In 1986, Charles Hull had the idea of commercializing the first rapid prototyping technology, which used UV light to cure and bond a photopolymer resin, that built up layer by layer. He became the co-founder of 3D Systems, which enabled him to commercialize his technology, this included the STL format that allows CAD software data to be translated into 3D printers (Khoshnevis, n.d.-b).

In the early 2000's Professor Behrokh Khoshnevis from the University of Southern California created the first technology that allowed the 3D printing of Portland cement, this received the name of contour crafting. Contour crafting is a technology that utilizes a machine very similar to the conventional 3D printer, but on a much larger scale. This allowed for the automation of the construction of walls, shafts, beams and pillars. The system is based on a nozzle extruder mechanism that pushes out a dough-like material, moved by a computer controlled robotic arm. (Khoshnevis, n.d.-a).



Figure 2 . ("A New House in Only 2 Days," Contour Crafting Begins Manufacture of 3D Printer for Construction - 3D Printing Industry, n.d.)

Requirements for 3D printing in construction

The main advantage of additive manufacturing is the ability to produce parts from a CAD model, and its main advantages are saving time and costs. The five types of 3D printing used in construction are: contour crafting (CC), concrete printing (CP), selective binder (cement) activation (SBA), selective paste intrusion (SPI) and D-Shape. The first two can be described as Extruded Material Systems and the last three as Powder Based Systems. (El-Sayegh et al., 2020)

Both contour crafting and concrete printing have similarities as they are both injecting a mixture (mortar) through a nozzle, generating the printed part.

In the recent years, there have been major improvements in the development of large-scale 3D printers, which have the ability to print industrial-scale buildings. The two most common methods utilized are gantry systems and articulated robot systems.

The gantry systems use as cartesian coordinate system, where the nozzle moves along three axes (X,Y,Z). When the head changes direction from a rectilinear motion, this extra degree of freedom is employed to spin the nozzle. To avoid filament twisting, the nozzle must remain tangent to the tool path, which necessitates a significant curve when the nozzle changes direction. Because of this constraint, 3D printing concrete with sharp corners is nearly impossible. (El-Sayegh et al., 2020)

Another method of delivering the 3D printing is through an articulated robot system. Robot systems require less space than a gantry system and can be mounted on-site, facilitating the transportation of the 3D printer. (El-Sayegh et al., 2020)

Nevertheless, the workspace is usually more limited than the gantry systems. When using a cylindrical robot there are three joints that are used: the first one is a vertical

translation, the second joint is a revolute and the third and final one is a telescopic translation. In this case, only three degrees of freedom are used, but when it is necessary to develop a more complex geometry, more degrees of freedom are needed. The degrees of freedom are used to alter the trajectory of the nozzle when executing complex 2D motions.(El-Sayegh et al., 2020)

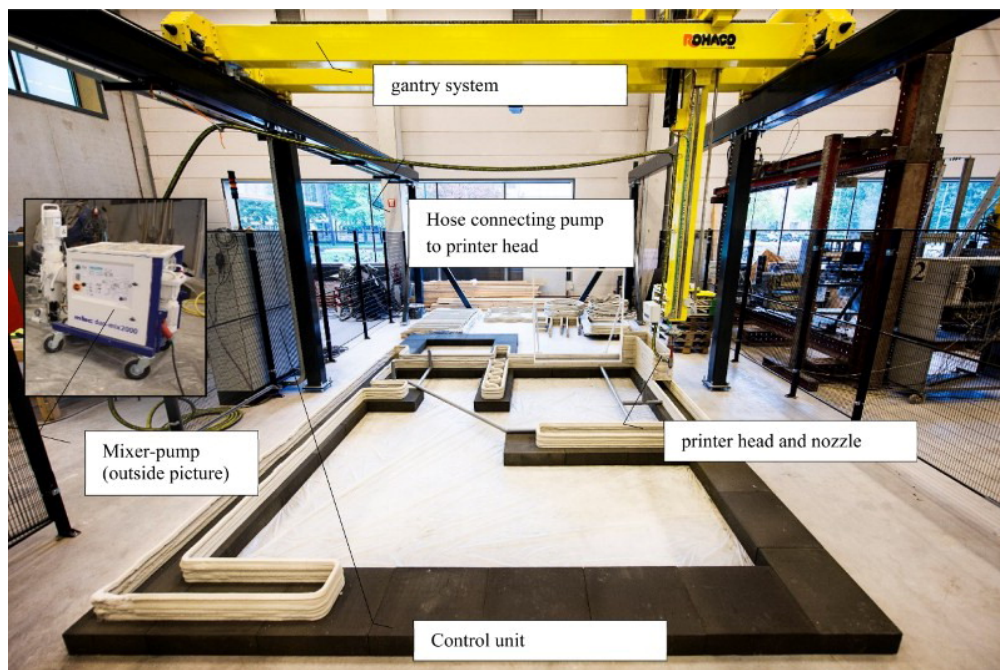


Figure 3. 3DP facility at TU Eindhoven with examples of printed objects. (Bos et al., 2016)

Finally, the two most common structures are the robot arm and the gantry system. The primary distinction between these two architectures is their accessible workspace. Indeed, the reach of robot arms is often limited to 3 m, limiting the size of printed items. Due to this constraint, printing a whole home, for example, using a fixed robot arm-based 3D printer would be impossible.(El-Sayegh et al., 2020) Two methods are given in this case: The first involves printing components of the building, which must then be assembled to form the final structure.

The second solution involves rotating the robot arm around the construction to create the various elements of the structure (El-Sayegh et al., 2020) In any scenario, this solution imposes certain constraints on the shape and size of the printed structure. A printer based on a robot arm with 6 DOFs, on the other hand, has the benefit of being able to manufacture complicated forms since the nozzle, which is coupled to the robot arm's end-effector, can have all six conceivable movements in space (3 translations and 3 rotations). This reach, however, may be increased by employing gantry 3D printers. An entire home may be constructed constantly using this sort of 3D printer without the need to shift the machine. (El-Sayegh et al., 2020)

Cement is one of the most used materials in the technologies mentioned earlier (contour crafting and concrete printing). For the printing to be successful it has to be used a high-performance concrete. (Le et al., 2012) confirmed that a high-performance concrete can withstand its form without the need for formwork, used in conventional concrete constructions. So to guarantee the effectiveness of concrete, four properties are needed for a successful printing: extrudability, pumpability, buildability and open time. Extrudability is the ease with which the material is pushed through the nozzle of the printer. Pumpability is the ease with which the material is extruded through the printers pump. Buildability is the ability to 3D print by adding the mixture layer by layer continuously to a certain level without any considerable deformation or collapse.(Le et al., 2012) Finally, the open time is a period of time where the pumpability, extrudability and buildability are in an expectable range. (El-Sayegh et al., 2020)

The printing speed has an effect on the qualities of the printed concrete and determines whether or not there are weak joints between the layers. Similarly, the printing orientation would influence the overall properties of the concrete. (*3D Printing In Construction: How Does It Work* | CEMEX Ventures, n.d.). Another important aspect to keep in consideration is the reinforcements. Reinforcements face a challenge in 3D printing. The ability for the mixture to keep upright when faced with multiple layers. One way of guaranteeing the reinforcement is by placing steel bars before or after the printing (El-Sayegh et al., 2020). However, this faces as a problem since it limits the movement of the printer, creating obstacles in the way. A reliable solution would be creating a hollow that can be printed as a solution, and the rebars can then be inserted with infilled concrete to link the steel reinforcement to the printed structure. However, by introducing the steel bars the automation is reduced and the labor is increased, this in part contradicts the whole purpose of 3D printing which is reducing manual labor.

Alternatives to cement in 3D printing

There have been various studies suggesting the replacement of cement in 3d printing, this includes materials such as geopolymers, which have in its composition fly-ash and silica-fume. Shown in Fig.4.

Geopolymer is one of the main and most studied alternatives to cement. It consists of an inorganic polymer obtained through the polycondensation reaction of some waste materials containing aluminosilicate with alkalis (N. B. Singh et al., 2020). Geopolymers can withstand temperatures up to 400°, from then on they may suffer shrinkage. (N. B. Singh et al., 2020)

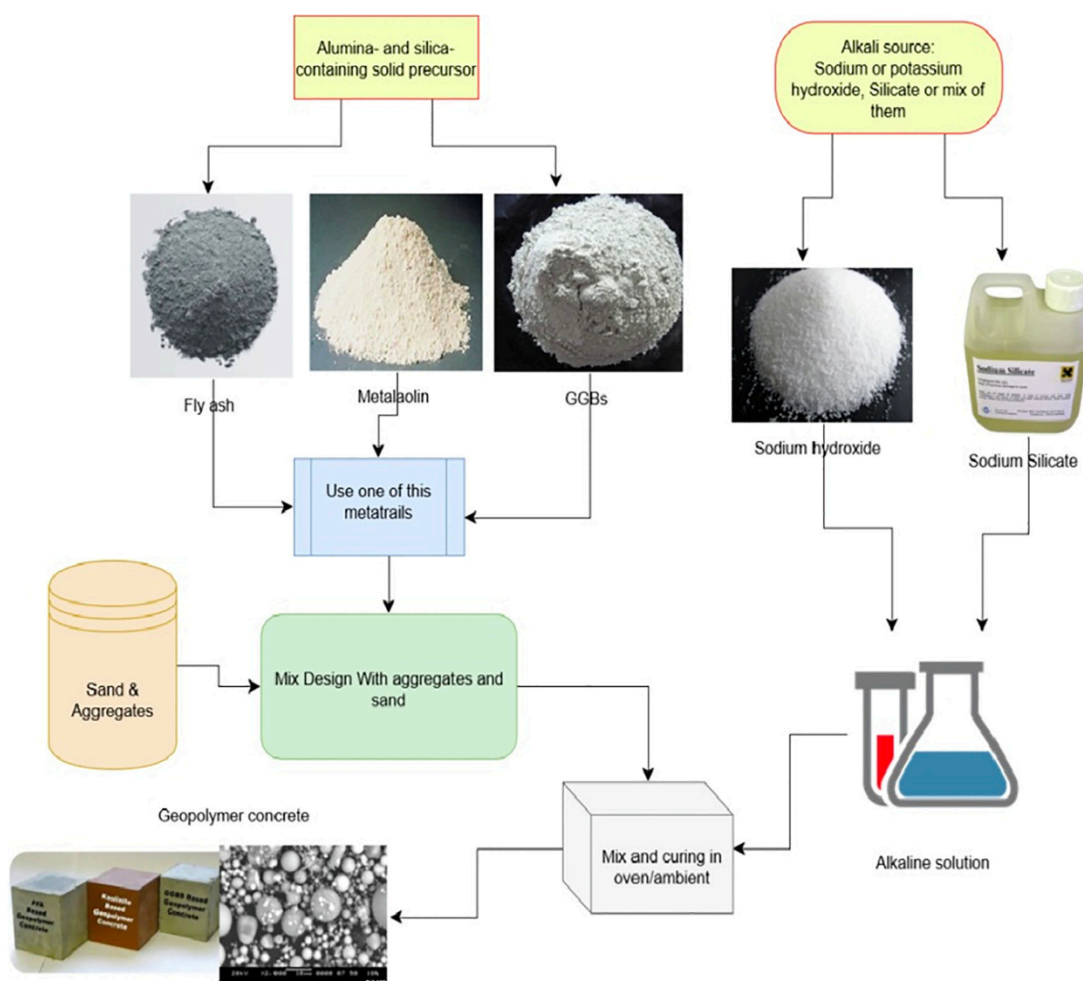


Figure 4. Geopolymer production (N. B. Singh et al., 2020)

Use of ornamental stone waste in 3D printing

The use of ornamental stone in 3D printing is an experimental area, due to the lack of literature published. What is known is that ornamental stone when transformed into a dust or powder state can partially substitute the use of sand in concrete. This is due to the strong presence of quartz in its crystalline phase, it resembles glass waste, which has in its components sand. Ornamental stone can be applied as fillers in mortars and concrete, influencing the stability of the material.

Composition of 3D Printable mixtures

Even though there has been published literature regarding 3d printing, little is published regarding the composition of the mixtures used to print. (Bos et al., 2016) suggest incorporating, Portland cement (CEM I 52,5 R), siliceous aggregate with a maximum diameter of 1mm, limestone filler and specific additives to ease the pumping, rheology modifiers in order to obtain thixotropic behavior of the fresh mixture and finally a small amount of polypropylene fibers in order to reduce cracks.

The following table was adapted from (Teixeira, 2018).

Material	Company / University	Elements	Characteristics	References
Mortar	Hwang and Khoshnevis	Cement, water, sand, superplasticizers	Resistance to compression of approximately 19 MPa.	(D. Hwang & B. Khoshnevis, n.d.)
Mortar	Lund University	Cement, sand, fly-ash, silica active, water, retarders, superplasticizers	Resistance to compression of 105 MPa and to traction of around 13 MPa	(Anell, n.d.)
Mortar	Weng, Li, Tan, Quian	Cement, silica active, silica sand, fly-ash, river sand, water, superplasticizer	The optimized mixture resists forces of 60 MPa of compression and 4,5 MPa to bending.	(X. Zhang et al., 2018)
Mortar	CyBe	Cement, sand, (...)	Resistance to compression of 25 MPa	(3D Concrete Printers CyBe Construction, n.d.)

Table 1. Mortars composition

Contour Crafting

Contour crafting can automatically construct custom-designed structures by repeatedly layering construction material. Contour Crafting (CC) uses computer control to the superior surface-forming capability in order to create a smooth and accurate surface out of extruded materials.

The most important aspects of CC are lower construction cost, higher construction speed and increased flexibility of architectural design. Larger Contour crafting machines such as the one shown below *Fig.5.* have been developed in order to print larger scale structures. These machines have an extrusion process for forming the object surfaces and filling process by pouring or extruding to build the object's core. This design is expected to be a good initial candidate for concrete wall construction. (J. Zhang & Khoshnevis, 2013)



Figure 5. Current Contour Crafting machine (J. Zhang & Khoshnevis, 2013)

Optimization and process planning of Contour Crafting

The operation planning in contour crafting plays an important role in improving the overall CC system efficiency, by generating the optimal path for the nozzle for the given structure design. This allows for maximum efficiency reducing printing time and overall construction efficiency.(J. Zhang & Khoshnevis, 2013)

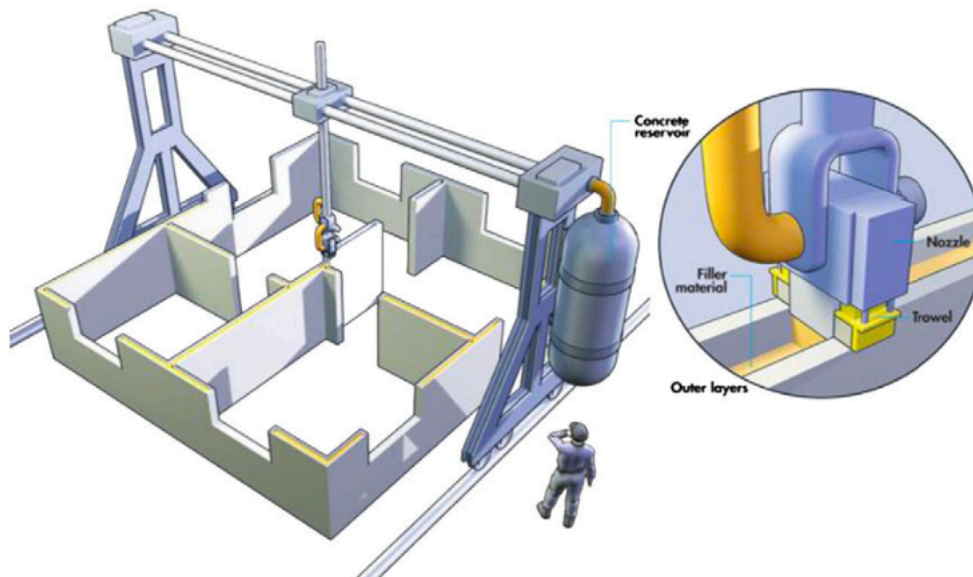


Figure 6. Contour crafting in construction operation (J. Zhang & Khoshnevis, 2013)

Whilst looking for the fundamental characteristics needed for 3D printing with cement, it's important to notice that the already existing projects are based on the contour crafting project, with the slight difference that the extruded filament is made of concrete (Bos et al., 2016). In numerous universities and companies have shown interest in this subject, such as Win-Sun in China, D-Shape in Italy and Concrete Printing in the United Kingdom. These are projects that technically have very little in common but practically they print large objects by overlapping concrete layers. (Lim et al., 2012)

Amongst the pioneers in the 3D printing context, in construction is the company WinSun, which has a giant printer that measures 6 meters in height, 10 meters wide and 40 meters long, capable of printing prefabricated elements. Win-Sun was able to build 10 houses in less than 24 hours by using concrete printing, which rounded up to an average cost of \$5000 per printed house. The same technology was also used in buildings up to 5 stories high. The used layer printing technique leaves a hollow wall for the insulation processes to be built inside the structure.

The Canal House project began in Amsterdam in 2014 by the DUS Architects company. It's a project dedicated to 3d printing pre-fabricated pieces that can later be assembled. It's made of a bio-plastic mix, about 75% plant oil. The pieces are assembled similarly to Lego bricks. Allowing the customer to have their own individual design according to each person's needs/desires. In some ways, this method of

building houses retrieves that geometric freedom that 3d printing a house from its origins gives, but in other perspectives this allows for a higher building speed of the houses since the “lego pieces” can be made in advance. (Quirk, n.d.). This is the first fully 3D-printed project in Europe using pre-molded printing technology, with a maximum size of 2 cubic meters and without requiring assembly. The city already has several homes constructed using this technology (Malaeb et al., 2015); (Wu, Wang, and Wang, 2016). Other companies have attempted direct printing without pre-molding, such as TotalKustom in the Philippines, which built a 130m² party house in just 100 hours. In another example from China, HuaShang Tengda constructed a two-story building totaling 400 m² on-site within 45 days.

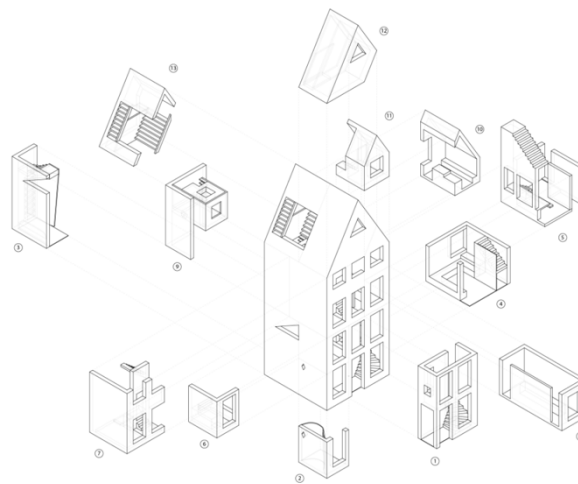


Figure 7. 3d printer for the Canal House Project and a layout of the “Lego pieces”(3D Print Canal House – DUS Architects, n.d.)

Evidence suggests that 3D printing technology is attractive from both an economic and environmental standpoint (Burem, 2016); (Burem, 2015). The COVID-19 pandemic in 2020 has led to the use of various 3D-printed items such as door handle protectors, masks, visors, lung ventilators, and oxygen pump valves (Wishbox, 2020). In the field of civil construction, WinSun has produced social isolation capsules, each with a floor area of 10m² and construction taking approximately 2 hours, with a maximum output of 15 capsules per day at a cost of around US \$4000 each. The company's president, Ma Yihe, claims that structures made from recyclable materials can be twice as durable as traditional concrete, and each capsule includes beds and an "eco-friendly bathroom" that washes without water and utilizes bacteria to decompose waste (GCR, 2020).

Chapter 2.1.

Delta | Gantry | Robot

2.1.1. Delta

Delta printers are under the category of FDM (Fused Deposition Modeling) printers, which means the process of making the physical objects by building up successive layers of material. In this case, layers of concrete based material are pushed through an extruder and deposited through a trajectory that is previously defined in order to complete the desired final product.

Joseph Pegna

The first concept of large scale 3d printing began with Joseph Pegna. He used 3 materials, cement, sand and water. This method consists of the deposition of a thin 1mm layer of sand, the cement is then deposited in a form that will construct the final product that is projected. The final step is the vaporization of water, together with the sand and cement it will harden, finishing of this step. This process is repeated layer by layer, until the final product is completed.

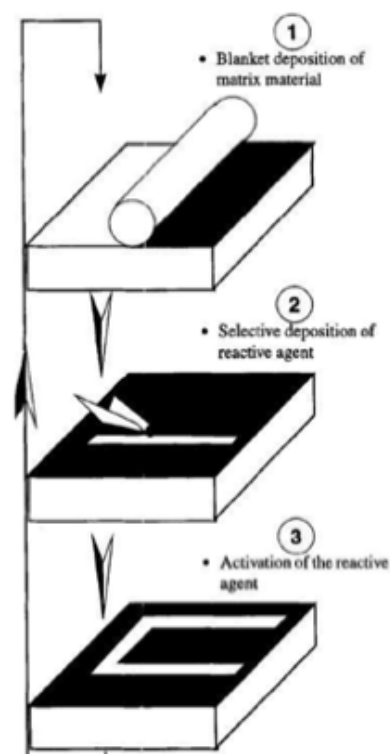


Figure 8. Printing diagram by Joseph Pegna. (Pegna, 1997)

Delta Wasp 3MT

The Delta WASP 3MT CONCRETE is manufactured in metal with strong steel cord belts and is equipped with special grid panels to work in complete safety. This is a stationary printer with a track setup, it can reach up to 5m in length and can be extended accordingly. It is a practical solution for building prefabricated houses.



Figure 9. Delta Wasp 3MT (Concrete 3D Printer Delta WASP 3MT CONCRETE, n.d.)

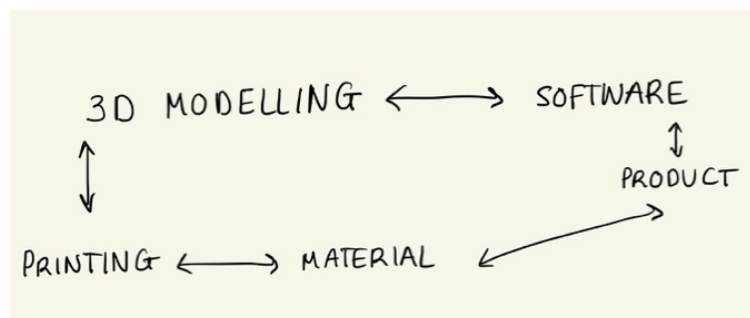


Figure 10. The 3d printing process with cement (adapted from CyBe construction, 2017)

With this big dimension 3D printer is possible to create concrete mortar products thanks to an innovative extrusion system equipped with a special mortar pump and a screw-driven extruder. Furthermore, the MDF pallet bed and the removable front lower beam allow to remove, once the printing activity is completed, the objects

2.1.2. Gantry

CyBe G (Gantry)

Another 3D concrete printer is the CyBe G (Gantry), which uses the gantry system. This system uses a x,y,z axes to achieve its final product. It can be set up in practically any area, only needing four columns and three beams. This kind of printer is best sorted for printing large modules. It's an ideal solution for building affordable housing due to its implementation costs and the total costs for the materials used.

CyBe has developed a Prefabricated Prefinished Volumetric Construction (PPVC), it consists of building completed units off-site, which are assembled on-site. The PPVC is advantageous as the CyBe G can continuously print multiple finished units, this saves in production time, as the printers configuration for that unit can be used as many times as necessary. (3D Concrete Printers | CyBe Construction, n.d.)



Figure 11. (3D Concrete Printers | CyBe Construction, n.d.)

Concrete Printing

The concrete printing was a technology developed by an English University, Loughborough University, with help from the department of Civil and Building Engineering. Concrete printing has many similarities compared to contour crafting, it's an extrusion-based construction process (Wolfs, 2015) . The process consists of data preparation similar to most AM processes, material preparation, and printing using a cement-based mortar, which satisfies specific characteristics and mechanical properties. (Lim et al., n.d.)

In order to maintain the freshness of the material, the distance between the nozzle and the delivery path should be kept short and fed in small batches. Studies show that the printing flow should be of less than 1,4kg/min in order for the 9mm nozzle to support the material flow.



Figure 12. The printing frame for concrete printing (Lim et al., n.d.)

D-Shape

D-Shape was a project created at the University of Pisa, Italy. This method involves a powder deposition selectively hardened by applying locally a binder material. There are layers of sand laid down to the desired thickness, then compacted. The printing head is composed of approximately 300 nozzles, which is mounted on an aluminum gantry frame (as shown in Fig.13). The printer then moves accordingly to the CAD drawing, depositing the binder where it is meant to be solid. Once solidified the hardened pieces are removed from the remaining sand around.

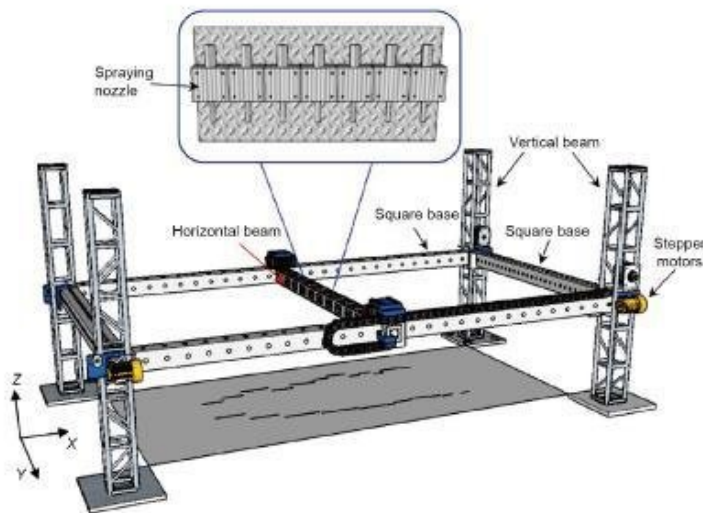


Figure 13. D. Shape Technique (D-Shape Technique [9] | Download Scientific Diagram, n.d.)



Figure 14. D-Shape by Enrico Dini (D-Shape, n.d.)

2.1.3. Robot

CyBe RT (Robot Track)

CyBe was a project created in 2013, in the Netherlands. Its main objective is to simplify traditional construction methods, through the automation of these processes. With this in mind the printer was created, its process works through the extrusion of a mortar, made of cement or other construction materials. (Cybe construction, 2017)

The company later on divided itself into a sector to better serve its clients. Engineering and design software, maintenance and 3d printers are there main sectors.

The CyBe RT is a 3D printer with an ABB robotic arm that moves along a stationary track setup. It can reach a length of 5 meters but can be extended accordingly. It's a practical solution to building prefabricated houses.



Figure 15. (3D Concrete Printers | CyBe Construction, n.d.)

CyBe RC (Robot Crawler)

This is a mobile 3D concrete printer and can therefore be used in multiple locations. Due to its configuration it is ideal for constructions on site. The ABB robotic arm is attached on a movable crawler with rubber tracks to guarantee mobility, independently of the terrain in which it is in. Due to its hydraulic feet the machine is able to stabilize while printing, also increasing the total projects height and length.



Figure 16. CyBe RC (robot crawler)/3D Concrete Printers | CyBe Construction, n.d.)

Contour crafting

Currently contour crafting is the only layer fabrication technology that is uniquely applicable to large-scale printing. It's a form of additive manufacturing that uses computer control to exploit the construction of smooth surfaces and accurate creation of planar and free-form surfaces. The main materials used for contour crafting are polymer, ceramic slurry, cement, and other aggregates used to ensure the smooth surface finish.

Some of the advantages of CC compared to other layered fabrication systems, are better surface quality, high-speed fabrication and a wider selection of materials.

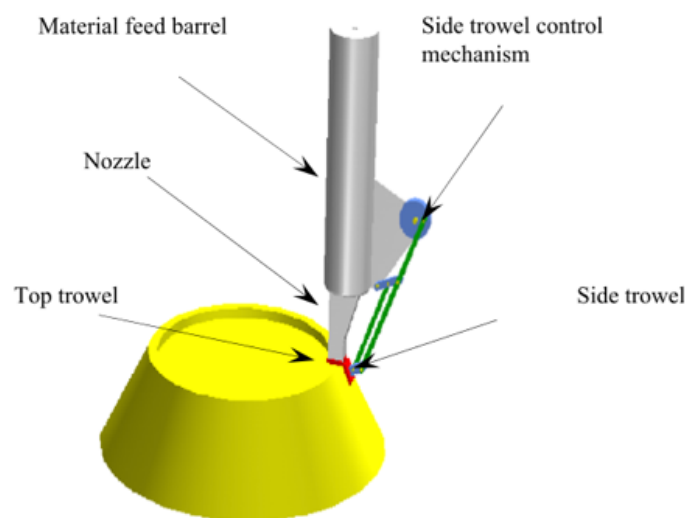


Figure 17. Contour crafting process (Khoshnevis, 2004)

Techniques similar to contour crafting have been developed over the years, an American constructor has developed TotalKustom, similar to Contour crafting, but with a much smaller layer height.



Figure 18. TotalKustom printer

Chapter 2.2.

The most widely used material on earth is cement-based materials like concrete. Its extensive use is justified by its qualities, including resistance to compression and fire, formal versatility, and most importantly, its low cost, which results from the abundance of its constituent materials. Even though a number of these characteristics are very important for construction, they frequently encourage careless and unconscious material use (Bos et al. 2016). Along with this, there are also extremely high emissions of CO₂ into the atmosphere, during the transformation process of cement.

Producing complex shapes using traditional manufacturing methods incurs in high costs. Even relatively simple shapes can be difficult and expensive to produce due to the complexity of the mold. This cost issue makes it challenging to execute construction projects with more ambitious shapes due to increased material and manufacturing expenses, the need for skilled labor, particularly when pouring concrete on site, the need for reinforcement in the structure to enhance tensile strength, which is a vulnerability of cementitious materials, and the transportation of more intricate prefabricated structural elements.

Chapter 2.2.1 Types of ornamental stone

Before focusing on one ornamental stone, it was necessary to do extensive research on the existing stones, their qualities and mechanical properties.

For this study, there will be only considered the granites that are mined in Portugal. Given the proximity of the mining location and the easy access to the material, for future printing tests.

Stone types: igneous, metamorphic and sedimentary

The igneous are those that result in the solidification of magma or the transformation of pre-existing rocks, respectively. Igneous rocks form from the cooling and solidification of magma or lava, which can occur both below and above the Earth's surface. Metamorphic rocks, on the other hand, result from the transformation of pre-existing rocks due to high temperatures, pressure, and/or chemical activity. Both igneous and metamorphic rocks are characterized by their unique mineral composition and texture, which can provide important clues about their formation history and the geological processes that shaped them. (Osinski et al., 2018)



Figure 19. Igneous rock (*Granite Blue Cristal*)



Figure 20. Metamorphic rock

Metamorphic rock
(*New York Stone* | *Bianco Estremoz Marble, Marble from Portugal*, n.d.)

Sedimentary rocks

Sedimentary rocks are one of the three major types of rocks, alongside igneous and metamorphic rocks. These rocks are formed by the accumulation and lithification of sediment over time. Sediment is a mixture of different particles that can come from various sources, including the erosion of pre-existing rocks, the remains of plants and animals, or precipitation from water. The sedimentary rock formation process begins with the deposition of sediment, which can occur on land or in water. The next stage involves the compaction of the sediment as it becomes buried under more layers. The final stage is lithification, which occurs when the sediment is transformed into rock through processes such as cementation or recrystallization. Some examples of sedimentary rocks are limestone, sandstone, siltstone, shale, conglomerate, and breccia. (Z.-X. Zhang, 2016)



Figure 21. Sandstone example



Figure 22. Limestone example

Marble

Marble is a crystalline and compact metamorphic rock that forms from limestone exposed to high temperatures and pressure. It is mainly composed of calcite and is known for its strength and natural beauty, making it an ideal material for both interior and exterior surfaces. It is also capable of withstanding changes in temperature and humidity. Its physical-mechanical characteristics include a compressive strength of 870 kg/cm², 950 kg/cm² after frost resistance testing, a flexural strength of 124 kg/cm², an apparent density of 2720 kg/m³, a water absorption at P. At.N. of 0.1%, an open porosity of 0.2%, a maximum thermal linear expansion coefficient of 7.3×10^{-6} per° C, a wear resistance of 3.7 mm, and a shock resistance with a minimum drop height of 50 cm. In addition, its frost resistance is superior to 25 cycles of freezing and thawing. (Rezende Leite et al., 2021)



Figure 23. Marble extraction in a quarry. (Marble, n.d.)

Granite

Granite is a rock that is primarily made up of three minerals: mica, feldspar, and quartz. It is harder and more durable than marble, and it has fewer veins and is less porous. Granite is formed from magma, that cools slowly at great depths in the Earth's crust. This slow cooling process allows for the formation of large crystals, which gives granite its unique crystalline texture. The main chemical properties of granite dust are: silica, alumina and potassium, with small amounts of calcium and magnesium. (S. Singh et al., 2016) The main minerals in granite are quartz (which can make up to 60% of the rock), feldspar, and mica. Visually, granite typically has a granular appearance and a coarse texture. The hardness and color of granite depend on its chemical composition, with darker granite having less quartz and therefore being less hard. Granite is a rock with low porosity, meaning it absorbs little water (though this amount can vary based on its composition and color). (*Granite: Igneous Rock - Pictures, Definition & More*, n.d.)



Figure 24. Granite stone (Granite, n.d.)

Limestone

The limestones more commonly found are compact rocks that have a non-crystalline appearance when viewed macroscopically, composed mainly of fine grains of calcite. They come in a range of colors, including white, black, beige, yellow, grey, red, brown, and pink. Limestone has a variety of uses, including being a chemical raw material for producing lime used in cement, which is an important component of concrete. Limestone is also the most commonly used rock for pavement because it fractures easily and is easier to transport and distribute. Its primary mineral is calcite, and it forms in the marine environment when carbon dioxide is lost. During the process of replacing this gas, calcite precipitates. Light-colored limestones have minimal amounts of other components besides calcite, while darker-colored ones have higher percentages of clays, oxides, sulfides, or carbonaceous materials. (Cement | Definition, Composition, Manufacture, History, & Facts | Britannica, n.d.)



Figure 25. Limestone example (*The Structure and Feature of Limestone*, n.d.)

It's important to understand the difference between these three types of ornamental stone, and for the continuation of this project shall be used igneous rocks, in specific, granite stone, due to its abundance in the north of Portugal, allowing for an easier access to the quarries, where these stone are retrieved from.

Granite dust

The industrial production of granite has recently witnessed steep growth resulting in higher waste generation. The inefficient disposal of waste poses severe environmental hazards. The granite dust shows an appearance and particle size distribution similar to the natural fine aggregate, sand. Such properties make it a viable replacement for sand in the concrete aggregate. (S. Singh et al., 2016)

Granite dust, marble chips, and dust are byproducts of the granite and marble production processes. The manufacturing of granite goods generates a large number of waste materials, which may be utilised to create concrete mixtures such as coarse aggregate, fine aggregate, and cement. Additive manufacturing is one of the possible uses for it, it's a new technique still with a lot of potential to evolve. Due to its pigment and raw color, there are many uses for granite dust in an artistic and architectural segment.

Due to the sharp rise in energy prices and the need to expand the raw material base, there has been a significant increase in the use of industrial waste. The construction industry is highly dependent on Portland cement, the most energy-intensive component of which is cement clinker. It is in the interest of the industry to develop and conduct research on technologies that ensure a reduction in the use of cement. When looking for alternatives to improve the environment, it's important to test alternative materials, such as marble, granite or limestone. It's been observed that when using granite powder the cement content can be reduced.

Granite powder as a waste material is a promising material for use in concrete, very similar to pozzolanic materials.

Due to its highly dispersible mineral components, it fills the space between the grains, forming a rigid structure, this improves the rheological properties of cement paste. It has been found that the addition of 40% granite powder improves the compressive strength of mortars and at the same time reduces the flexural tensile strength of mortars. It increased the drying shrinkage and decreased the water absorption of mortars.

Granite powder, when compared to marble powder, shows better effects on the self-compacting properties of concrete. (Stempkowska et al., 2022)

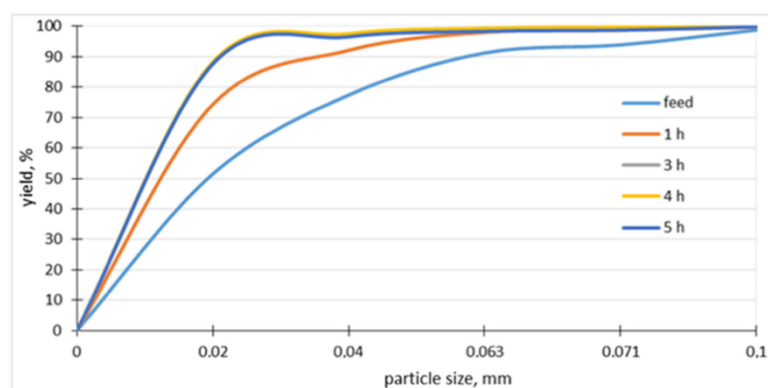


Figure 26. Grain composition curves of feed and grinding samples obtained with analytical sieves on wet method. (Stempkowska et al., 2022)

Granite characteristics compared to Marble characteristics

Table 2. Granite vs. marble characteristics

	Granite	Marble
Hardness (Mohs scale)	6 to 7	3 to 4
Liquid absorption	Low	Medium-high
Resistance to wear	High	Low
Resistance to impacts	High	Low
Porosity	Low	High
Staining	Low	High
Application	Outdoor and indoor environments	Interior environments: kitchens, bathrooms, tables

Based on the table above it is possible to conclude that granite is a suitable material for outdoor use compared to marble, due to its properties. Whereas marble has much higher maintenance to keep its visual effects. This was decisive in choosing between granite and marble. When designing for outdoor furniture it is important to choose the one that will not only maintain its aesthetic aspect but also its properties when it comes to enduring all types of weather conditions.

Properties of hardened granite dust concrete

The development of strength in concrete is governed by water to cement ratio. The strength of the material has some influence on the strength of concrete mix. The investigation made by (S. Singh et al., 2016) shows that the granite particles are comparable in strength with natural sand particles. (S. Singh et al., 2016) evaluated the effects of using granite cutting waste in place of some of the natural sand in the concrete. Replacements were implemented in 10%, 20%, 30%, and 50% increments. The highest value of compressive strength was found to be 30% replacement of the maximum value. The compressive strength observed at 50% replacement was comparable to the control concrete.

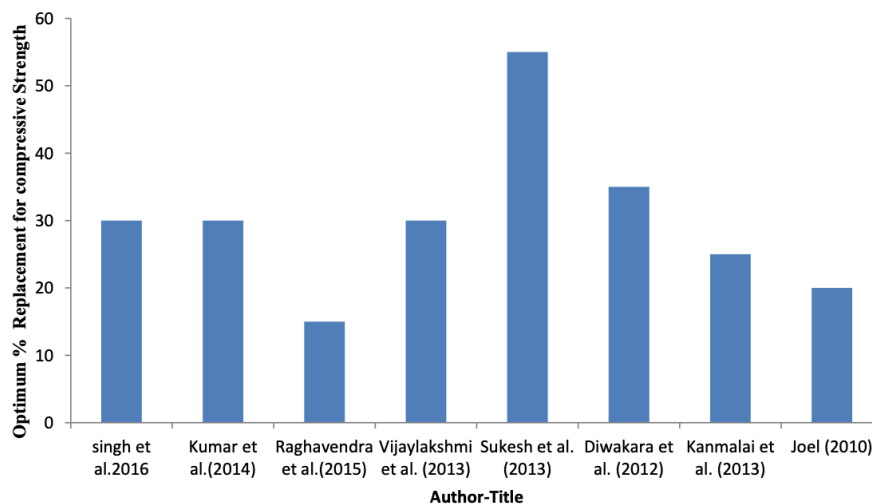


Figure 27. Optimum percentage replacement proposed by various researchers for maximum compressive strength. (S. Singh et al., 2016)

2.2.2. 3D printing with ornamental stone

Recently, researchers have produced concrete with granite waste as cement replacement with a focus on pozzolanic activity, durability, and higher substitution ratios. Medina et al., in 2017, evaluated the performance of a new blended cement incorporating 10% or 20% granite sludge as clinker replacement, analyzing the chemical, rheological, mechanical and microstructural properties of the end product. They found that the granite sludge as partial cement replacement shortens the initial time setting, with higher ratios resulting in less of an effect on the setting time. The results of this study highlighted the potential effects of granite on the enhancement of the durability of concrete abrasion, freeze, and thaw cycle. The inclusion of different size particles of granite dust has a filler effect, which increases the resistance of the cement based material. (Shamsabadi et al., 2018) .

The cement used in this study is a type 2 Portland, with the following particle distribution.

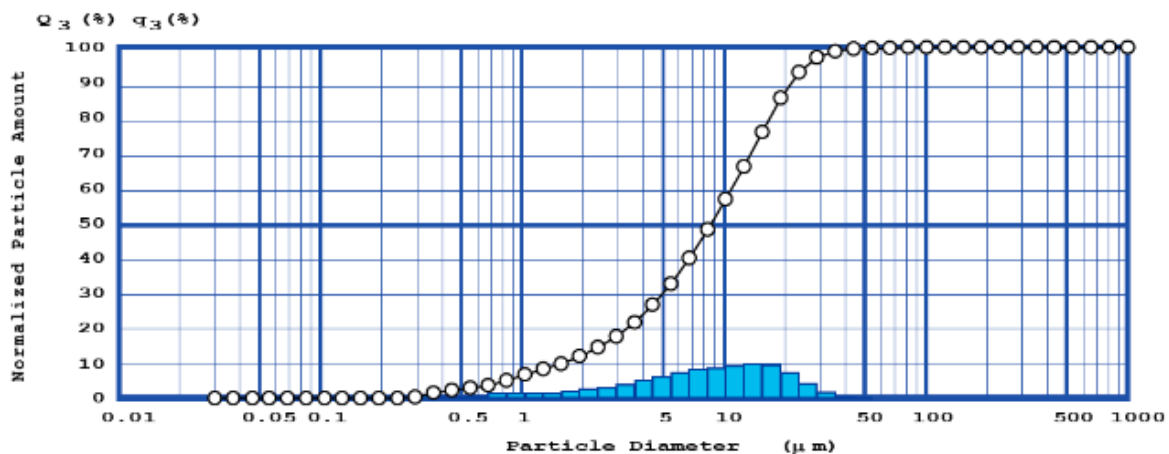


Figure 28. Particle size distribution of cement. (Shamsabadi et al., 2018) .

The granite waste powder (GWP), a by-product from the granite processing industry, was used in this study. The following graphic shows the granite powder grain size distribution. The average diameter of the cement is lower than the diameter of the granite grain and can be considered a reason for the decrease of the mechanical characteristics of the concrete. (Shamsabadi et al., 2018)

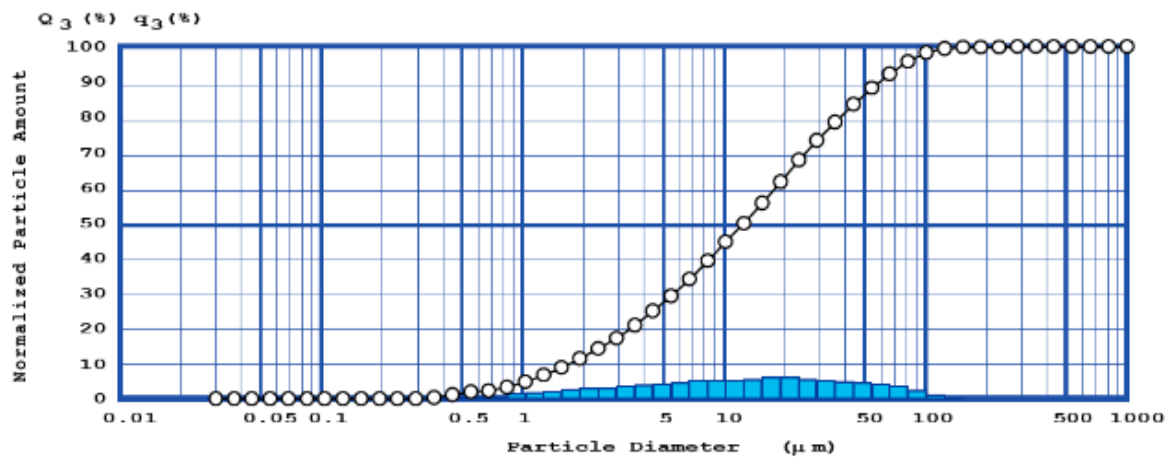


Figure 29. Grain size distribution of waste granite powder obtained by laser diffraction (Shamsabadi et al., 2018) .

2.3. The performance of concrete with granite dust

Granite waste has accumulated over the years and only small portions have been used, whilst the rest is dumped, with this resulting in environmental issues. Open sky mining, as is the case of granite and other type of stone quarries. These open sky quarries, lead to environmental problems. A study by Ramos obtained the influence of “granitic-quarry” waste incorporation on the durability and mechanical performances of mortars. In general most of the granitic waste has more or less the same chemical composition and therefore, can be used as pozzolanic matter to produce concrete. It’s been reported that if the particle size is even finer than the cement particles, an improvement of almost 70% can be seen in the mechanical resistance. (Shamsabadi et al., 2018)

The inventory and characterization of the Portuguese ornamental stones is one of the missions of the Portuguese Geological Survey (LNEG – Laboratório Nacional de Energia e Geologia). This systematic work resulted in the preparation of the Portuguese Catalogue of Ornamental Stones, which is continuously updated and is available online at the Geological Survey Geoportal (<http://geoportal.lneg.pt/>). (Manuel et al., n.d.)

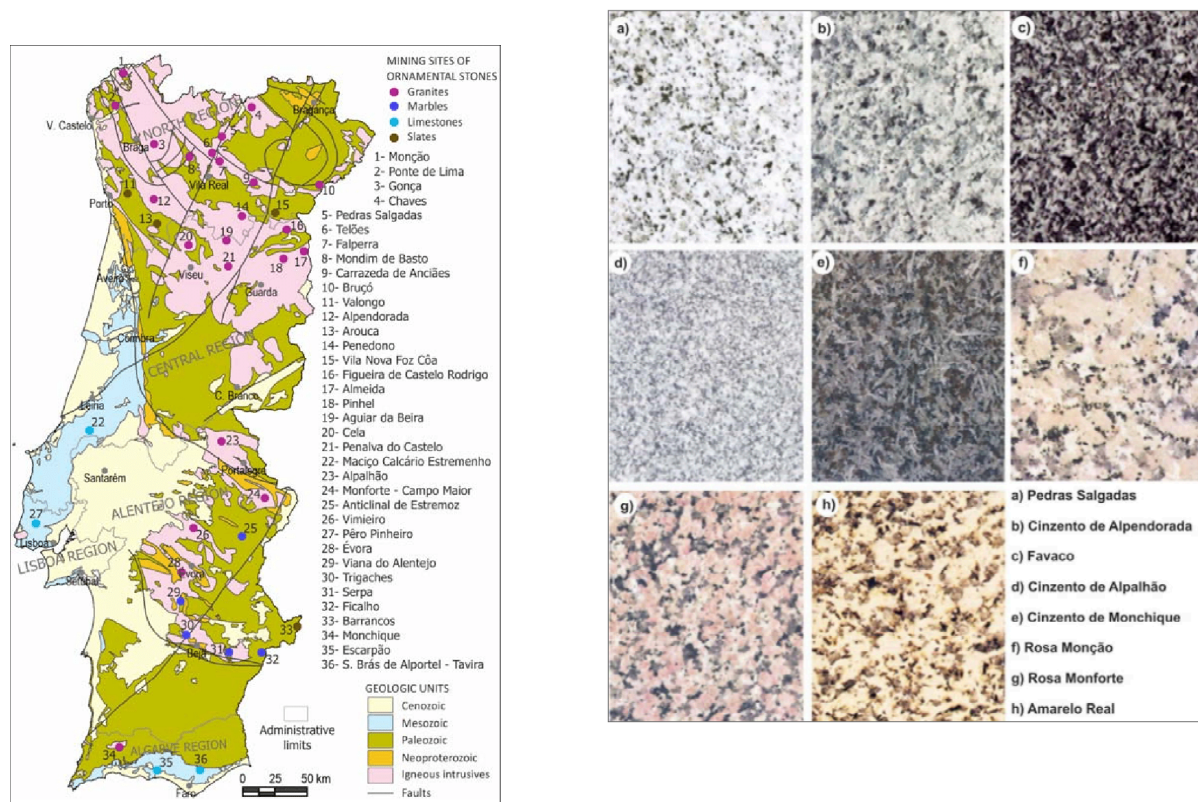


Figure 30. Location of the main Portuguese ornamental stones mining sites. (Manuel et al., n.d.)

The majority of Portuguese granites have greyish, blue undertones and a coarse granular texture. These kinds are mostly exploited in the mining sites marked on fig.x. at Pedras Salgadas and Alpendroadada sites Fig.30. Regarding colour and texture it's important to point out other varieties: The Cinzento de Monchique is mined in the Algarve region, it's coarse grain nepheline syenite with a greyish general colour is highlighted from it's reddish-brown grains that stand out. The most common granite in the market are the greyish granites, therefore the quarrying conditions are required in order to maximize the exploitation efficiency for these types of granite. The depth of these quarries vary from 30m to 70m, at Apalhão. Nevertheless, the most profitable quarries are those that involve mining large balls of granite. (Manuel et al., n.d.)

Chapter 3 - Market research

3.1. 3D Printed structures

Vincent Maillet – ConCreative

ConCreative is an american large scale concrete 3d printing company. ConCreative is releasing architects from the constraints imposed by conventional construction methods such as formwork. The aim is to create elegant, functional, sustainable and aesthetic, yet flexible enough so the client can decide it's own concept and distinctive style. (*Civil Engineering Construction Expertise for Concrete 3D Printing* | LinkedIn, n.d.)

Freyssinet a civil engineering company partnered with concreative to develop a concrete 3d printing shell to support the desired designs, with the necessary technical knowledge.



Figure 31 Concreative Bench (*Civil Engineering Construction Expertise for Concrete 3D Printing* | LinkedIn, n.d.).

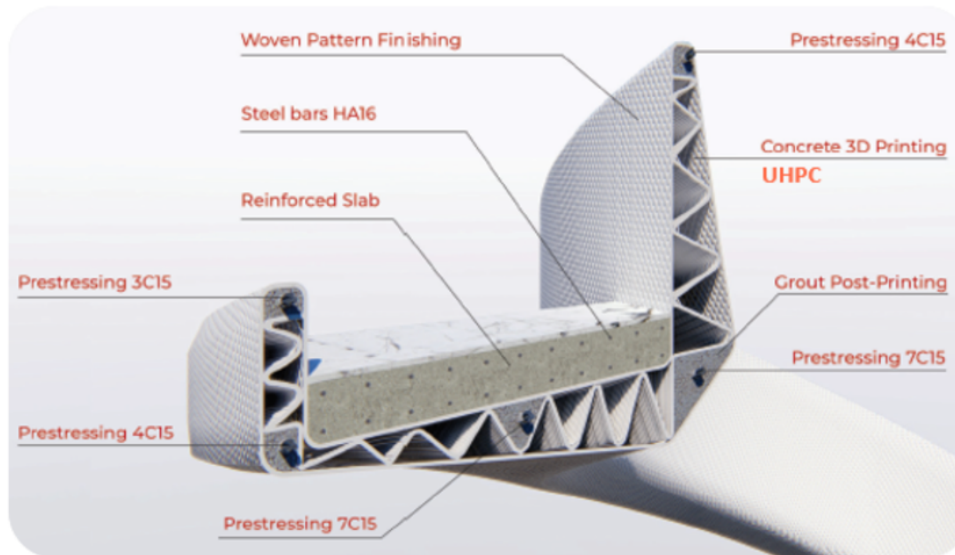


Figure 32. Freyssinet post tension within Concreative concrete 3D printing shell for helicoidal suspension stair. (Freyssinet, Your Specialist Partner to Build and Repair, n.d.)

A sufficient level of design and construction expertise with reinforced or post tensioned concrete is necessary for developing structural elements in concrete 3D prints. The regular inserted part within the concrete 3D printed shell helps to build the structural stability. Fiber concrete can be utilized to provide the component with ductility and traction resistance when irregularity or singularity prevent the cast in situ reinforced section from falling apart.

3D printed outdoor concrete furniture by Phillip Aduatz

The biggest challenge for this project was to develop a sustainable reinforcement that provides structural strength for the intricate design from Phillip Aduatz. By nature, concrete is a material that provides very little tensile strength, therefore the reason for reinforcement. For this particular project a semi-automatic strategy was used, reinforced with glass fiber rods and carbon textile reinforcement.

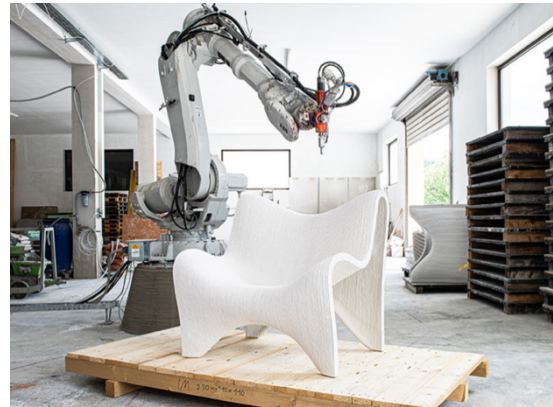
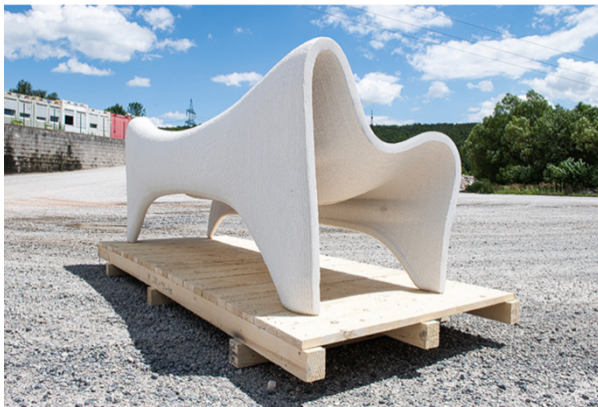


Figure 33. 3D printed concrete benches by Phillip Aduatz

XtreeE Benches – 3D printed concrete

Berlin-based designers Studio 7.5 collaborated with Parisian 3D printing experts XtreeE to create a series of continuously printed concrete benches with a woven pattern.

The main advantages to this process 3d printing, is the minimal amount of concreted used compared to traditional mold forms, this by itself reduces the amount of carbon dioxide emissions released. Complicated patterns are more economic to produce through 3d printing, also reducing the amount of people needed on site. This exact pattern was exclusively made for this bench. It also serves an important aspect it reduces the weight of the bench.

The three benches commissioned for this project where printed using XtreeE's printing technology and equipment. This includes a six-axis 3D printing robot, that can extrude both concrete and clay with an extreme precision (*Collection of Benches Woven in 3D-Printed Concrete*, n.d.)

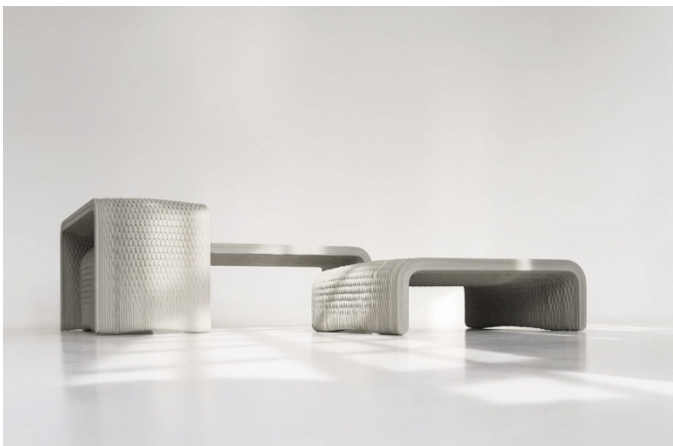


Figure 34. 3D printed woven benches by studio 7.5 and XtreeE

Fly-Ash 3D Concrete Printed Bench

The concept for a fly ash concrete printed bench extends this approach to industrial design through the on-site manufacture of one of the heaviest and bulkiest mainstream products. (Fly-ash: coal combustion ashes). This highly sustainable street furniture product concept exploits the emerging technology of 3D concrete printing. By mounting the printing process on a flatbed truck, these notoriously heavy products will be manufactured on-site and on demand; removing the need for resource intensive production facilities, warehousing and shipping. Moreover, 50% of the concrete build material is fly ash waste that typically ends up as landfill or is released into the atmosphere as a by-product from coal-fired electric generating plants. Since 50% of the material is fly-ash from concrete, which by itself is a by-product. It would also add to the concrete's final strength and increase it's chemical resistance and durability (*Fly Ash 3D Printed Concrete Bench - Core77, n.d.*)

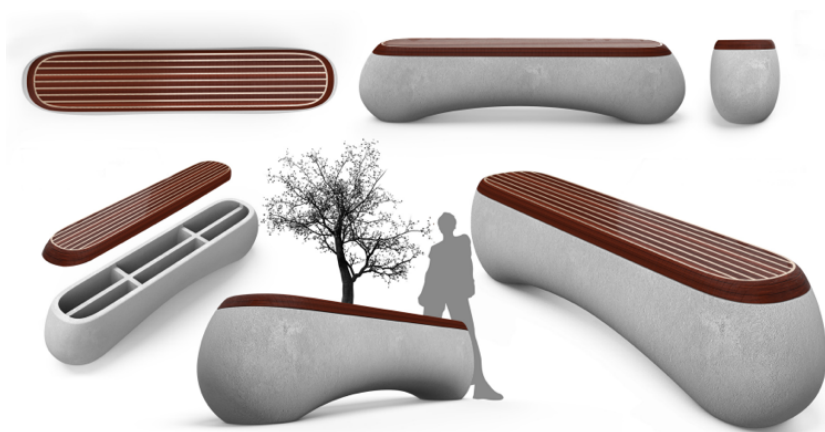


Figure 35. Fly Ash- 3D Printed Concept Bench. (*Fly Ash 3D Printed Concrete Bench - Core77, n.d.*)

Slicelabs Spiderheads – 3D Print

A US based design studio – Slicelab has developed a new concrete table using a 3d printed mold. The table is entirely made of white-cast concrete. For this project the 3d printing was mainly focused on the mold. Making it a different approach to the 3d printing process with concrete. The mold consists of 23 individual 3d printed parts that were later assembled together.



Figure 36. Slicelab table (Slicelab Spiderheads Concrete Furniture Using 3D Printing Technology - 3D Printing Industry, n.d.)



Figure 37. Close up of the air bubbles formed from the setting of the concrete.

Contour Pipeline by Hagen Hinderdael

Hagen Hinderdael is a design duo composed by Sofia Hagen and Lisa Hinderdael. Their main objective is to merge recycled materials with traditional craftsmanship and leading technology. This project “Contour” was a project in collaboration with Concrete3D, an Austrian startup focused on 3d printing with concrete. The project consists of 5, 3d printed concrete benches, organic curvatures are printed layer by layer to reveal the topographical layers of the mountainscapes coupled together to form the seat. The bench comes in two sizes, small and large, that can nestle into one another; leaving a negative space in between to enhance the playful character of the benches. The graphic coloring of the print uses a unique algorithm to print varying gradients of gray. (CONTOUR PIPELINE - HagenHinderdael, n.d.)



Figure 38. Contour benches, chromatic differences (left) and organic curvatures (right)



Figure 39. Different sizes showcased (left) and the 3d printing process (right)

3D Printed Concrete Bench – Cemento

For over three years, Cementos Progreso's research and development (R&D) team has been dedicated to researching, developing, and implementing a cementitious material that can be 3D printed. Their groundbreaking efforts have positioned them as pioneers in Guatemala, spearheading the application of 3D construction printing to tackle the housing deficit prevalent in both the country and the broader region. The aim is to utilize this innovative technology to make substantial strides in reducing the housing shortage and improving the living conditions of individuals in the area.



Figure 40. (Cementos Progreso Spearheads Use of 3D Construction Printers in Latin America | COBOD International, n.d.)

3D Printed House

This project was conceived by Houben and Van Mierlo Architecten for Project Milestone. The choice for concrete was due to its heavy use in the industry being one of the most used materials, everybody knows what it looks like. Given the flexibility 3D printing offers, it's possible to alter each house to the customer's need without the full cost it would take to alter each one if there were required framework and additional work in a traditional method.

This project aims to house five different families. The design process was to construct a house that would fully integrate with the surroundings in this case, the Meerhoven district, in Eindhoven.



Figure 41. Milestone Project 3D printed Houses in Eindhoven

Conclusions - Chapter 3

The conclusions for this chapter will be divided into three parts: main 3d printing methods, materials used and products printed.

There are three main printing forms: Delta printers are FDM based printers, which means the process of making the physical objects by building up successive layers of material. In this case layers of concrete based material is pushed through an extruder and deposited in successive layers in order to achieve the desired product. Gantry printers are normally large scale, stationary 3D printers. There are three main methods for the Gantry printers: Cybe G, Concrete Printing and D-Shape. The gantry in these situations acts as the frame structure that supports the printers nozzle, it moves along cartesian coordinates (X,Y,Z). The CyBe G is a 3D concrete printer that can print anywhere as long as the four columns and three beams are setup, it is most suitable for printing large modules. As for Concrete Printing it has many similarities compared to contour crafting, it's an extrusion based construction process (Wolfs, 2015). Lastly, D-Shape, this method involves a powder deposition selectively hardened by applying locally a binder material. Once solidified the hardened pieces are removed from the remaining sand around.

The CyBe Robotic Track is a printers where the arms moves along a stationary track setup. Allowing for variability in the geometric form.

[illegible][illegible]

Table 3. Main Characteristics of the 3d printing technologies (adapted from (Impressão 3D Com Extrusão de Materiais Cimentícios, n.d.)

Chapter 4 - Case study

In this chapter it is explored the concept of 3d printing through the extrusion of a granite based cement. In the first part, its presented the extrusion system for the printer used (Delta WASP 40100 Clay) and the printing mechanism this printer uses.

The next step consisted of the study of the mixture, experimenting with different percentages of cement, granite and water. The mixture needs to withhold the following layers in order for the print to be successful. This was tested out through many different tests. The mortars were characterized through there texture and colour.

The last step consisted on printing the bench in a smaller scale, in order to have more realistic results in the end.

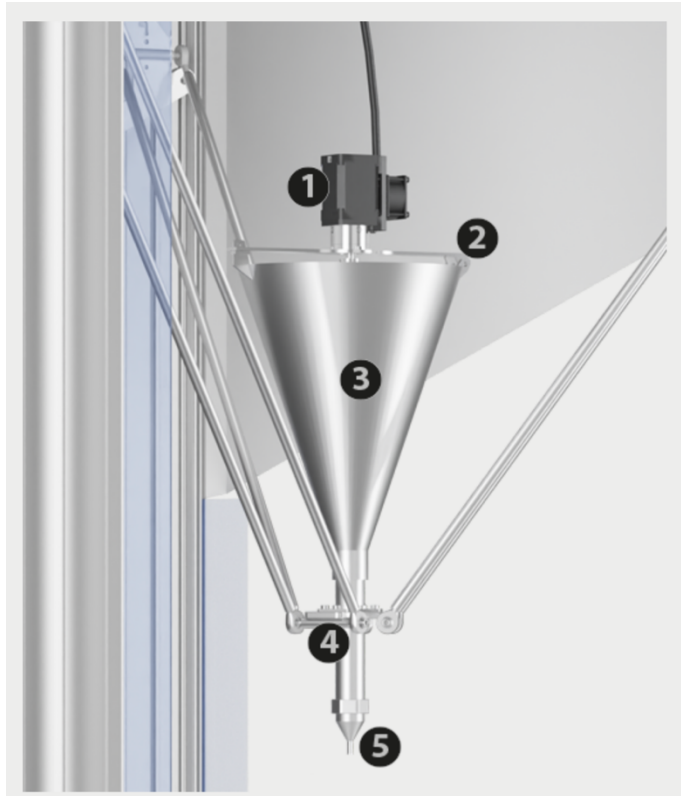
Delta WASP 40100 CLAY

The Delta WASP 40100 CLAY is a ceramic 3D printer, its dimensions are 77 cm x 85 cm x h 195 cm, weighs 80kg. It prints with porcelain, earthenware, gres, refractory materials, clays, cement. The maximum printing dimensions are Ø 400mm x h 1000 mm. Printing at a maximum speed of 150mm/s.



Figure 42. Delta WASP 40100 CLAY

The printer used for this thesis utilizes a manual feeding extruder, liquid deposition modelling technology for 3D printing concrete and geopolymers. The components are described in the Fig.43.



- 1- Motor
- 2- Connection Joint
- 3- Hopper with stainless steel mixer
- 4- Technopolymer screw
- 5- Stainless steel nozzle

Figure 43. Components of the manual feeding extruder, adapted from (Geopolymer Extruder - WASP Manual Feeding Extruder, n.d.)

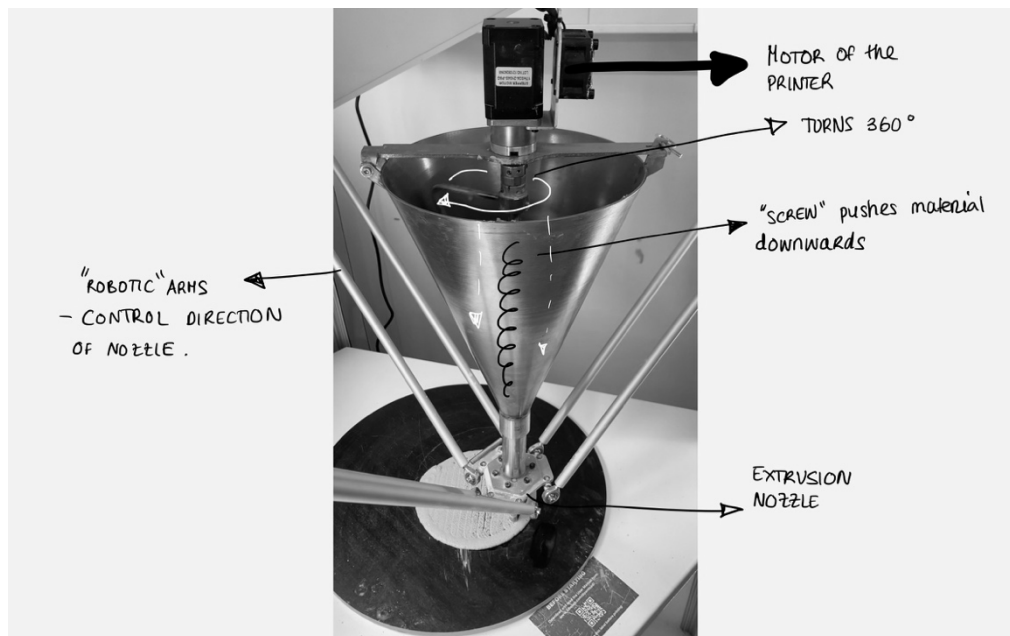


Figure 44. The figure above is a hand drawn representation of the manual feeding extruder by the author.

4.2. Ergonomics

Anthropometric study of the Portuguese workers

For the design of the bench it is important to have an understanding of the average height of the Portuguese population. The measurements used for the product were based off this article (Barroso et al., 2005).

Anthropometry consists on the measurements of body characteristics such as reach, body segment length, widths and heights among other factors. A big part of the data reported belongs to the Laboratory of Applied Anthropology (LAA). (Barroso et al., 2005)

The sample consisted of 492 men and 391 women. The sample consisted mainly of individuals from the industry and some workers from the tertiary sector. Age varied between 17 and 65 years old. Underlying the choice of subjects from industry is the fact that this accounts for approximately 23% of the active population in Portugal. (INE (Instituto Nacional de Estatística), 2001).

Mean (*M*), standard deviation (*SD*) and percentiles for anthropometric dimensions of the male population (*n* = 492), values in mm

Dimensions	<i>M</i>	<i>SD</i>	First percentile	Fifth percentile	Ninety-fifth percentile	Ninety-ninth percentile
Abdominal depth	265	32	191	213	317	339
Buttock–knee length	590	33	513	536	644	667
Buttock–popliteal length	485	32	410	432	538	560
Chest (bust) depth	265	23	211	227	303	319
Elbow height	1050	51	931	966	1134	1169
Elbow–knuckle length	350	18	308	320	380	392
Eye height	1585	74	1412	1463	1707	1758
Forward grip reach	730	62	584	627	833	876
Hip breadth	380	24	323	340	420	437
Knee height	525	30	455	475	575	595
Knuckle height	735	43	635	664	806	835
Lumbar height	215	20	169	183	247	261
Popliteal height	400	26	341	358	442	459
Shoulder breadth (biacromial)	335	22	284	299	371	386
Shoulder breadth (bi-deltoid)	475	30	404	425	525	546
Shoulder height	1395	65	1245	1289	1501	1545
Sitting elbow height	255	30	185	206	304	325
Sitting eye height	810	34	730	754	866	890
Sitting height	920	37	833	859	981	1007
Sitting shoulder height	630	33	552	575	685	708
Stature	1690	76	1514	1566	1814	1866
Thigh thickness	175	17	134	146	204	216
Vertical grip reach (sitting)	1250	55	1123	1160	1340	1377
Vertical grip reach (standing)	2030	94	1810	1875	2185	2250
Weight	74	11	48	56	92	100

Figure 46. Mean (*M*), standard deviation (*SD*) and Dimensions, percentiles for anthropometric dimensions of the male population (*n* 1/4 492), values in mm. (INE (Instituto Nacional de Estatística), 2001)

From the table above its possible to conclude that the mean sitting height is 920mm or 92cm and the average knee height is 525mm or 52,5cm. This means that the bench height should be no lower that 52,5cm.

The following figures is complemented with a table below that serves as a caption for the scheme in Fig.47.

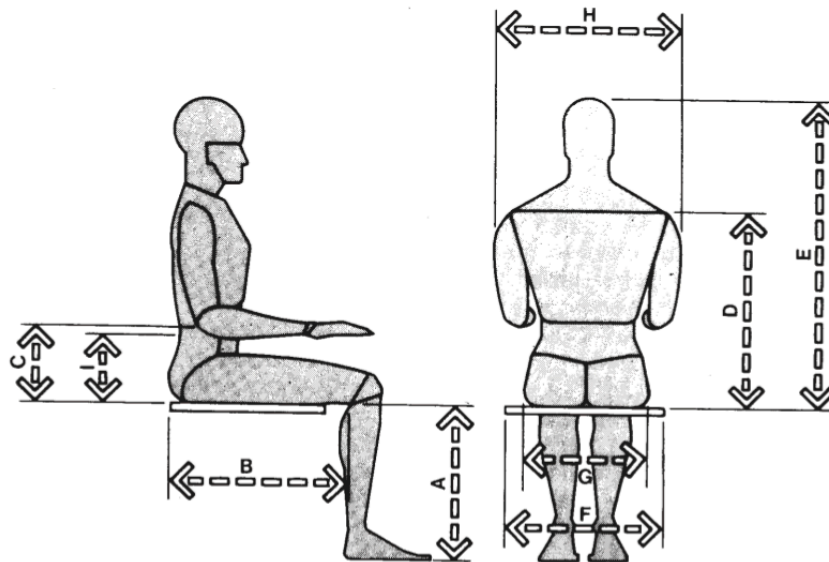


Figure 47. Fundamental anthropometric dimension, necessary for the design of seats.
(Panero & Zelnik, 1979)

	Men		Women	
	Percentile		Percentile	
	5	95	5	95
	cm	cm	cm	cm
Knee height (A)	39,4	49	35,6	44,5
Sitting length (B)	43,9	54,9	43,2	53,3
Sitting height (E)	80,3	93	75,2	88,1
Back height (D)	53,3	63,5	45,7	63,5

Table 4. Adapted from (Panero & Zelnik, 1979)

Average A= 46,75 cm (men and women)
Average B= 48,83 cm (men and women)
Average D= 56,5 cm (men and women)
Average E= 90,55 cm (men and women)

Design Guidelines (Weber Saint-Gobain)

Weber Saint-Gobain, is the company which produces the cement that was used throughout the experimental part of the project.

These design guidelines are made by the company producing the cement, in this case the cement that was selected was the Weber Saint-Gobain.

These guidelines were taken in mind when designing the final product.

Print Path

When designing for 3d printing with concrete starts with having conscious of the print path. Doing this will ensure proper printing strategies, corners, interconnecting layers and overhangs.

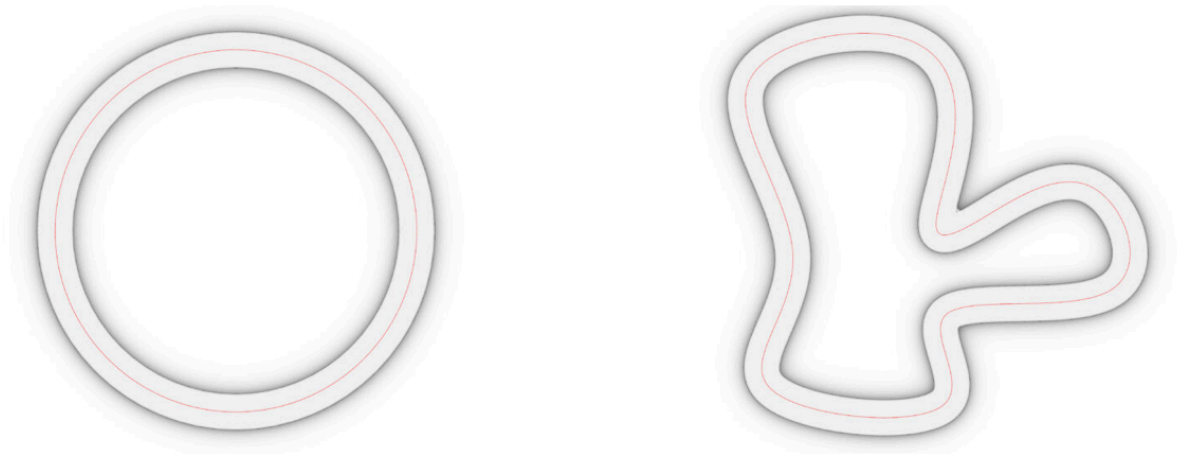


Figure 48. Saint Gobain - Weber Print Paths

Traditional 3DP designs are formed in closed loops in order to ensure seamless and continuous printing.

It is also possible to simply stack layers one on top of the other, this is an open loop type of design.

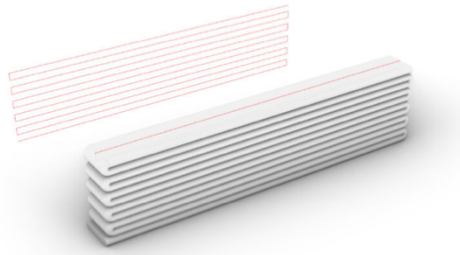


Figure 49. Open Loop Path - Weber Saint Gobain

Layers can also overlap on certain points, this is helpful for when designing stairs. When doing so layers should overlap for a minimum of 5 millimeters in depth and 10 millimeters in length.

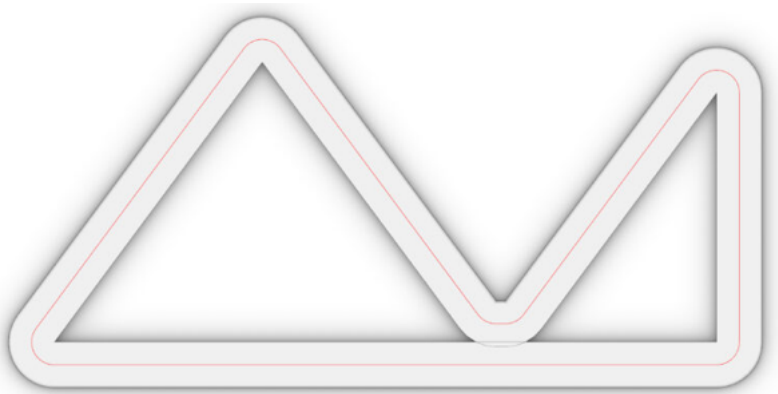


Figure 50. Overlapping path - Weber Saint Gobain

4.3. Concept development

Moodboard

This moodboard represents the inspiration gathered for the design of the bench.

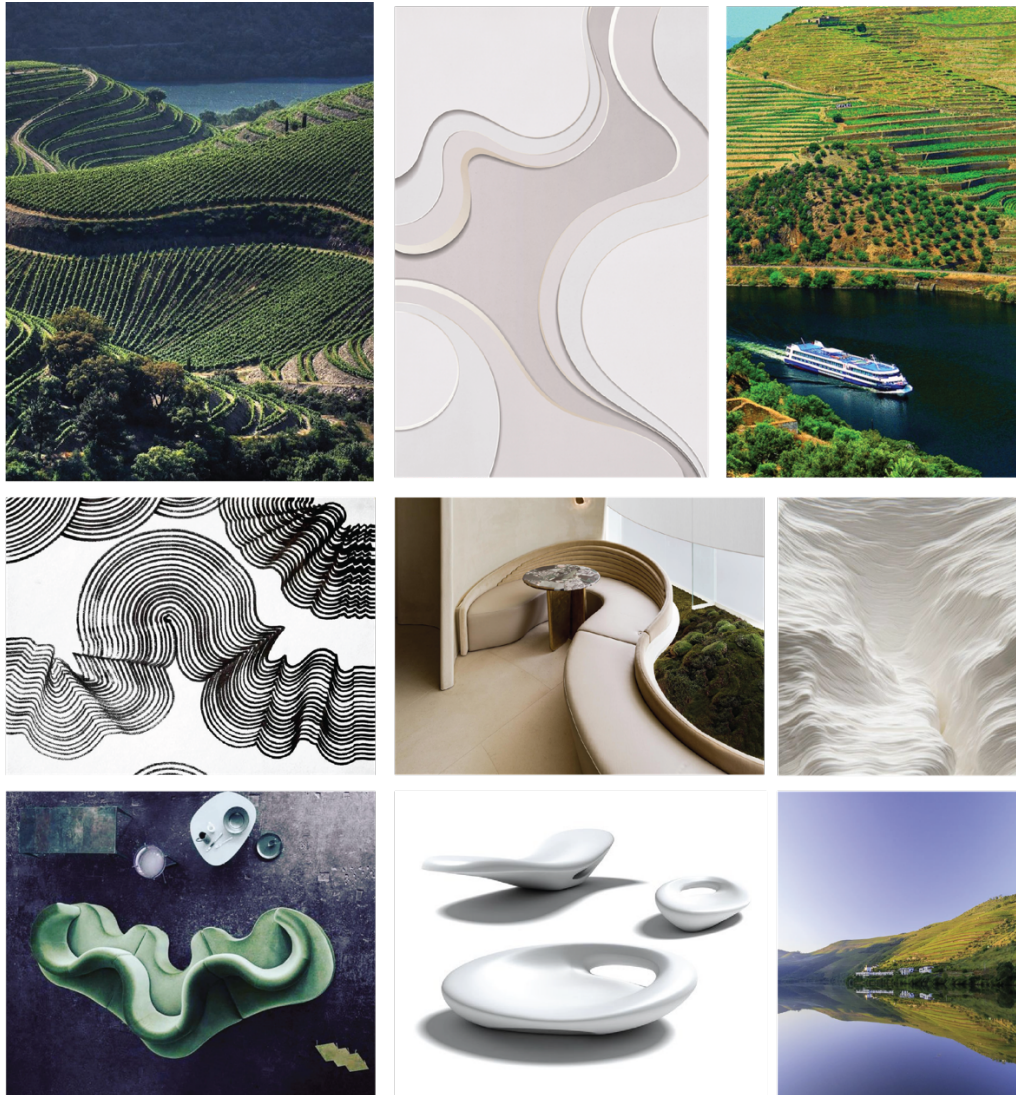


Figure 51. Moodboard by author

(Circle Patterned Banner Royalty Free Stock Vectors | Rawpixel, n.d.; Colour of the Month White - July — Suna & Toast - Suna & Toast, n.d.; Garden Pavilion | Gestalten, n.d.; Park Furniture on Behance, n.d.; Please.Dont.Touch on Instagram: “Cloveleaf Sofa by Verner Panton . #pleasedonttouch #vernerpanton #furniture #furniture design #interiordesign,” n.d.; Secrets Itinerary: Top Places In The Douro Valley, n.d.; Untitled No. 26 Drawing by Sumit Mehndiratta | Saatchi Art, n.d.; Viking River Cruises - Cruising Portugal Douro Valley, n.d.; Wine Partners of The Yeatman Wine Hotel - The Yeatman Hotel, n.d.)

Creativity plays an important role in designing a new product, therefore it must be integrated into the product design process. This design process is based on a systematic design methodology “Sensuous Association Method (SAM)”, whose main aim is to produce creative ideas both for the designer and the surrounding stimulation. This method includes four natural behaviors of the human being: thinking, looking, comparing and describing. This proposed design method includes three stages: divergence, transformation and convergence. (Hsiao & Chou, 2004)

For this project minimalism was the main concept. The use of clean and simple shapes was essential for the design of this outdoor bench.

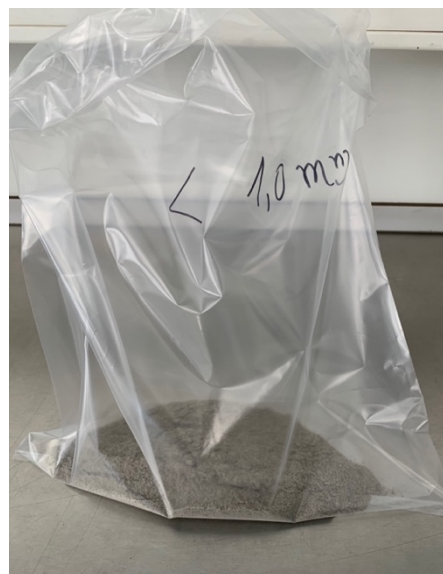
4.4. Separation of different calibers of granite dust

This step was fundamental to completing the whole printing process. The granite was provided by the DST Group, which it then had to be separated into different granulometric sizes. The grains had to be smaller than 0,84mm in order for the Delta WASP 40100 CLAY be able to print without having the grains obstructing the extrusion nozzle.

1. 1kg of Granite with a caliber $>1\text{mm}$.
2. The next step was the calibration of the dust. Next it was necessary to put the dust in an electric granulometric sieve, with a 0.84 sieve.
3. The caliber of the dust was separated in two different categories $>0.85\text{mm}$ and $<0.85\text{mm}$
4. The caliber $<0.85\text{mm}$ was put through a fragmentation process by using a hammer mill.
5. After reaching the $<0.85\text{mm}$ caliber, the granite powder was put back in the calibration process to guarantee the same granulometric size for all the granite powder.



Figure 52. Electric Granulometric Sieve



4.4.1. Slump test

A slump test measures the consistency of a mixture to see how easily the mixture will flow. This test not only allows for the observation between different batches but also gives the opportunity for improvements between mixes. The main purpose of a slump test is to ensure the different batches have the same quality and strength. Water weakens the concrete, so the more water is added to the mixture the weaker it gets. (Concrete Slump Tests - Measuring the Workability of Concrete | Total Concrete, n.d.)

Steps to achieving a successful slump test:

1. Place the cone on a level, smooth, horizontal surface and stand on either side of the footholds to ensure the cone is securely placed on the ground.
2. Fill the cone in three stages, compacting — or tamping — the concrete after each layer in an even, regular way (this should be done 25 times each layer).
3. Once the cone has been filled, remove any excess concrete from the top, ensuring that the concrete completely fills the cone to the top level. Remove any poured concrete from the cone's base as well.
4. Slowly and steadily lift the cone upwards until it is free of the concrete. Next, place the cone on the surface upside down.
5. The concrete will sink — or subside. Place the steel rod over the top of the upturned cone so that it overhangs the concrete to measure the slump.
6. Now, take a measurement from the rod to the top of the slump. The amount of slump is calculated to the closest 5mm.

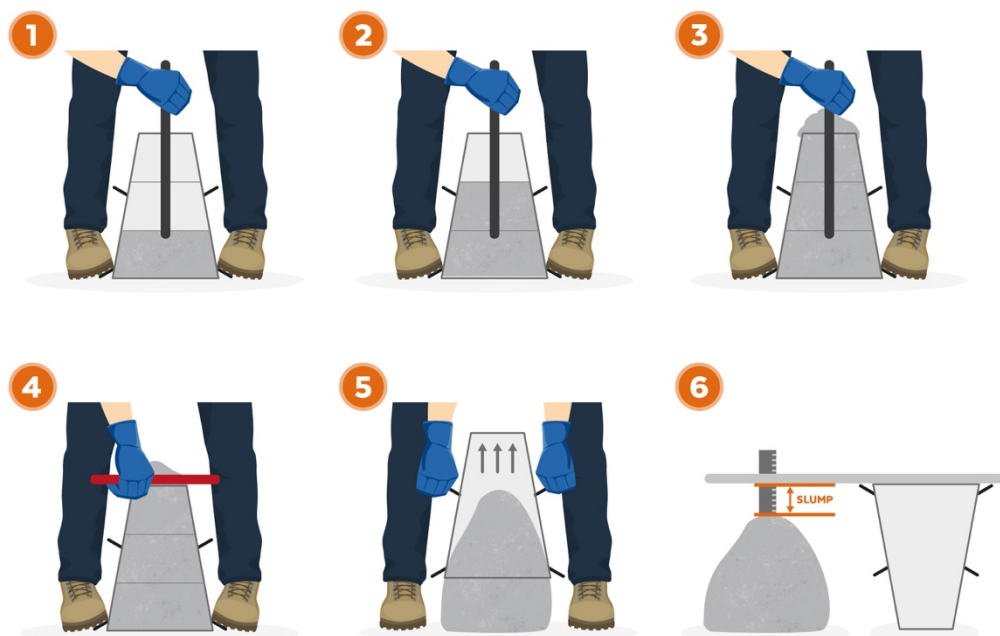


Figure 53. Slump test diagram explanation (Concrete Slump Tests - Measuring the Workability of Concrete | Total Concrete, n.d.)

4.4.2. Extrudability test

The extrudability test consists of the ability of a mixture to be squeezed from a nozzle in a continuous form. Extrudability is directly linked to flowability, so the higher the flowability there will be better outcome in the extrudability results and vice versa. This shows that whatever factors affect the flowability will have counter effects on the extrudability.



Figure 54. . Extrudability test with syringe. (Youssef et al., 2021)

4.4.3. Flowability test

The flowability test can be defined as the ease with which the mixture flows under certain given conditions. With this test, the mix is poured into a cone and is timed, until the mixture reaches a certain specific diameter. This way the mixture flow can be calculated. The easier the mixture expands the more flowability and workability it has. (Malaeb et al., 2019)

4.4.4 Buildability test

Buildability is a complex and specific process, it not only depends on the characteristics of the material but also on the layer geometry. These two factors are important to keep in consideration because if both aren't in harmony the 3D printed structure will collapse.(Nerella et al., 2020) This way, buildability is the ability to 3D print by adding the mixture layer by layer continuously to a certain level without any considerable deformation or collapse.



Figure 55. Buildability test

4.4.5. Chromatic test

This way it is possible to compare different chromatic tones of the material extruded once dried. All of them appear very similar, due to the different percentages of granite dust some may appear lighter, some may appear darker.

Tests from 1-10 have the highest percentage of cement, therefore they will appear with a lighter colour.



Figure 56. All samples displayed - chromatic evaluation

4.4.6 Experimental Plan

When using cement, the most used material with it is sand, to give the consistency more structure. So for these tests, sand was substituted with granite dust.

1. Slump test: testing the consistency of the mixture
2. Buildability test: 20mm long, overlaying 5 layers
3. Extrudability test: 200mm layer, if successful repeat until 4 layers have been achieved. Each layer is added every 2 minutes.
4. Workability test: Observation of the mixture to check if there need to be any alterations done
5. Chromatic test: Visual observation of the differences in colors of the tests done

	Cement	Granite <0.85mm	Granite <0.75mm	Water
1)	250 g	450 g	350 g	232 g
2)	250 g	400 g	350 g	205 g
3)	250 g	500 g	200 g	200 g

	Cement	Granite <0.85mm	Granite <0.75mm	Water	Marble Dust
1)	300 g	500 g	200 g	205 g	
2)	300 g	300 g	200 g	245 g	200 g

With test 2) it was added marble dust due to the lack of granite <0,75mm and due to the fact that the printer doesn't withstand such grainy textures.

Cement	Granite <0.85mm	Granite <0.74mm	Water
250 g	400 g	350 g	232 g
250 g	400 g	350 g	205 g
250 g	500 g	200 g	200 g
300 g	500 g	200 g	205 g
300 g	300 g	200 g	245 g
300 g	300 g	200 g	205 g
150 g	300 g	-	100 g
200 g	300 g	-	113 g
220 g	300 g	-	105 g
200 g	300 g	3 g (pigment)	120 g

Cement	Granite <0.85mm	Water
200 g	300 g	110 g
210 g	290 g	110 g
220 g	300 g	110 g
250 g	250 g	115 g
240 g	260 g	115 g
230 g	270 g	115 g
220 g	280 g	117 g
210 g	290 g	108 g
200 g	300 g	107 g
190 g	310 g	105 g
180 g	320 g	100 g
170 g	330 g	100 g
160 g	340 g	100 g
150 g	350 g	105 g

The objective of these tests was to figure out how much percentage of cement can be reduced, whilst adding the most amount of granite dust. Keeping the mixture well aggregated. These tests were conducted in a certain order, the cement was reduced from 10g in 10g, whilst the granite dust was added from 10g in 10g.

In the first table, there are two different sizes of granite dust, these tests were the first ones to be made, so it was a trial to see if the different granulometric sizes had an impact on the 3D printing process.

Below are the materials used during the experimental plan.

Materials used:

- Water recipient
- Scale (g)
- Automatic mixer
- Silicone Funnel
- White board

Quantities – Test 1

Cement (g)	Granite <0.84mm (g)	Granite <0.4mm (g)	Water (g)
250	400	350	232



Figure 57. Test 1

This was the first test that was prepared. From here forward different percentages of cement and granite were used in order to fit all the tests that were prepared for these materials. The main objective of using two different granulometries in this mortar was to have a bigger granulometric range, this way the mixture would be more even. However throughout the different tests, it was verified that by using only the smallest size of granite dust the results would be just as interesting.

Quantities - Test 2

Cement (g)	Granite <0.84mm (g)	Granite <0.74mm (g)	Water (g)
250	400	350	205



Figure 58. Test 2

This tests had a low percentage of water, which resulted in a difficult extrusion process. When overlapping layers they were capable of withstanding each other. This happened because the mortar had a thick consistency. Tests after this one, had a higher percentage of granite dust, keeping the same amount of water.

Quantities- Test 3

Cement (g)	Granite <0.84mm (g)	Granite <0.74mm (g)	Water (g)
250	500	200	200

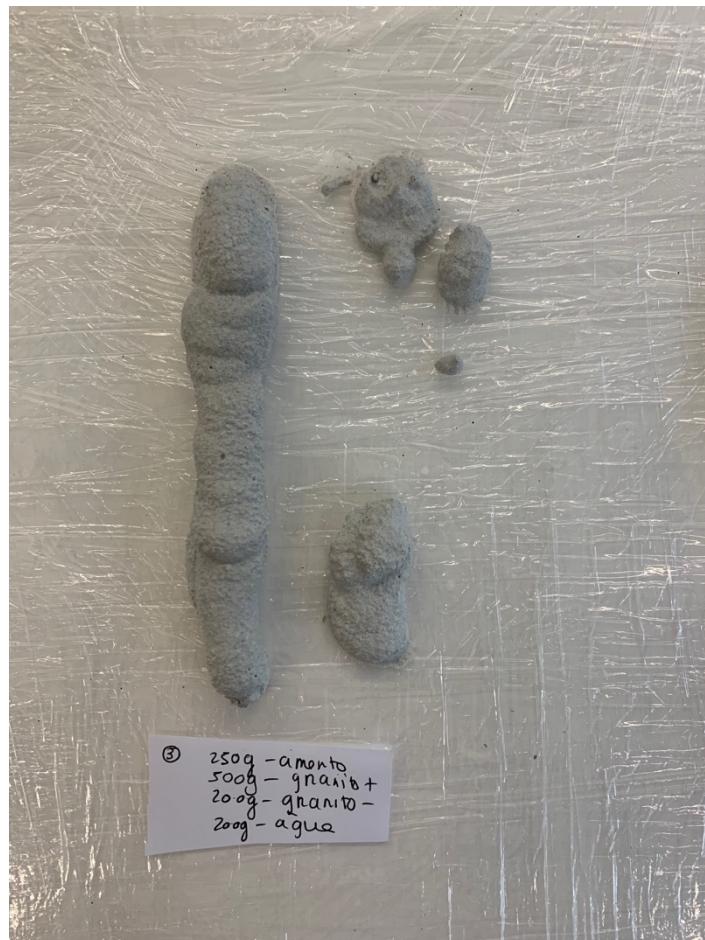


Figure 59. Test 3

Due to the nature of this experimental plan, sometimes a percentage of a material was put in too much, which in this case, there was a high amount of water put into the mortar, making it too fluid. So, this made the buildability test impossible to conclude after the first layer.

Quantities – Test 4

Cement (g)	Granite <0.84mm (g)	Granite <0.74mm (g)	Water (g)
300	500	200	205



Figure 61. Test 4 - top view

This mortar presented good qualities both, in the buildability test and in the extrudability test. As seen in Fig. 60 and Fig. 61, the amount of water absorbed by the cement and granite dust was good, which allowed for a good extrudability.



Figure 60. Test 4 - stacked layers

Quantities – Test 5

Cement (g)	Granite <0.84mm (g)	Granite <0.74mm (g)	Water (g)
300	500	200	205



Figure 62. Test 5

Test 5 was increased in the amount of cement, because during the earlier tests water absorption was low, and by adding more amount of a binder, the water would more easily hold onto the granite dust. In terms of extrudability and buildability, the material was successful. The grainy texture, shown in fig.62 is present in all tests, this is due to the characteristics of the granite when broken down into granite dust.

Quantities – Test 6

Cement (g)	Granite <0.84mm (g)	Granite <0.74mm (g)	Water (g)
300	300	200	245

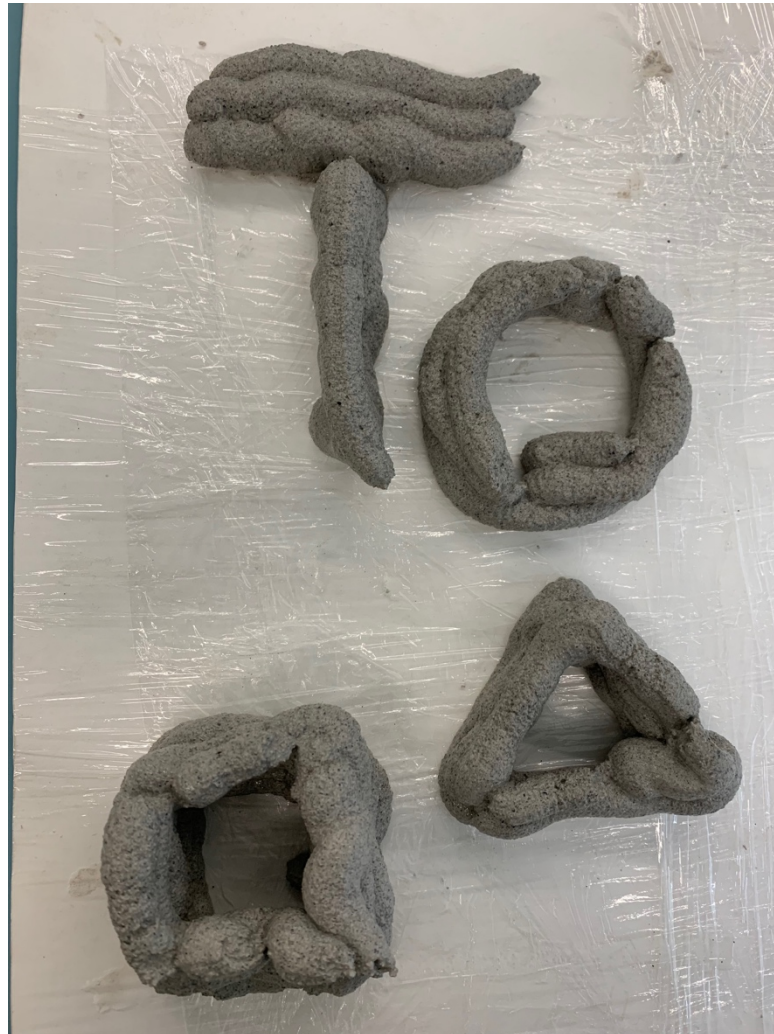


Figure 63. Test 6

This material presented successful results, the amount of cement available for the amount of granite dust available was more than enough. The layers adhered very well in between each other.

With test 6, it was to conclude that the amount of cement could be reduced, whilst still keeping good properties with the material.

Quantities – Test 7

Cement (g)	Granite <0.84mm (g)	Water (g)
150	300	100



Figure 64. Test 7

Test 7, when extruding through the silicone funnel, unfortunately didn't hold itself enough. This is why fig. 64, has cracks throughout the segments extruded. It is important to note that both humidity and temperature affect the performance of the material.

So whilst the amount of cement was reduced to half, of the amount of granite dust, the temperature inside the laboratory, had a negative impact on the test results.

Quantities – Test 8

Cement (g)	Granite <0.84mm (g)	Water (g)
200	300	113



Figure 65. Test 8 - stacked layers

For test 8, the same cracks appeared as in test 7, even though the amount of cement (acts as a binder) was increased. When adding more binder and still experiencing the same difficulties as test 7, the conclusion taken was that, the high humidity levels and high temperature levels had a negative impact on the extrusion of the mortar.

Quantities – Test 9

Cement (g)	Granite <0.84mm (g)	Water (g)
220	300	105



Figure 66. Test 9 - on the left extrudability tests and on the right slump test

Test 9, performed differently than test 8, the adherence between layers was better. But still the cracks were clearly visible when extruding with the silicone funnel. When trying out different percentages of each material, the importance of the material not breaking apart when printing is extremely important. So even though test 9 performed better than test 8, the results were still insufficient.

Quantities – Test 10

Cement (g)	Granite <0.84mm (g)	Water (g)	Pigment (g)
200	300	120	3



Figure 67. Test 10 - extrudability test

Test 10, didn't succeed as expected because, the material didn't extrude correctly through the manual nozzle. Unfortunately, no further tests were proceeded to be done, because the material turned out to be unsuccessful in the initial test, which was fundamental do completing the others.

Quantities – Test 11

Cement (g)	Granite <0.84mm (g)	Water (g)
200	300	107



Figure 68. Test 11 - stacked layers

Test 11 presented good results. Both extrudability and buildability were successful as seen in fig. 68. Five layers were able to be stacked each on top of each other, whilst the structure maintained its form.

Quantities – Test 12

Cement (g)	Granite <0.84mm (g)	Water (g)
210	290	105



Figure 69. Test 12

Test 12, had a completely different composition. More cement was added to the mortar. The segments when extruded completed 12 cm in length maximum, before separating and creating cracks. These cracks in the material are highly influenced by the temperature inside the laboratory. When the temperature is above 30°, the material easily creates small fissures even when extruding.

Quantities – Test 13

Cement (g)	Granite <0.84mm (g)	Water (g)
200	300	07



Figure 70. Test 13

Test 13, had good results in terms of printability, as seen in the image above, each segment reached a total length of 25cm. It is important to note, that when the mortars are teste manually the width of each segment is more unpredictable and difficult to control.

When building layers the material was able to hold each layers successfully.

Quantities – Test 14

Cement (g)	Granite <0.84mm (g)	Water (g)
190	310	105



Figure 71. Test 14



Figure 72. Test 14 - stacked layers

Test 14, when extruded immediately had a big tendency to create small fissures, which later on results in an incoherent material, that doesn't hold itself together. The amount of cement was reduced by 10g in comparison to test 13. The results could be better, but the temperature inside the laboratory is not possible to control.

Quantities – Test 15

Cement (g)	Granite <0.84mm (g)	Water (g)
180	320	100



Figure 72. Test 15



Figure 71. Test 15

Test 15, had a good performance in terms of extrudability, the filaments that were extruded reached sufficient length when manually printed, which is a very important aspect. The amount of cement could still be decreased, as the mortar was well bonded.

Quantities – Test 16

Cement (g)	Granite <0.84mm (g)	Water (g)
170	330	100



Figure 73. Test 16 - Extrudability test

The results for test 17 were good, this mortar was tested out to print in the WASP 3D printer due to flowability rate of the mixture when hand printed. The results above show a simple circular shape being printed out, in order to test the buildability properties of the mortar.

Quantities – Test 17

Cement (g)	Granite <0.84mm (g)	Water (g)
160	340	100



Figure 74. Test 17 - Extrudability test

Test 17, also had good results in terms of extrudability, but the possibility to reduce the amount of cement utilized in this mortar was still possible. So although this sample had good results, better one were able to be tested out.

Quantities - Test 19

Cement (g)	Granite <0.84mm (g)	Water (g)
150	350	100

Slump test

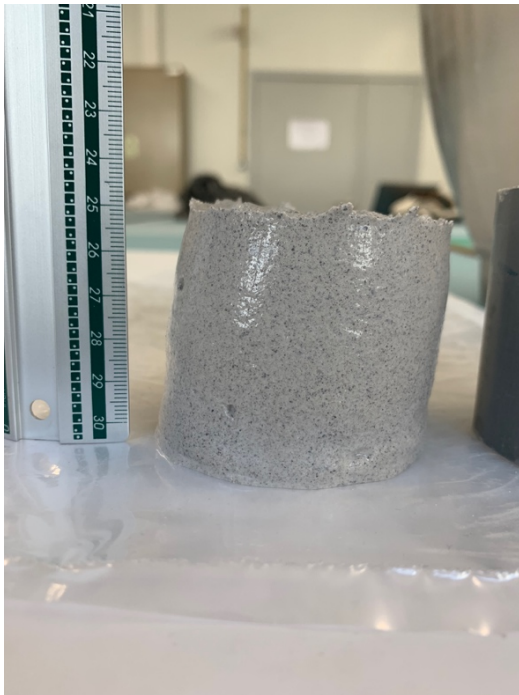


Figure 75. Slump test

The initial height of the cylindric tube is 5,7cm.

After the slump test the height was reduced to 5,2cm resulting in a 5mm decrease in height.

After concluding the slump test it is possible to conclude that the mixture contained too much water making it reduce by 5mm in height.

This mortar, presented both good extrudability qualities as buildability qualities, as was one of the three chosen materials for mechanical testing.

Quantities - Test 20

Cement (g)	Granite <0.84mm (g)	Water (g)
200	300	110

Slump test

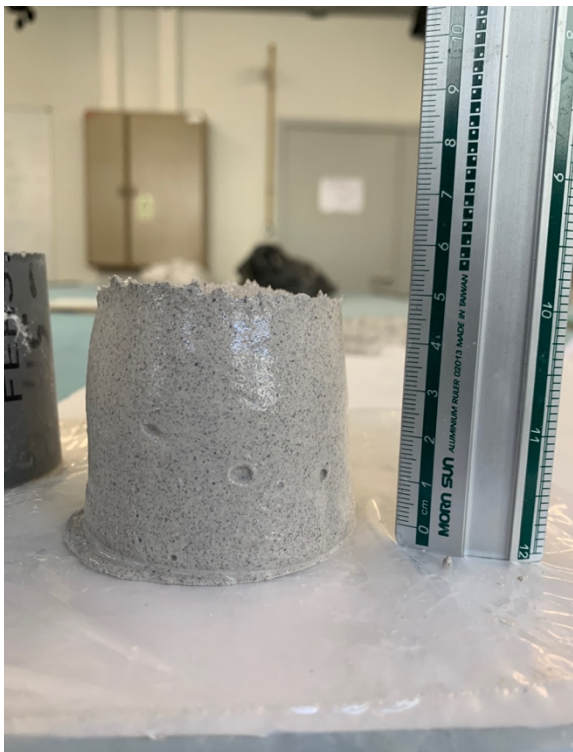


Figure 76. Slump test

The initial height of the cylindric tube is 5,7cm.

After the slump test, the height was reduced to 5cm, resulting in a 7mm decrease in height.

After concluding the slump test it is possible to conclude that the mixture contained too much water reducing it by 7mm in height.

The mixture needed less water in order to maintain its form. This mortar, presented both good extrudability qualities as buildability qualities, as was one of the three chosen materials for mechanical testing.

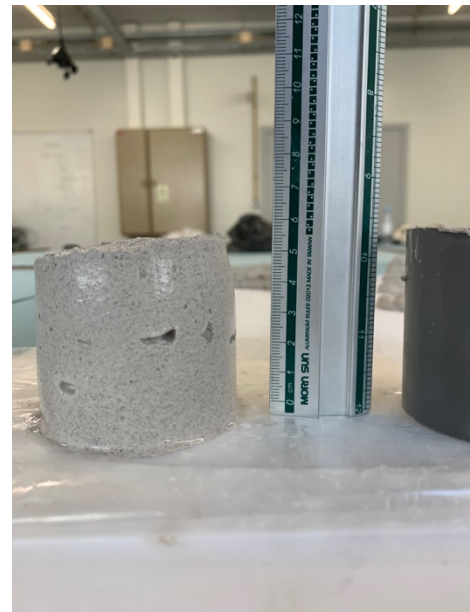
Quantities - Test 22

Cement (g)	Granite <0.84mm (g)	Water (g)
200	300	113

Slump Test



Figure 77. Preparation of the mortar



The initial height of the cylindric tube is 5,7cm.

After the slump test, the height was reduced to 5,5cm, resulting in a 2mm decrease in height.

After concluding the slump test it is possible to conclude that the mixture contained enough making it reduce by 2mm in height. In terms of extrudability, it would be necessary to add the slightest amount of water just to ensure that it would be easy to pump the mixture through a nozzle. This mortar, presented both good extrudability qualities as buildability qualities, as was one of the three chosen materials for mechanical testing.

Quantities - Test 23

Cement (g)	Granite <0.84mm (g)	Water (g)	Pigment (g)
200	300	110	5g

Slump Test



Figure 78. Extrudability test



Figure 79. Slump test

The initial height of the cylindric tube is 5,7cm.

After the slump test the height was reduced to 5,3cm, resulting in a 4mm decrease in height.

After concluding the slump test it is possible to conclude that the mixture contained enough making it reduce by 2mm in height. In terms of extrudability, it would be necessary to add the slightest amount of water just to ensure that it would be easy to pump the mixture through a nozzle.

Quantities – Test 24

Cement (g)	Granite <0.84mm (g)	Water (g)
250	250	115

Slump Test

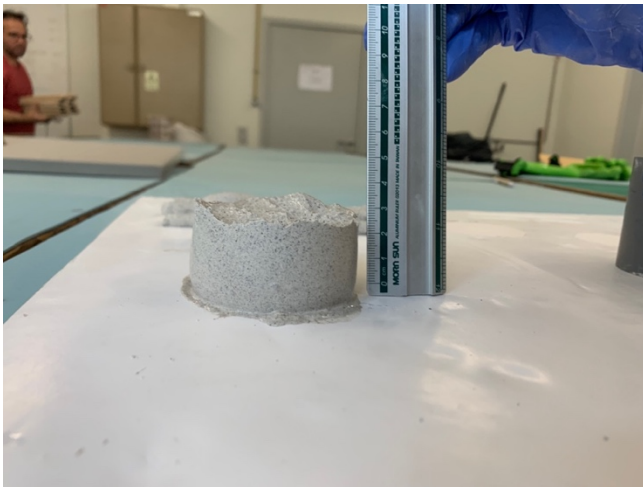


Figure 80. Slump test



Figure 81. Extrudability and buildability test

The initial height of the cylindric tube is 4cm, after removing the tube the height reduced to 3,5cm. This resulted in a 0,5cm decrease.

After concluding the slump test it is possible to conclude that the mixture contained enough making it reduce by 5mm in height. In terms of extrudability it has the right texture for printing.

Determination of compressive strength (Cubic sample)

Table 5. Results of the compressive strength tests

Sample n°	Dimension of the sample (mm)						Breaking strength (kN)	Compressive strength (MPa)
	Base							
	a1	a2	$\bar{a}$	b1	b2	$\bar{b}$		
1	47.77	49.98	48.88	48.51	51.08	49.80	20.3*	8.3
2	48.56	50.35	49.46	47.89	50.32		14.5	6
3	48.67	51.16	49.92	48.55	49.77		16.6	6.8
1'	48.32	50.67	49.50	48.13	49.45	48.79	6.4	2.6
2'	48.7	50.04	49.50	47.58	50.70	49.14	6.9	2.8

With these results it was possible to determine that the most resistant material was the one that had the most percentage of cement. It's important to determine amount that has sufficient compressive strength.

The first sample was first subjected to a initial high impact which, later on had implications on the compressive strength, increasing the compressive strength of the sample. Samples 2 and 3 both had a single force applied once for about 5min, until the structure started to rupture, appearing small fissures.

Table 6. Components of the samples

	Sample n°1	Sample n° 2	Sample n°3	Sample n°1'	Sample n°2'
Cement	150 g	180 g	140 g	150g	180g
Granite powder	350 g	320 g	360 g	350g	320g
Water	105 g	105 g	100 g	105g	105g

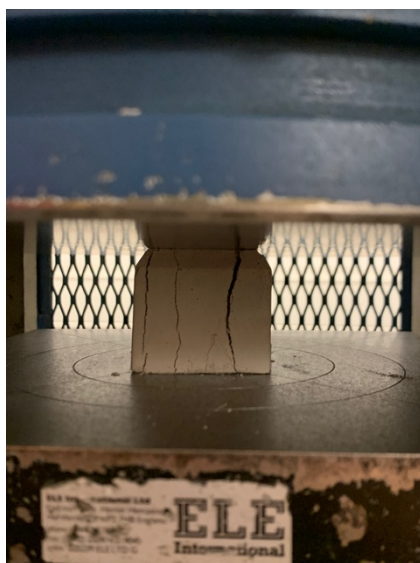
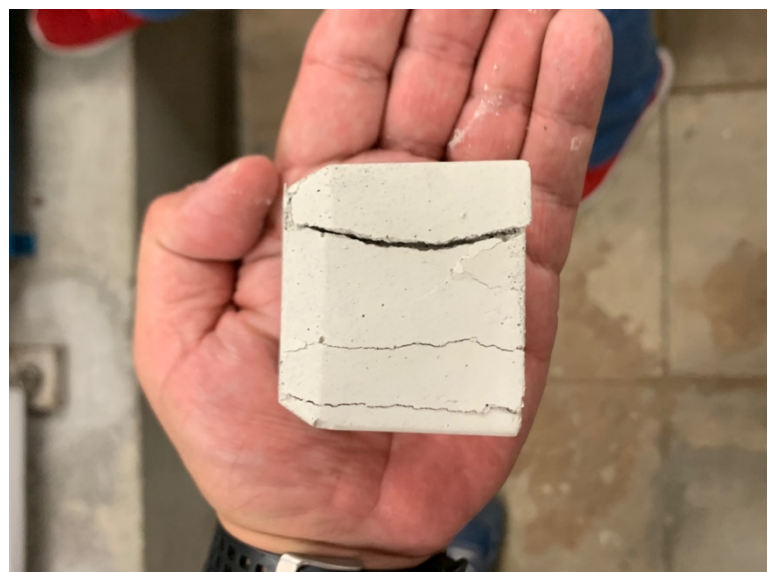


Figure 82. Compressive strength test on sample n°1



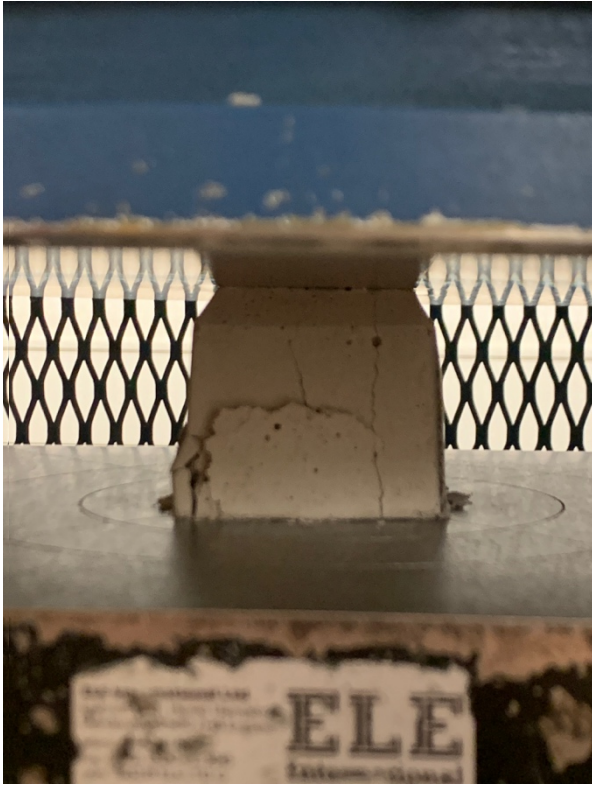


Figure 84. Compressive strength test sample n°2



Figure 83. Compressive strength test sample n°2

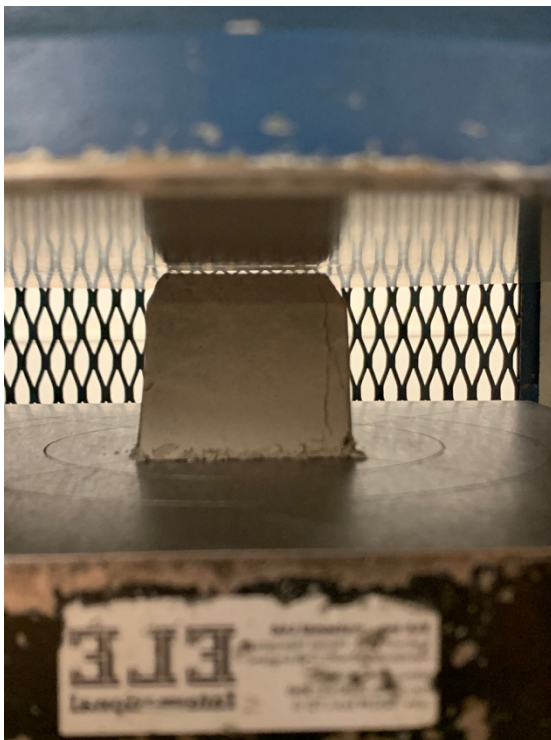


Figure 86. Compressive strength test on sample n°3



Figure 85. Compressive strength on sample n°3

Conclusions

After concluding the compressive strength test on these three samples, it was able to analyse that the sample which resisted the most was sample nº1. It has the right amount of cement and granite powder ratio, which allowed for such a high initial impact resistance. The chosen material for printing the urban bench is sample nº1 with 150g of cement, 350g of granite dust.

The material chosen with the best printing and mechanical properties was the one described above. For future uses of this material the percentages of each were calculated below, this way when using for larger amounts of material and bigger designs the calculations done can be easily sorted with these percentages.

In order to calculate de percentages of each material the following calculations were made:

For 600g of mortar:

350g – Granite dust <0,85mm
150g – Cement
105g – Water

For 1000g of mortar:

700g – Granite dust <0,85mm
300g – Cement
210g – Water

In order to calculate de percentages:

350g granite dust – 600g of mortar
Xg (granite dust) – 1000g of mortar

$$(350 \times 1000) / 600 = \underline{58\% \text{ of Granite dust}}$$

150g cement – 600g mortar
Xg (cement) – 1000g mortar

$$(150 \times 1000) / 600 = \underline{25\% \text{ of cement}}$$

105g water – 600g of mortar
Xg (water) – 1000g of mortar

$$(105 \times 1000) / 600 = \underline{17\% \text{ of water}}$$

Hygrothermal performance of building materials and products - Determination of water absorption

The hygrothermal performance of building materials is used in order to determine the water absorption of a given material. (ISO 15148 - *Capilaridade*, n.d.) In this case the material used was a mixture of cement and granite dust. This test was made in order to determine the water absorption rate of three mixtures with different percentages of granite, cement and water.

The mixture samples are weighed at a rate of 5min, 20min, 1 hour, 2 hours, 4 hours, 8 hours and 24 hours. It's then possible to conclude the absorption rate of each mixture tested.



Figure 88. Materials used to measure the weight of the samples



Figure 87. The three samples tested

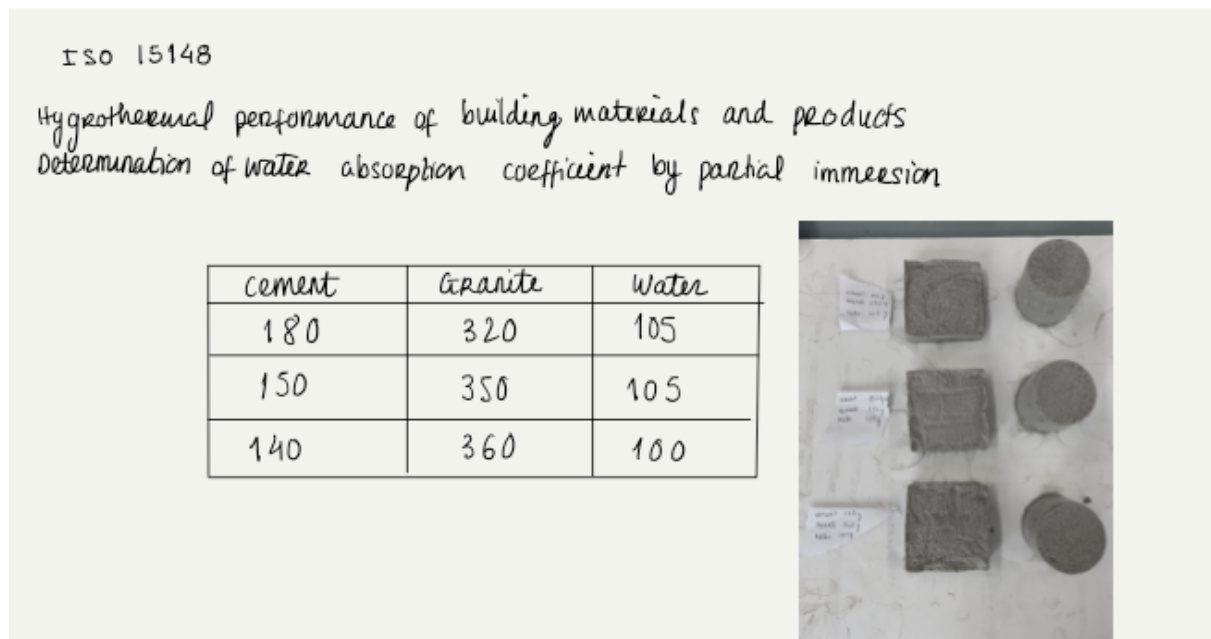


Figure 90. Quantities of cement for the 3 different samples

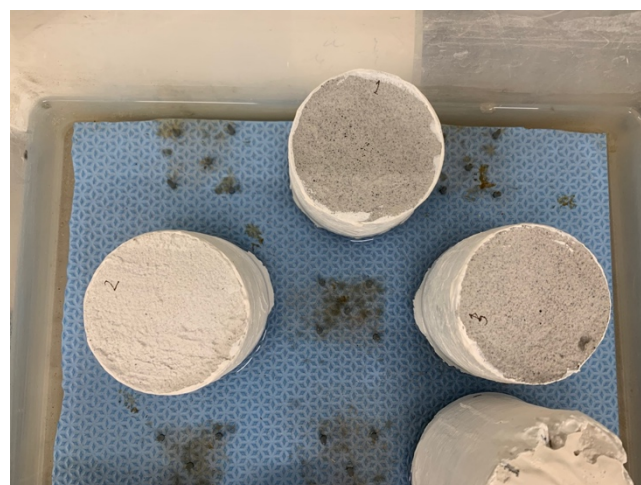


Figure 89. Water Absorption Test

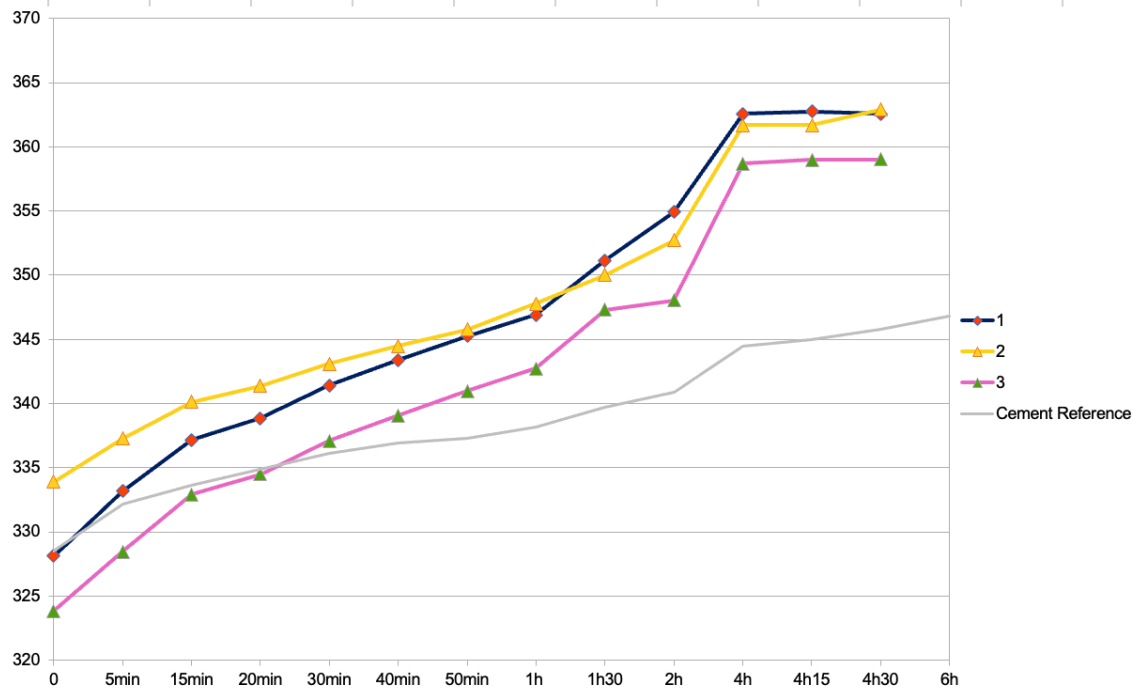


Figure 91. Graphic reflecting the values of the water absorption during 24h

The material that presented less water absorption was material number 3, material number 3 was the one that had the highest percentage of granite and less percentage of cement. Throughout this test it is noticeable that the more amount of granite that there is the less water absorption there will be. Therefore keeping in mind all the other tests that were made, the material chosen to print the final product will be material number 1.

Conclusions

- Temperature affects the consistency of the material
- Necessary to have sufficient binder to hold the granite dust together and the water

After concluding approximately 24 different tests, with different percentages of each component, the mixture that was chosen for printing consists of 150g (cement), 350g (granite) and 105g (water).

Creative Process

The creative process consisted on creating a visual mood board for inspiration for the urban bench. Followed by simple but assertive sketches which helped develop the final product.

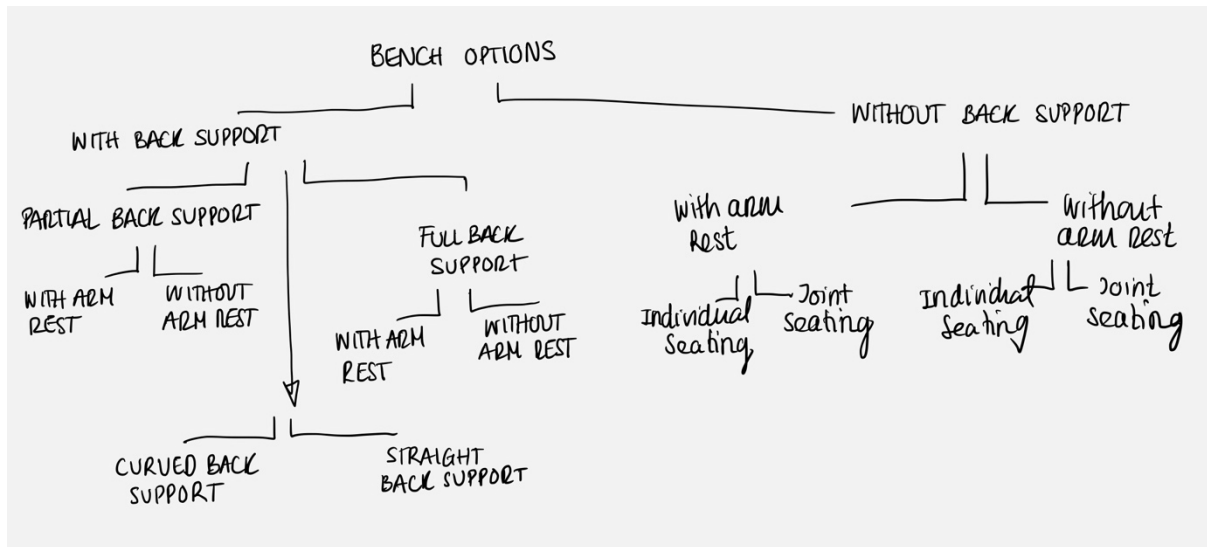
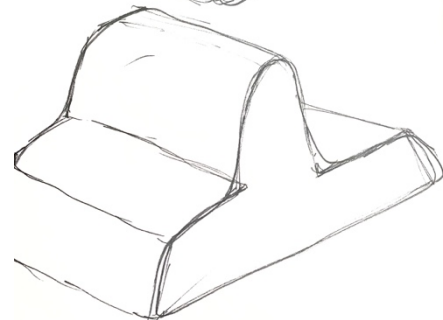
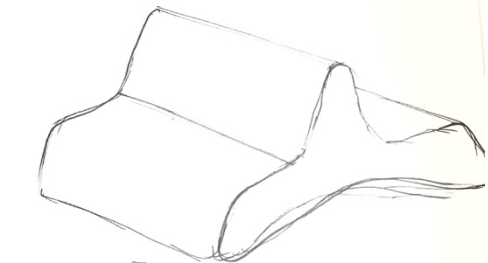
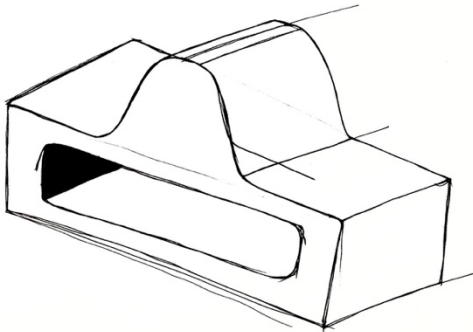
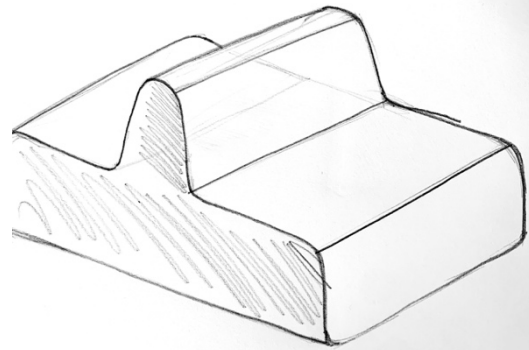
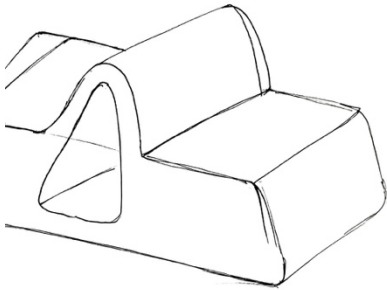
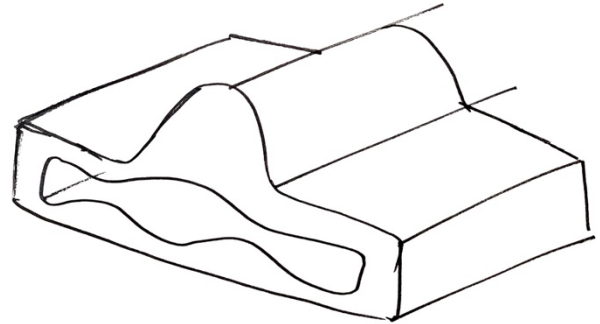
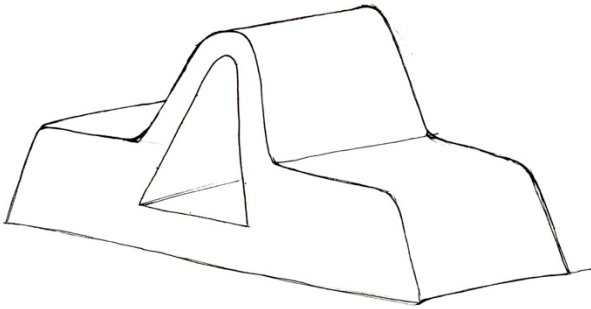


Figure 92. Scheme with variable bench options

So for this product, there were several decisions that had to be made. Such as deciding whether there would be back support or no back support and arm rests or no arm rests. In this case, the product will have back support, but no arm rests.

Initial Sketches



DOUBLE SITTING URBAN BENCH

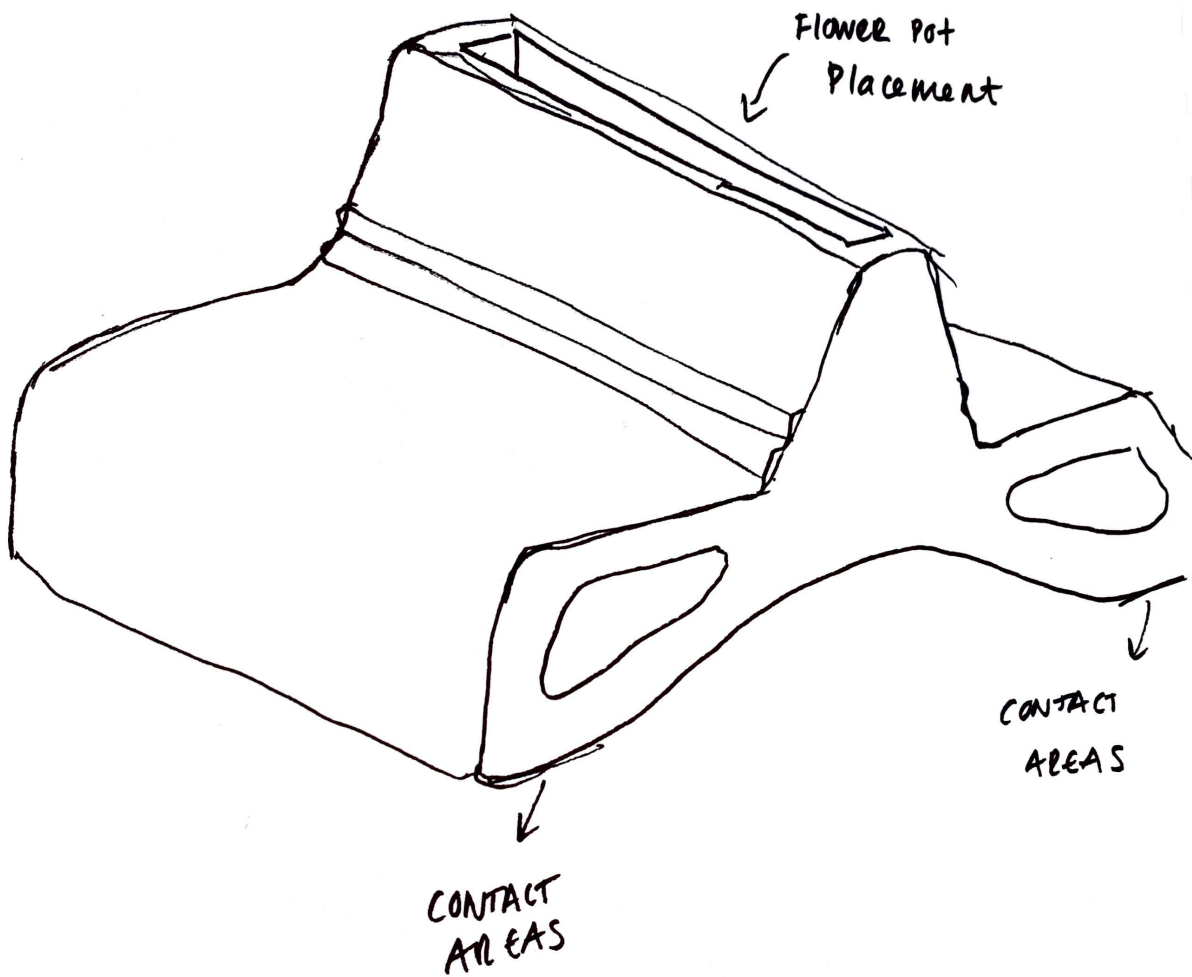


Figure 93. Schematic drawing of urban bench

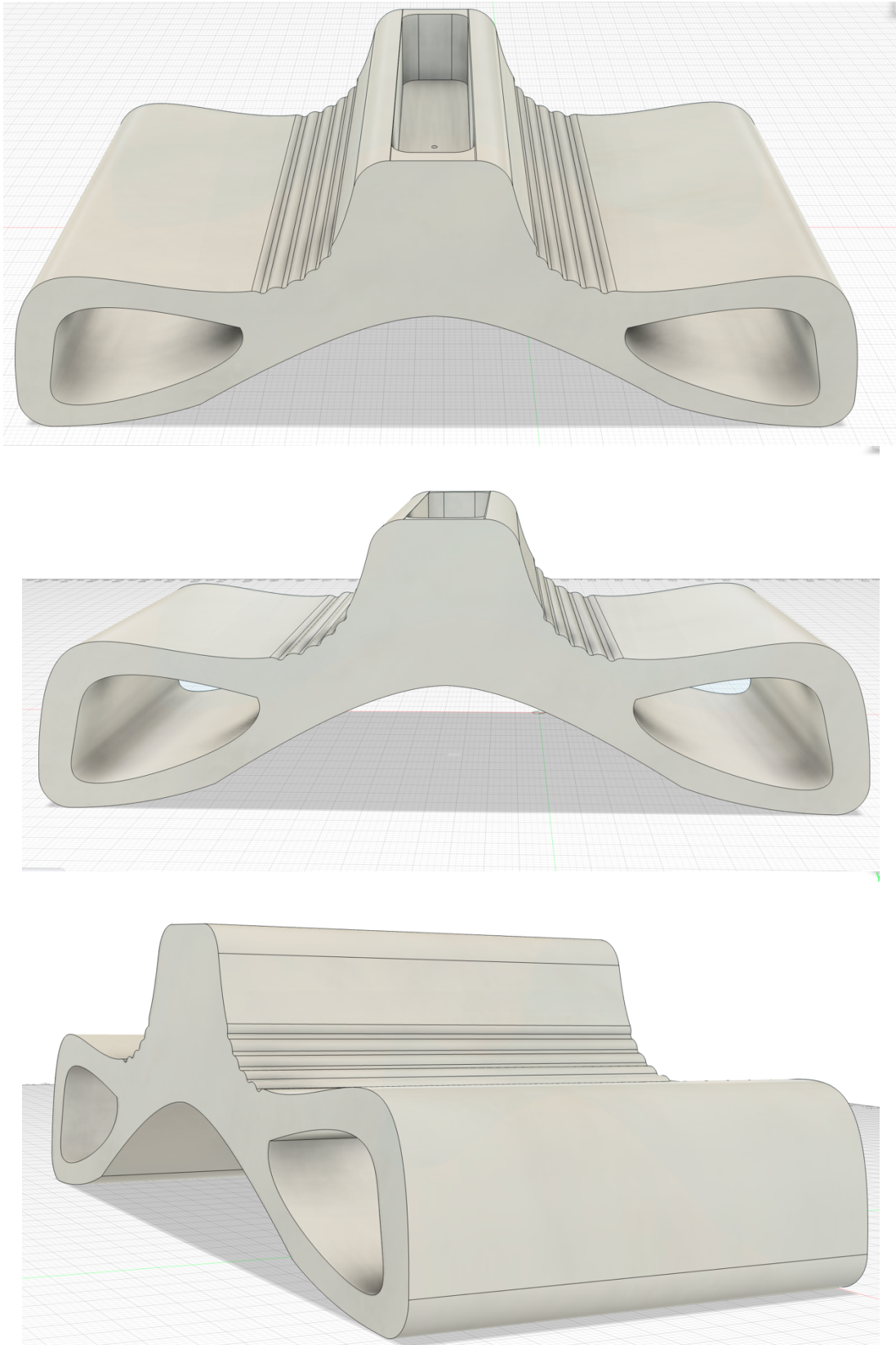


Figure 94. 3D Modelling process

This project was designed for an outdoor urban space, to be used by many people. So the main focus of the design is absence of straight lines, very simple yet minimalistic lines. The empty spaces underneath the seating area were created to remove substantial weight from the bench since this is a concrete and granite bench, both heavy materials, the need to create a product that would use the least amount of both possible was a very important aspect.

The center piece was designed in order to fit both flowers and plants, as it is important to integrate this piece with it's surroundings and instead of just creating a product made of grey cement and granite, the complement with green plants makes it stand out more. Since there will be plants in the middle it was also important to create a place where the water will flow, in order to create less humidity possible inside the bench.

The printing process of the bench was made with clay, due to the small scale of the printer and due to the sharp corners presented in the design of the bench. The material studied during the investigation could only be printed in a larger scale, due to the graininess of the material. So in order to print a small scale of the bench, to comprehend the 3D model, clay was used during the prototyping stage of the project. Images below show and describe how the urban bench prototype was printed.

In order to print given the small nozzle of 4mm some small details presented on the bench had to be removed in order for the software Ultimaker Cura 3D, to be able to analyze the model and create the slices necessary for the printing process.

The program Ultimaker Cura 3D prepares a G Code ready for the printer to be able to read the layers and patterns it will print out.

The printing time was approximately 52min, this was only possible to do the reduction in width of the bench. This prototype aims to show the curvatures created and how the hollowness of the area underneath the sitting zone, allows for a lighter and stable bench production.

So there was another prototype of the bench printed in a PLA printer, which gives the full details and curvatures of the bench. With a PLA printer, the nozzle and filament is much smaller and can attend to these smaller details, as with the 3D Wasp Clay, the nozzle's size is 4mm and the printing area is limited so a simplified version of the bench was created.

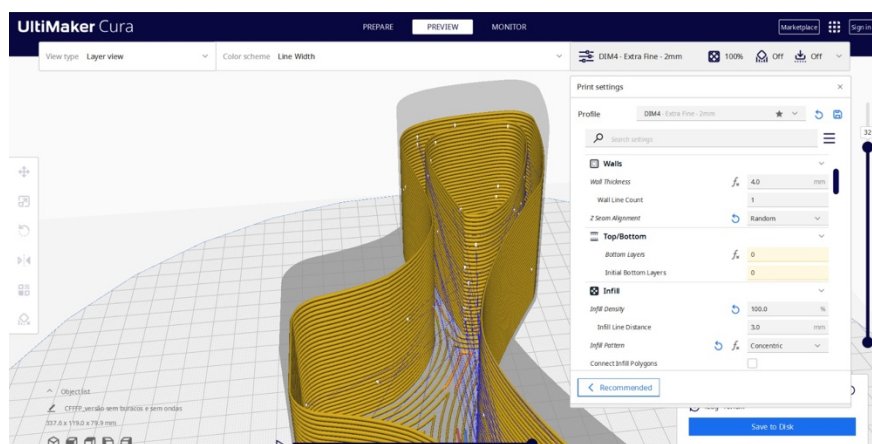


Figure 95. G Code for printed bench

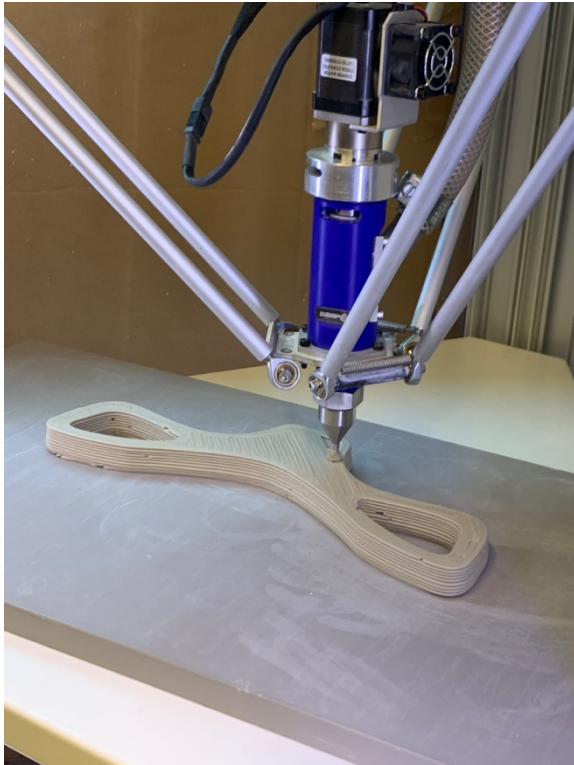


Figure 99. The printing process in Wasp Clay 3d Printer (1)

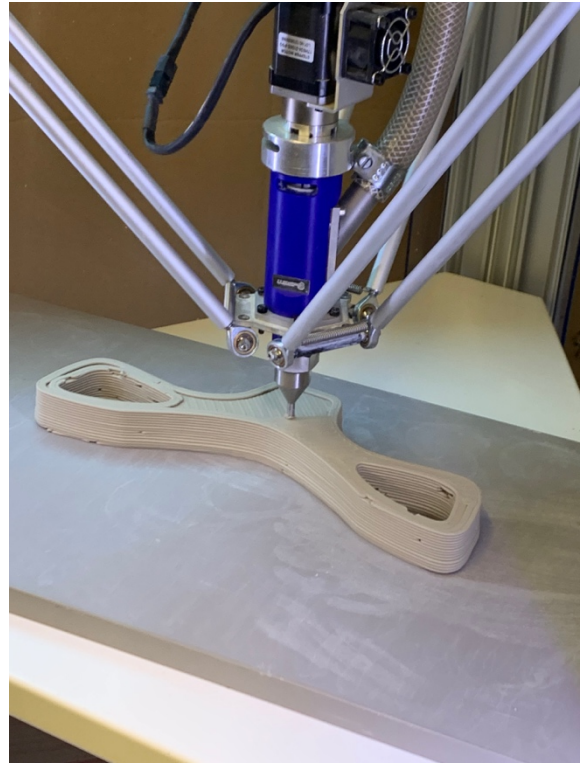


Figure 98. The printing process in Wasp Clay 3d Printer (2)

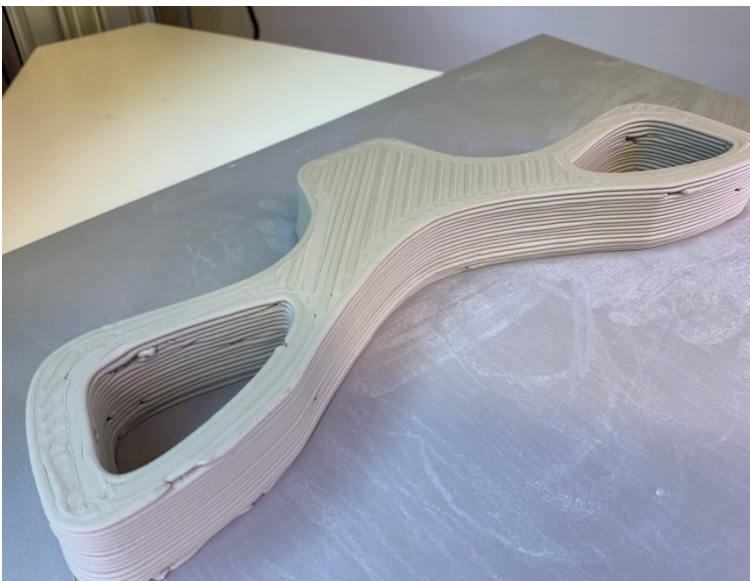


Figure 97. Printing completed



Figure 96. Wasp Clay Printer

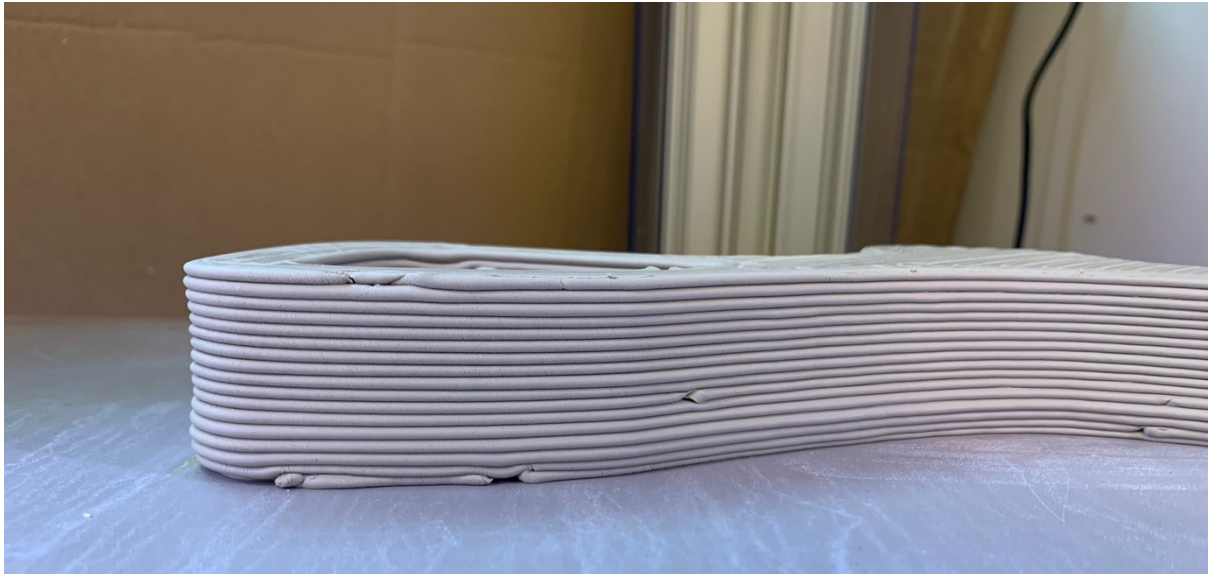


Figure 100. 3d printed layers

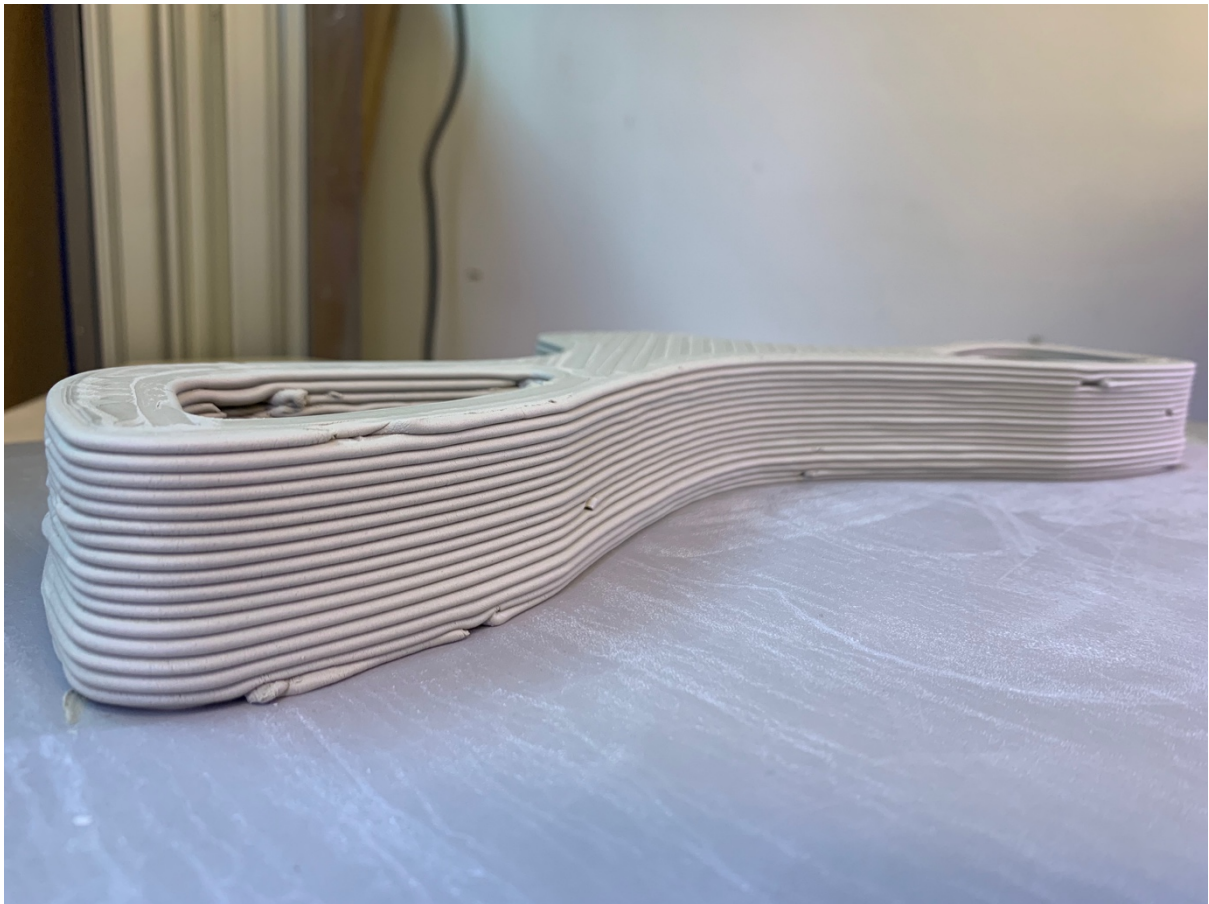


Figure 101. 3d printed layers (2)

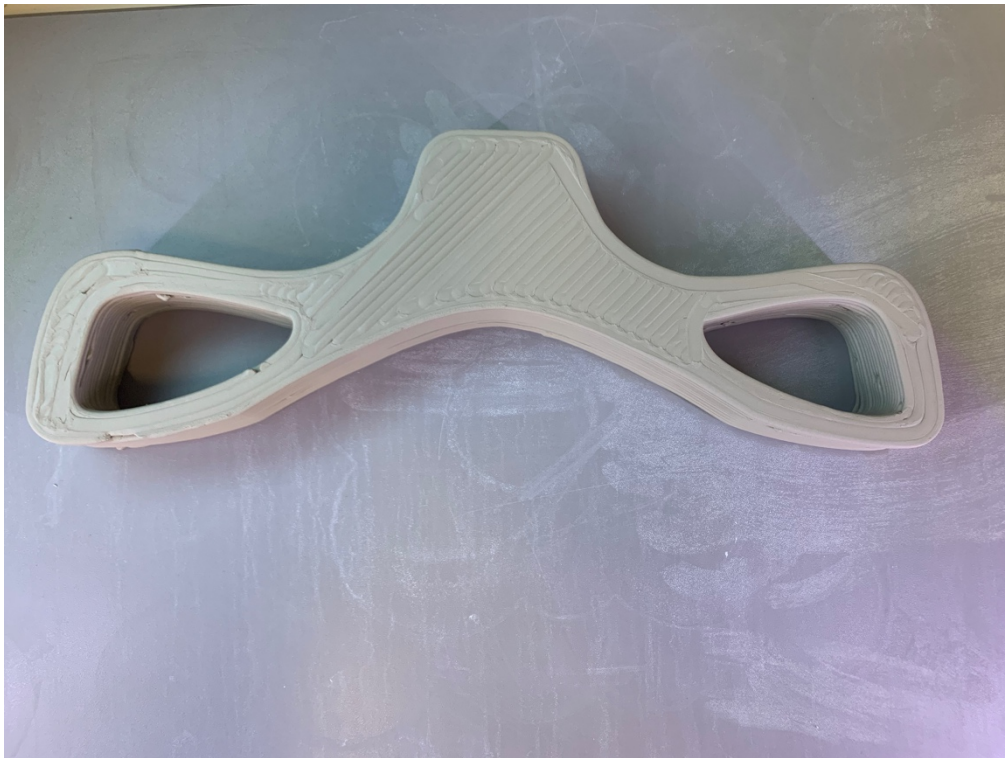


Figure 103. Top view 3D printed bench (1)

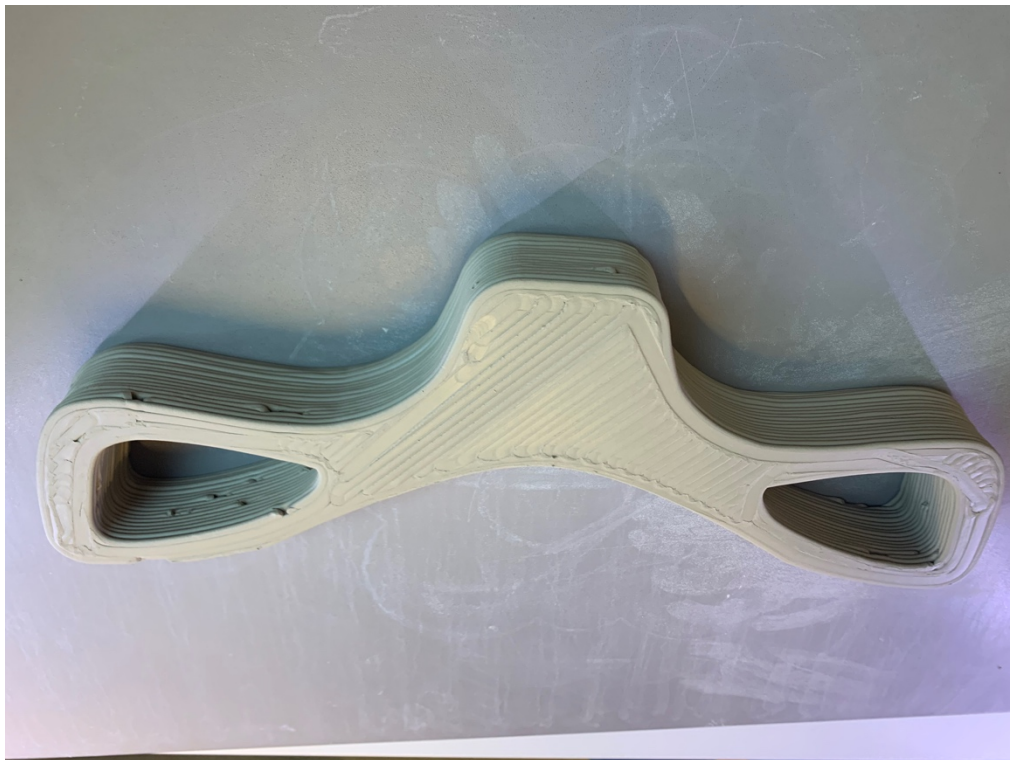


Figure 102. Top view 3D printed bench (2)

3D Modelling

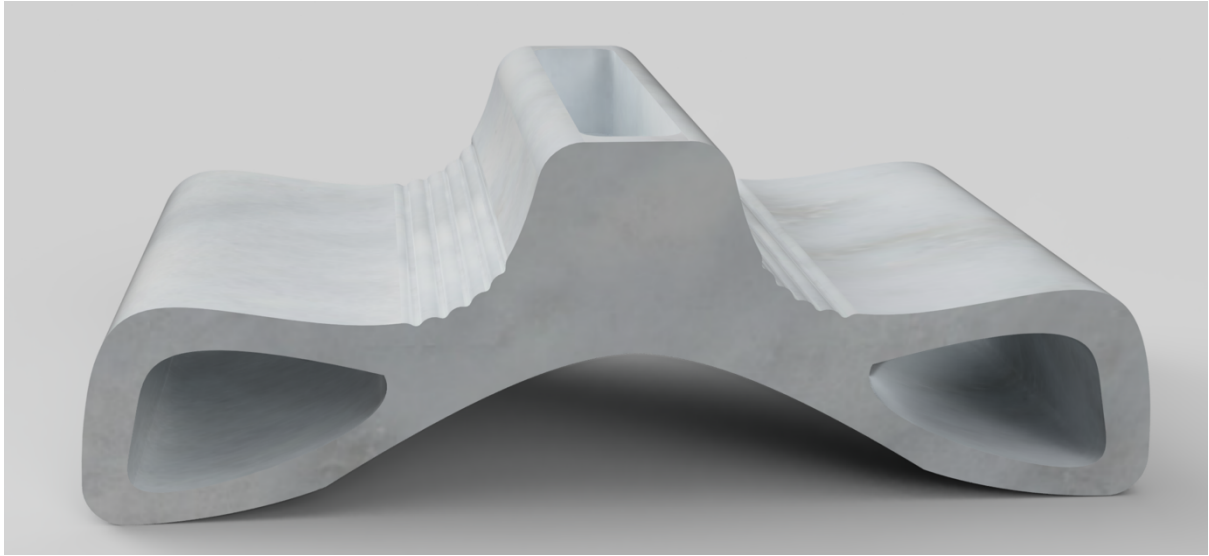


Figure 104. 3D modelling



Figure 105. 3D Modelling

3D Renders

The images below show how the bench is designed and modelled.

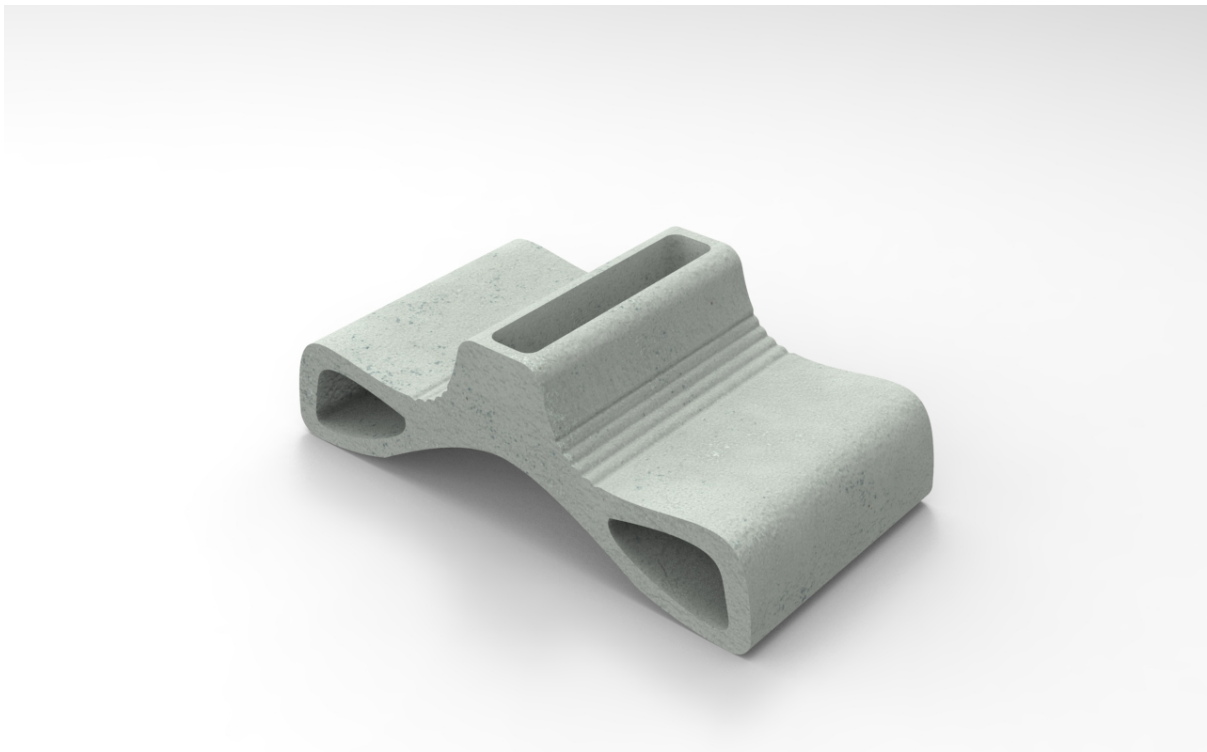


Figure 106. 3D renders (1)



Figure 107. 3D Renders (2)

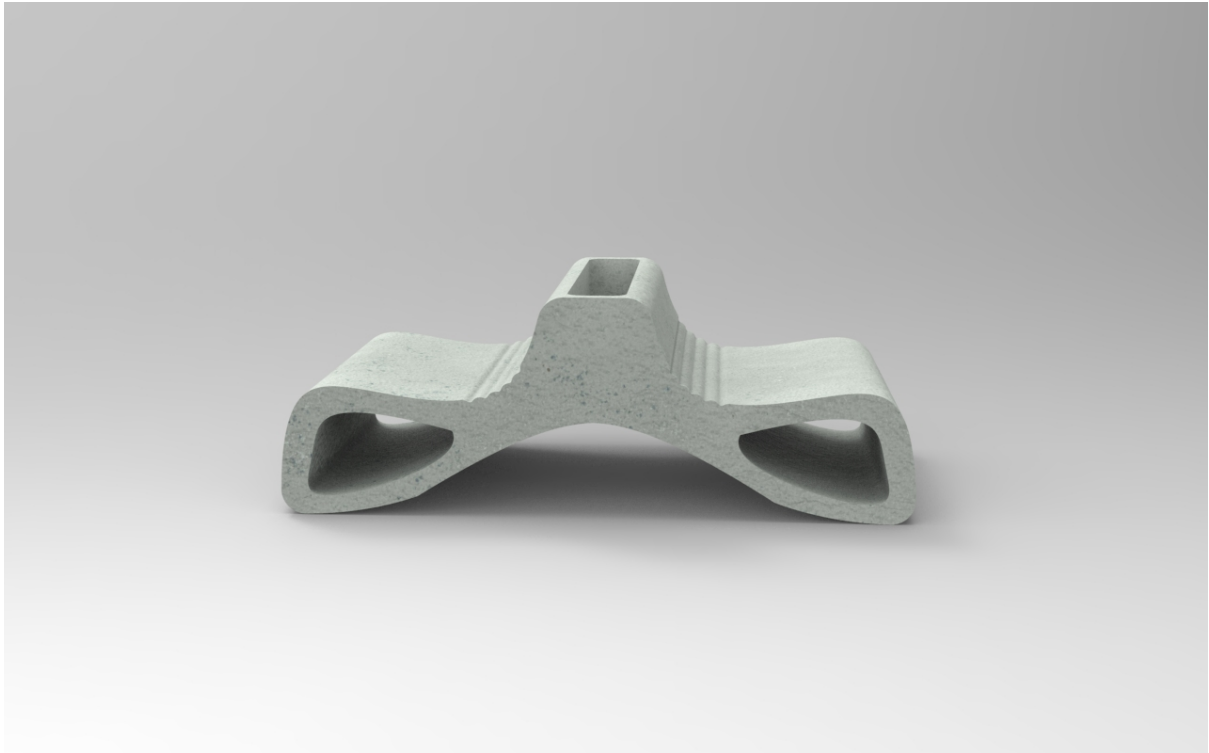


Figure 109. 3D Renders (3)

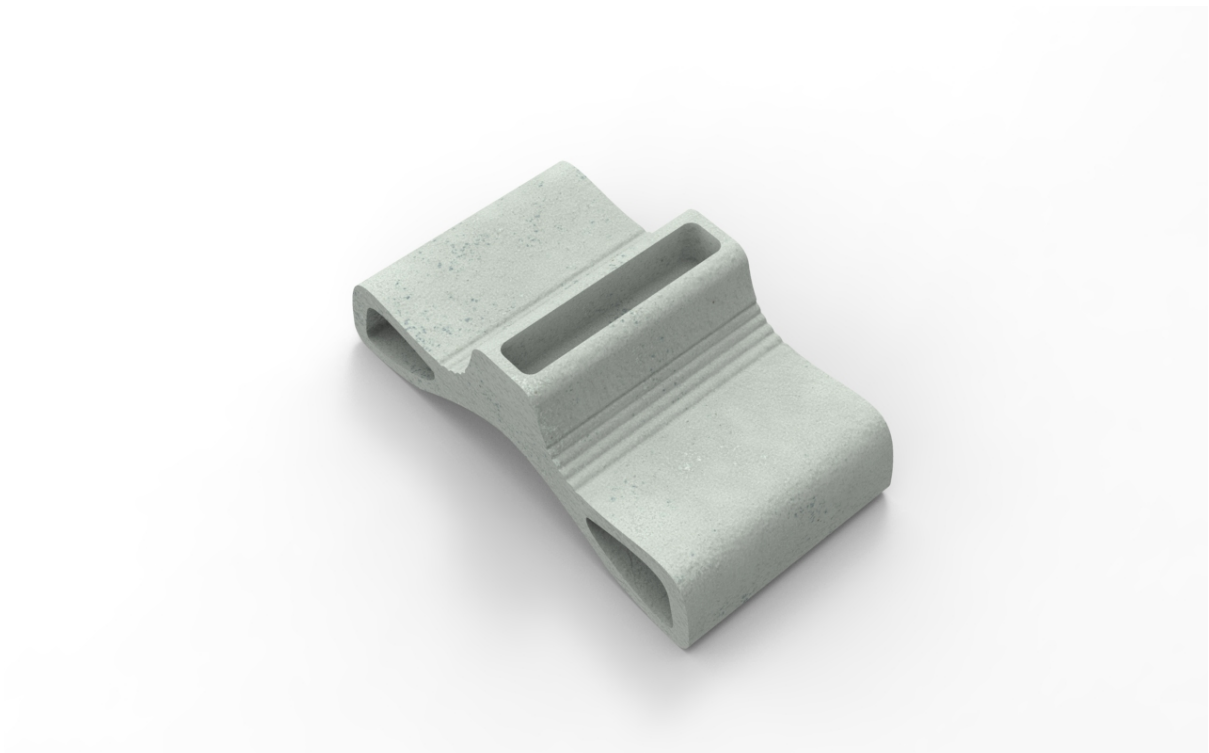


Figure 108. 3D Renders (4)

3D Printed Clay prototype

As described before, the bench was printed using the Delta WASP 40100 CLAY. The bench was printed with clay due to the restrictive characteristics of the printer. The width of the bench had to be reduced in 1/3 of the original length (20cm) at the scale of 1:10, this was due to the large printing time of the Delta WASP 40100. So a smaller prototype was printed, showing the side profile of the bench.



Figure 110. 3D Printed Clay prototype

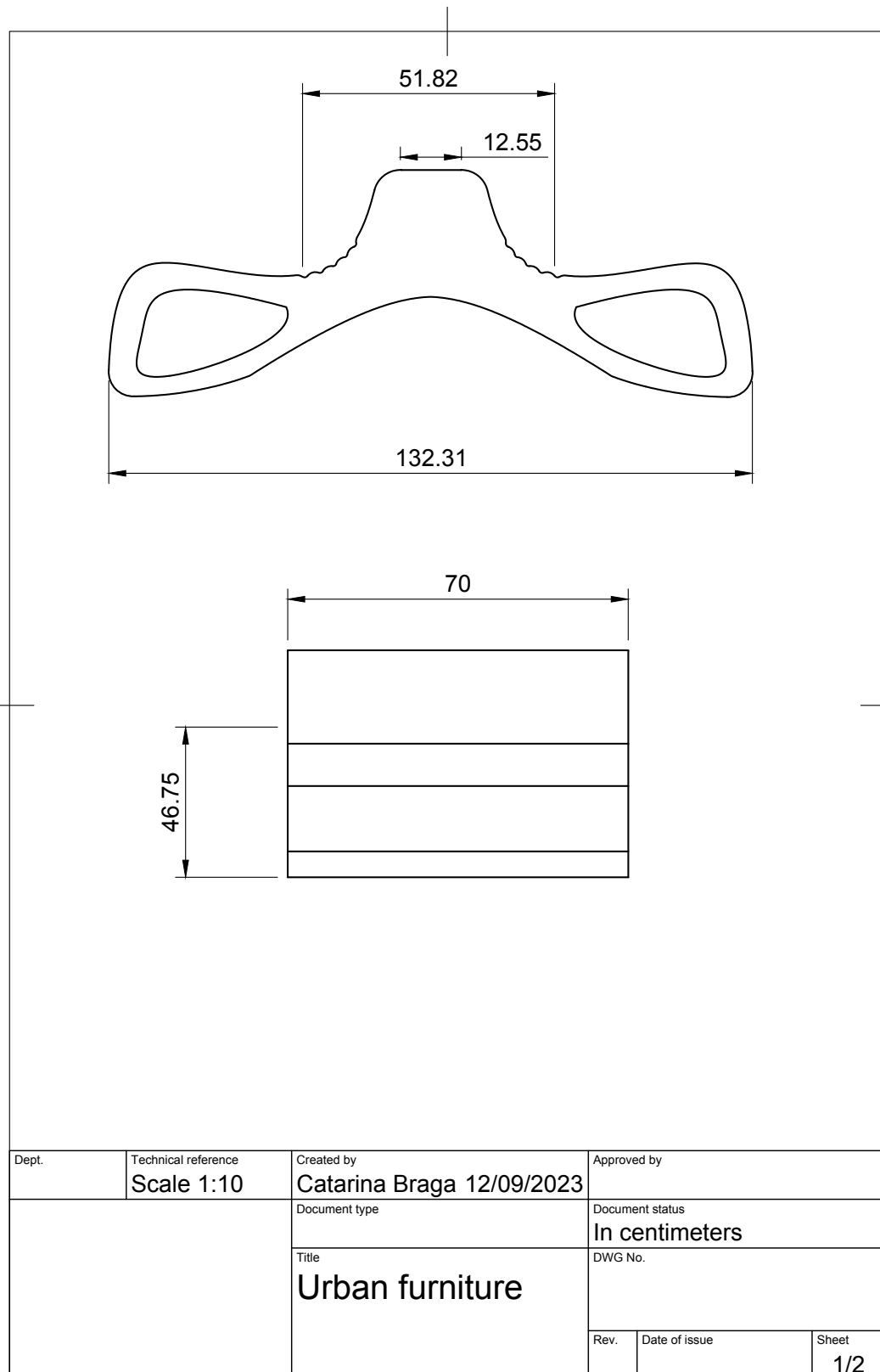
3D Printed PLA prototype

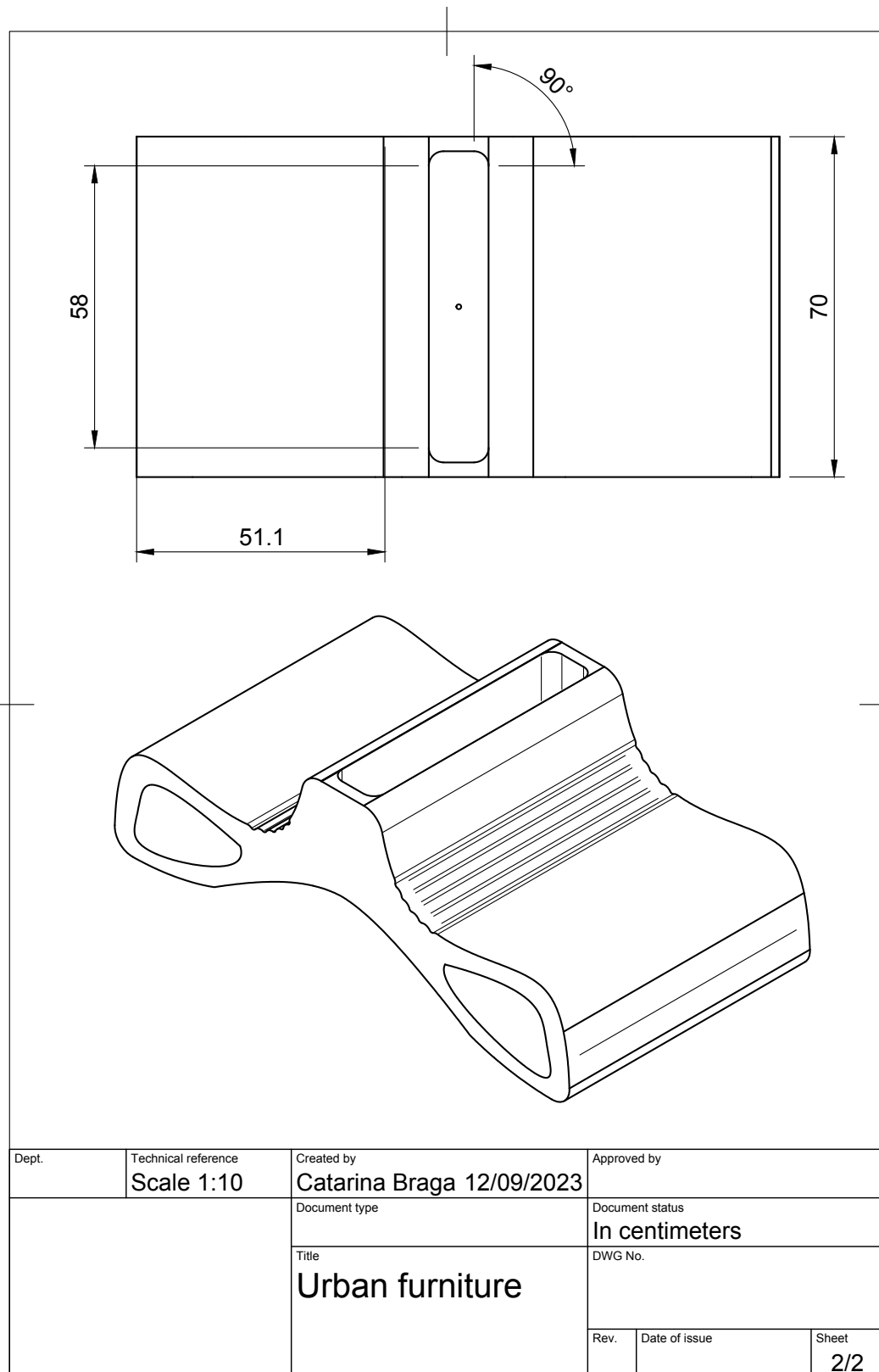
This prototype was printed in PLA at a scale of 1:10. The photographs were taken outside in order to replicate how it would seem at a larger scale when printed.



Figure 111. Photography of 3D printed PLA bench

Technical drawings





Chapter 5

Conclusions

This dissertation emerged with the main goal of creating a new and sustainable printing material to be used in 3D large scale printing. With this in mind, the aim was to find added value to a new material, made of residue and leftover pieces from granite quarries and the already well known material Portland cement.

Portland cement is already a utilized material in 3D printing, and the mechanical properties have been already studied innumerable times. So, by combining granite waste and incorporating it with cement, the results were beyond what was expected. Different types of 3D printing were explored, as well as different ways of creating a more sustainable mortar and the characteristics required in order to be printable.

By studying different mortar compositions, through trial and error, it was able to achieve a well performing mortar. All the mortars had to undergo tests such as, extrudability tests, slump tests, printability tests, workability tests and buildability tests, where the capability of overlaying a certain amount of layers was tested. In terms of mechanical tests two different tests were concluded, the compression tests and the hygrothermal capability of the material was tested.

In the end of the testing process, the material that had the best results had a mixture of 58% granite dust, 25% cement and 17% water.

After concluding the experimental tests of the mortar, the design of the bench was the next step, in order to achieve a design that would favor the materials being used. The creative process was completed, beginning with a moodboard that would later on inspire the flow and direction of the urban furniture that was designed.

The main idea was to create a fluid and minimalistic design that would easily fit in almost every environment. The centrepiece incorporated in the centre of the bench, has the purpose of fitting plants and flowers. When adding both cement (white) and granite dust (grey), the chromatic palette becomes a grey tone. So when combining, the grey mortar and the green from the plants, the results are a more natural and balanced product, that can be placed in several versatile environments.

This design ended up being printed in clay, due to the limitations of the printer used at the faculty of engineering.

The main advantages of 3D printing at a large scale is the ability for customization according to each clients need, reducing the need for creation of pre-fabricated moulds. This thesis could be an asset in the creation of 3D design pieces using waste. However, this research has left much to be explored and the next chapter will set out some limitations and future proposals.

Limitations and perspective of future work

Even though the knowledge acquired was valuable, there were aspects left to discover and investigate.

The printing of the bench on a larger scale, at a 1:2 scale, would have been valuable to study, in order to fully comprehend the limitations of a 3D printed urban bench. Having people test out the ergonomics and comfort of the bench, would have been a big step in the development of the material and the design.

The mortar developed, didn't undergo all the tests that could have been done. As the project had a small time span, compared to some durability tests that last up to months.

In future works in this area, the further development of this material based on granite dust and cement would be beneficial for the further creation of a commercially available material, compatible with many large scale 3D printers.

Although 3D printing presents many advantages, in terms of geometrical shapes, the adherence between layers should also be studied. Due to the nature of this masters degree, which is design, some aspects weren't as deepened as they could have been, although the creation of a new material was very important, the design aspect was also of big importance.

Attachments

Samples

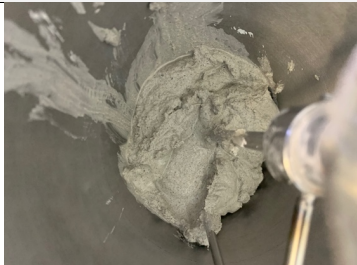


3	Granite dust <0.85mm	500	1. Add all materials to the mixer	
	Granite dust <0.75mm	200	2. Wait 4min until mixture is ready	
	Cement	250	3. Insert mixture into silicone funnel	
	Water	200	4. Proceed to make small samples of material	
Conclusion	Mixture did not extrude well through silicone funnel. Needed more binder and water to be able to extrude correctly.			
NOTES:				
More photography: Comparison side by side of three samples				
				

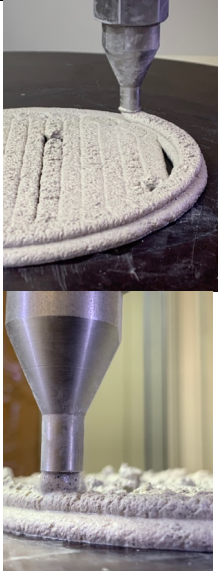


RESEARCH PROJECT		3D printing with granite based cement				
SESSION TITLE		Experimenting with percentages of granite powder			CODE	
RESPONSIBLE		João Teixeira			DATE	25/05/23
EXPERIMENTAL OBJECTIVES		Achieving an extrudable mortar made of granite powder and cement				
3D MODEL DATA				CONDITIONS		
Number of samples		3		Hour of the day		14h00
Sample dimension				LAB Temperature (°C)		26.3
Equipments				Relative Humidity (%)		50
MIX DESIGN						
Mixture	Materials	Quantities (g)	Activities	Photography		
1	Granite dust <0.85mm	400	1. Add all materials to the mixer			
	Granite dust <0.75mm	350	2. Wait 4min until mixture is ready			
	Cement	250	3. Insert mixture into silicone funnel			
	Water	232	4. Proceed to make small samples of material			
Conclusion	Too much water added. Granite powder needs less amount of water than marble powder does. Needed to add more binder (cement).					
2	Granite dust <0.85mm	400	1. Add all materials to the mixer			
	Granite dust <0.75mm	350	2. Wait 4min until mixture is ready			
	Cement	250	3. Insert mixture into silicone funnel			
	Water	205	4. Proceed to make small samples of material			
Conclusion	Consistency of material was almost good, needed to add more cement to guarantee that the water is absorbed and doesn't sit on top.					

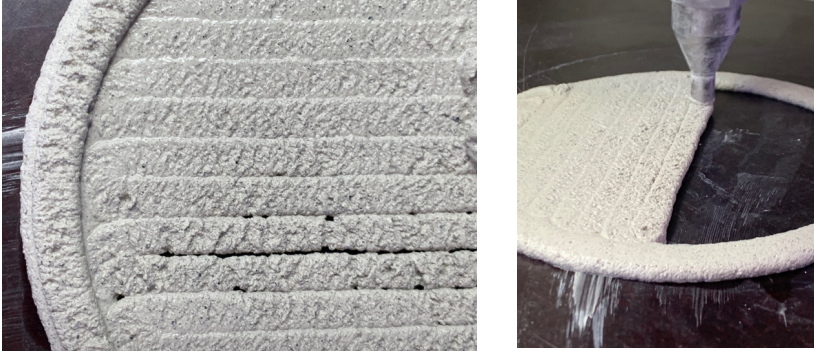


RESEARCH PROJECT		3D printing with granite based cement			
SESSION TITLE		Experimenting with percentages of granite powder		CODE	
RESPONSIBLE		João Teixeira		DATE	26/05/23
EXPERIMENTAL OBJECTIVES		Achieving an extrudable mortar made of granite powder and cement			
3D MODEL DATA			CONDITIONS		
Number of samples		2	Hour of the day		14h00
Sample dimension			LAB Temperature (°C)		23.9
Equipments			Relative Humidity (%)		41
MIX DESIGN					
Mixture	Materials	Quantities (g)	Activities	Photography	
1	Granite dust <0.85mm	500	1. Add all materials to the mixer		
	Granite dust <0.75mm	200	2. Wait 4min until mixture is ready		
	Cement	300	3. Insert mixture into silicone funnel		
	Water	205	4. Proceed to make small samples of material		
Conclusion	Too much granite powder <0.85mm. Needed more smaller powder to allow the mortar to be extruded.				

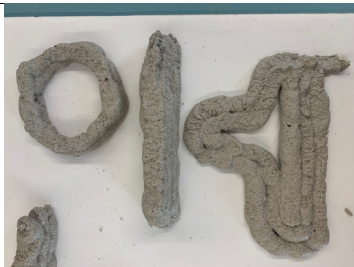


2	Granite dust <0.85mm	300	1. Add all materials to the mixer	
	Granite dust <0.75mm	350	2. Wait 4min until mixture is ready	
	Cement	300	3. Insert mixture into silicone funnel	
	Water	245	4. Proceed to make small samples of material	
	Marble powder	200		
Conclusion	Due to the lack of granite powder it was necessary to add more marble powder, and since it was in more abundance it was used to compensate the lack of granite powder. The results were favorable. The mixture was able to extrude.			
NOTES:				



More photography:			
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RESEARCH PROJECT		3D printing with granite based cement			
SESSION TITLE		Experimenting with percentages of granite powder		CODE	
RESPONSIBLE				DATE	16/06/23
EXPERIMENTAL OBJECTIVES		Achieving an extrudable mortar made of granite powder and cement			
3D MODEL DATA			CONDITIONS		
Number of samples		4	Hour of the day		14h00
Sample dimension			LAB Temperature (°C)		26.5
Equipment			Relative Humidity (%)		53
MIX DESIGN					
Mixture		Materials	Quantities (g)	Activities	Photography
1		Granite dust <0.85mm	300	1. Add all materials to the mixer	
		Cement	150	2. Insert mixture into silicone funnel	
		Water	100	3. Proceed to make small samples of material	
Conclusion					
2		Granite dust <0.85mm	300	1. Add all materials to the mixer	
		Cement	200	2. Insert mixture into silicone funnel	
		Water	110	3. Proceed to make small samples of material	
Conclusion					
3		Granite dust <0.85mm	300	1. Add all materials to the mixer	
		Cement	200	2. Insert mixture into silicone funnel	
		Water	105	3. Proceed to make small samples of material	



4	Granite dust <0.85mm	300	1. Add all materials to the mixer	
	Cement	200	2. Insert mixture into silicone funnel	
	Water	120	3. Proceed to make small samples of material	
	Pigment	3	4.	
Conclusion				

NOTES:

More photography:





RESEARCH PROJECT		3D printing with granite based cement			
SESSION TITLE		Experimenting with percentages of granite powder		CODE	
RESPONSIBLE				DATE	22/06/23
EXPERIMENTAL OBJECTIVES		Achieving an extrudable mortar made of granite powder and cement			
3D MODEL DATA			CONDITIONS		
Number of samples		3	Hour of the day		11h00
Sample dimension			LAB Temperature (°C)		28º
Equipment			Relative Humidity (%)		50
MIX DESIGN					
Mixture	Materials	Quantities (g)	Activities	Photography	
1	Granite dust <0.85mm	300	1. Add all materials to the mixer		
	Cement	200	2. Insert mixture into silicone funnel		
	Water	110	3. Proceed to make small samples of material		
Conclusion	The initial height with the mixture inside the cylinder was 3,3cm. After removed the cylinder the height was 2,9cm.				
2	Granite dust <0.85mm	290	1. Add all materials to the mixer		
	Cement	210	2. Insert mixture into silicone funnel		
	Water	110	3. Proceed to make small samples of material		
Conclusion					
3	Granite dust <0.85mm	300	1. Add all materials to the mixer		
	Cement	220	2. Insert mixture into silicone funnel		
	Water	110	3. Proceed to make small samples of material		
Conclusion					



RESEARCH PROJECT		3D printing with granite based cement			
SESSION TITLE		Experimenting with percentages of granite powder		CODE	
RESPONSIBLE				DATE	23/06/23
EXPERIMENTAL OBJECTIVES		Achieving an extrudable mortar made of granite powder and cement			
3D MODEL DATA			CONDITIONS		
Number of samples		3	Hour of the day		12h
Sample dimension			LAB Temperature (°C)		28º
Equipment			Relative Humidity (%)		55
MIX DESIGN					
Mixture	Materials	Quantities (g)	Activities	Photography	
1	Granite dust <0.85mm	280	1. Add all materials to the mixer		
	Cement	220	2. Insert mixture into silicone funnel		
	Water	117	3. Proceed to make small samples of material		
Conclusion	The initial height with the mixture inside the cylinder was 3,3cm. After removed the cylinder the height was 2,9cm.				
2	Granite dust <0.85mm	290	1. Add all materials to the mixer		
	Cement	210	2. Insert mixture into silicone funnel		
	Water	108	3. Proceed to make small samples of material		
Conclusion					
3	Granite dust <0.85mm	300	1. Add all materials to the mixer		
	Cement	200	2. Insert mixture into silicone funnel		
	Water	107	3. Proceed to make small samples of material		
Conclusion					



4	Granite dust <0.85mm	310	1. Add all materials to the mixer	
	Cement	190	2. Insert mixture into silicone funnel	
	Water	105	3. Proceed to make small samples of material 4.	
Conclusion				

NOTES:

More photography:

Bibliography

- 3D concrete printers* | CyBe Construction. (n.d.). Retrieved April 13, 2023, from <https://cybe.eu/3d-concrete-printing/printers/>
- 3D Printing in Construction: Growth, Benefits, and Challenges*. (n.d.). Retrieved May 7, 2023, from <https://constructionblog.autodesk.com/3d-printing-construction/>
- 3D Printing In Construction: How Does It Work* | CEMEX Ventures. (n.d.). Retrieved June 16, 2023, from <https://www.cemexventures.com/3d-printing-in-construction/>
- Anell, L. H. (n.d.). *Concrete 3d printer*.
- Barroso, M. P., Arezes, P. M., Da Costa, L. G., & Miguel, A. S. (2005). Anthropometric study of Portuguese workers. *International Journal of Industrial Ergonomics*, 35(5), 401–410. <https://doi.org/10.1016/j.ergon.2004.10.005>
- Bolkaner, M. K., İnançoğlu, S., & Asilsoy, B. (2019). A Study on Urban Furniture: Nicosia Old City. *European Journal of Sustainable Development*, 8(2), 1. <https://doi.org/10.14207/ejsd.2019.v8n2p1>
- Bos, F., Wolfs, R., Ahmed, Z., & Salet, T. (2016). Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. *Virtual and Physical Prototyping*, 11(3), 209–225. <https://doi.org/10.1080/17452759.2016.1209867>
- Cement | Definition, Composition, Manufacture, History, & Facts* | Britannica. (n.d.). Retrieved April 20, 2023, from <https://www.britannica.com/technology/cement-building-material#ref276856>
- Chapman, A. (2022). *The complete history of 3D printing*. <https://ultimaker.com/learn/history-of-3d-printing>
- Circle Patterned Banner Royalty Free Stock Vectors* | rawpixel. (n.d.). Retrieved June 3, 2023, from <https://www.rawpixel.com/board/1212803/circle-patterned-banner-royalty-free-stock-vectors>
- Civil engineering construction expertise for Concrete 3D Printing* | LinkedIn. (n.d.). Retrieved April 21, 2023, from <https://www.linkedin.com/pulse/concreative-civil-engineering-construction-expertise-concrete/>
- Collection of benches woven in 3D-printed concrete*. (n.d.). Retrieved April 24, 2023, from <https://www.dezeen.com/2018/08/27/3d-printing-woven-concrete-benches-xtreee-studio-75-design/>
- Colour of the month White - July — Suna & Toast - suna & toast*. (n.d.). Retrieved June 3, 2023, from <https://suna-hasan-8f2n.squarespace.com/blog/2017/5/30/www.sunaandtoast.com?epik=dj0yJnU9VGlxNHhOYm9JUmp0aGJ0LXo2NGJoR2JyOUw0QjEyNWlmcD0wJm49amdIYW80dFFISDZFMUd4NldacG1jdyZ0PUFBQUFBR1I3U18w>
- Concrete Slump Tests - Measuring the Workability of Concrete* | Total Concrete. (n.d.). Retrieved June 9, 2023, from <https://www.totalconcrete.co.uk/news/concrete-slump-tests-measuring-the-workability-of-concrete/#>
- CONTOUR PIPELINE - HagenHinderdael*. (n.d.). Retrieved April 26, 2023, from <https://hagenhinderdael.com/installations/pipeline/>

- D. Hwang, & B. Khoshnevis. (n.d.). *An innovative construction process-contour crafting*.
- El-Sayegh, S., Romdhane, L., & Manjikian, S. (2020). A critical review of 3D printing in construction: benefits, challenges, and risks. In *Archives of Civil and Mechanical Engineering* (Vol. 20, Issue 2). Springer.
<https://doi.org/10.1007/s43452-020-00038-w>
- Fly ash 3D printed concrete bench - Core77*. (n.d.). Retrieved April 25, 2023, from [https://www.core77.com/projects/35571/Fly-ash-3D-printed-Garden Pavilion](https://www.core77.com/projects/35571/Fly-ash-3D-printed-Garden-Pavilion) | *Gestalten*. (n.d.). Retrieved June 3, 2023, from <https://news.gestalten.com/community/blackboard/garden-pavilion>
- Gebhardt, A., & Fateri Hochschule Aalen, M. (2013). *3D Printing and it's applications*. <https://www.researchgate.net/publication/267433899>
- Granite: Igneous Rock - Pictures, Definition & More*. (n.d.). Retrieved April 20, 2023, from <https://geology.com/rocks/granite.shtml>
- Hsiao, S. W., & Chou, J. R. (2004). A creativity-based design process for innovative product design. *International Journal of Industrial Ergonomics*, 34(5), 421–443.
<https://doi.org/10.1016/j.ergon.2004.05.005>
- INE (Instituto Nacional de Estatística). (2001). *Anuário de Estatística de 2001*.
- ISO 15148 - *Capilaridade*. (n.d.).
- Khoshnevis, B. (n.d.-a). *A Impressora 3D que Constrói Casas* | *EngenhariaCivil.comsafari-web-extension://04496166-0D6E-4EDC-8558-4EE4E6A0AB55/results/0*. Retrieved February 16, 2023, from <https://www.engenhariacivil.com/impressora-3d-constroi-casas>
- Khoshnevis, B. (n.d.-b). *Who Invented the 3D Printer - contour crafting*. Contour Crafting; Behrokh Khoshnevis; University of Southern California. Retrieved February 16, 2023, from <https://www.invent.org/inductees/charles-hull>
- Kumar Mehta, P. (n.d.). *Concrete international / OCTOBER 2001* 61.
- Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Gibb, A. G. F., & Thorpe, T. (2012). Mix design and fresh properties for high-performance printing concrete. *Materials and Structures/Materiaux et Constructions*, 45(8), 1221–1232.
<https://doi.org/10.1617/s11527-012-9828-z>
- Lim, S., Buswell, R., Le, T., Wackrow, R., Austin, S., Gibb, A., & Thorpe, T. (n.d.). *DEVELOPMENT OF A VIABLE CONCRETE PRINTING PROCESS*.
<https://dspace.lboro.ac.uk/>
- Malaeb, Z., Alsakka, F., & Hamzeh, F. (2019). *3D Concrete Printing: Machine Design, Mix Proportioning, and Mix Comparison Between Different Machine Setups*. <https://doi.org/10.1016/B978-0-12-815481-6.00006-3>
- Manuel, J., Carvalho, F., Carvalho, C., Vitor, J., Lisboa, V., Carvalho, J. M. F., Carvalho, C. I., Lisboa, J. v, Moura, A. C., & Leite, M. M. (n.d.). *Portuguese ornamental stones*. <https://www.researchgate.net/publication/237008021>
- Matos, A. M., Pêgo, P., Rangel, B., & Alves, J. L. (2022). *Waste Marble Powder Valorisation in 3D-Printable Cement-Based Composites*. 62.
<https://doi.org/10.3390/materproc2022008062>
- Nerella, V. N., Krause, M., & Mechtcherine, V. (2020). Direct printing test for buildability of 3D-printable concrete considering economic viability. *Automation in Construction*, 109. <https://doi.org/10.1016/j.autcon.2019.102986>

- New York Stone | *Bianco Estremoz Marble, Marble from Portugal*. (n.d.). Retrieved March 21, 2023, from <https://www.newyorkstone.com/stone/bianco-estremoz>
- Osinski, G. R., Grieve, R. A. F., Bleacher, J. E., Neish, C. D., Pilles, E. A., & Tornabene, L. L. (2018). Igneous rocks formed by hypervelocity impact. *Journal of Volcanology and Geothermal Research*, 353, 25–54.
<https://doi.org/10.1016/J.JVOLGEORES.2018.01.015>
- Park furniture on Behance*. (n.d.). Retrieved June 3, 2023, from <https://www.behance.net/gallery/365164/Park-furniture>
- Please.Dont.Touch on Instagram: “Cloveleaf sofa by Verner Panton . #pleasedonttouch #vernerpanton #furniture #furnituredesign #interiordesign.”* (n.d.). Retrieved June 3, 2023, from <https://www.instagram.com/p/B2XV3HQB-53/?igshid=f8npzjmszsjzw&epik=dj0yJnU9MEQ5M2I5N2t2NU9EckNrRGJuYXI4SDVmczJ3T2o1d1lmcD0wJm49XzA5YUZxXzROVWhxOHNMZW84YW5EQSZ0PUFBQUFBFR1I3U21r>
- Quirk, V. (n.d.). *First 3D Printed House to Be Built In Amsterdam* | *ArchDaily*. Retrieved March 7, 2023, from <https://www.archdaily.com/491666/first-3d-printed-house-to-be-built-in-amsterdam>
- Rezende Leite, F., Lúcia Pereira Antunes, M., Aparecido Lopes Silva, D., Cipriano Rangel, E., & Cristino da Cruz, N. (2021). An ecodesign method application at the experimental stage of construction materials development: A case study in the production of mortar made with ornamental rock wastes. *Construction and Building Materials*, 293, 123505.
<https://doi.org/10.1016/J.CONBUILDMAT.2021.123505>
- Sá Caetano, P., Ribeiro, T., Costa, C., & Vendas, D. (2020). Marble Quarry Waste Rock Piles and Evaluation of Their Reprocessing Potential for Lime and Cement Production (Marble Zone, Alentejo, Portugal). *KnE Engineering*.
<https://doi.org/10.18502/KEG.V5I4.6807>
- Secrets Itinerary: Top Places In The Douro Valley*. (n.d.). Retrieved June 3, 2023, from <https://secretsfromportugal.com/secrets-itinerary-top-places-in-the-douro-valley/>
- Shamsabadi, E. A., Ghalehnovi, M., de Brito, J., & Khodabakhshian, A. (2018). Performance of Concrete with Waste Granite Powder: The Effect of Superplasticizers. *Applied Sciences* 2018, Vol. 8, Page 1808, 8(10), 1808.
<https://doi.org/10.3390/APP8101808>
- Singh, N. B., Kumar, M., & Rai, S. (2020). Geopolymer cement and concrete: Properties. *Materials Today: Proceedings*, 29, 743–748.
<https://doi.org/10.1016/J.MATPR.2020.04.513>
- Singh, S., Nagar, R., & Agrawal, V. (2016). A review on Properties of Sustainable Concrete using granite dust as replacement for river sand. In *Journal of Cleaner Production* (Vol. 126, pp. 74–87). Elsevier Ltd.
<https://doi.org/10.1016/j.jclepro.2016.03.114>
- Stempkowska, A., Gawenda, T., Chajec, A., & Sadowski, Ł. (2022). Effect of Granite Powder Grain Size and Grinding Time of the Properties of Cementitious Composites. *Materials*, 15(24). <https://doi.org/10.3390/ma15248837>
- Teixeira, J. (2018). *Impressão 3D com Extrusão de Materiais Cimentícios. Untitled No. 26 Drawing by Sumit Mehndiratta* | *Saatchi Art*. (n.d.). Retrieved June 3, 2023, from <https://www.saatchiart.com/art/Drawing-Untitled-No->

26/593840/3955064/view?epik=dj0yJnU9Q1BYeFQtRjFCcDVXUXVfcmQyMHN
mNnlhM085VGh6bEsmcD0wJm49eUhXUENQYnRRTUxYTmFYdkNvaVRzZyZ0
PUFBQUFBR1I3U2Fn

Viking River Cruises - Cruising Portugal Douro Valley. (n.d.). Retrieved June 3, 2023, from <https://misadventureswithandi.com/viking-river-cruises-douro/>

Wine Partners of The Yeatman Wine Hotel - The Yeatman Hotel. (n.d.). Retrieved June 3, 2023, from <http://www.the-yeatman-hotel.com/en/wine/partners/>

Wolfs, R. (2015). *3D PRINTING OF CONCRETE STRUCTURES.*

Zhang, J., & Khoshnevis, B. (2013). Optimal machine operation planning for construction by Contour Crafting. *Automation in Construction*, 29, 50–67. <https://doi.org/10.1016/j.autcon.2012.08.006>

Zhang, X., Li, M., Lim, J. H., Weng, Y., Tay, Y. W. D., Pham, H., & Pham, Q. C. (2018). Large-scale 3D printing by a team of mobile robots. *Automation in Construction*, 95, 98–106. <https://doi.org/10.1016/j.autcon.2018.08.004>

Zhang, Z.-X. (2016). Rock Fracture and Rock Strength. *Rock Fracture and Blasting*, 69–88. <https://doi.org/10.1016/B978-0-12-802688-5.00003-8>

