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Development of a cement-based extrusion system for application in 3D printing

A thesis presented by

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Dedication

This work is dedicated to my family because since I was little, they have seen the potential in me and have let me be who I want to be. To my friends in Colombia for their support and encouragement. To my friends in Mexico who have become my second family.

And finally, I want to dedicate this work to this country because it has given me life-changing experiences that made me grow as a human being, even though being away from my homeland has made me learn to value it more than I did before.

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Abstract

Traditional construction has forged a paradigm in which any object made of concrete is limited to having a square or round shape due to the high cost of the molds used to cast the cementitious material. On the other hand, being an activity with a high degree of manpower required, it is highly dangerous since workers are exposed to hazards such as working at heights, in unstable structures, in confined places, and surrounded by heavy materials and machinery.

Additive manufacturing has been implemented in multiple industries; construction is no exception. Where flexibility in design, speed, and automation are the factors that attract the most attention. However, for its application in a context such as the Mexican, ways must be found to develop materials and equipment that allow simplifying the technique, so that its massification is facilitated.

In a context of confinement due to pandemic, this project explored the components and proportions that constitute a basic mortar to be 3D printed by extrusion. Qualitative methods were developed for the evaluation of mortars and compared with quantitative methods.

The design and manufacture by 3D printing of an extruder were carried out that allows depositing layers of material stably and continuously. In addition, its design allows easy material feeding, easy coupling to a printing robot, and easy assembly and disassembly for cleaning.

Finally, with the mortar and extruder developed, they were incorporated into a printer in which an experimentation process was carried out that led to defining the parameters of movement speed, extrusion speed, and distance from the nozzle.

Some of the main contributions of this thesis, apart from the basic mortar for 3D printing with Mexican materials, and the design of the extruder. were the qualitative evaluation methodologies and the definition of printing parameters. that can be used for future projects to scale the technique.

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1 Chapter 1: Introduction

1.1 Introduction

1.1.1 Additive manufacturing

In industry 4.0, the principles of instantaneousness and modularization have allowed the development of technologies like additive manufacturing (AM), where the aim is to make a physical 3D object from a digital 3D model through the superposition of successive layers of material. This technology has the advantage of being able to manufacture complex geometric shapes by using only the necessary amount of resources [1]. Fused filament fabrication (FFF) is one of the most used AM techniques, applied mostly to plastics and some metals. It uses a solid filament that is fused and extruded through a nozzle, depositing layers of material that solidifies almost immediately. Computer Numerically Controlled (CNC) robots are in charge of precisely position the extrusion head, and depending on their degrees of freedom, more complex structures can be printed, and the aesthetic quality of the final piece can be improved [1], [2].

1.1.2 The use of cement in 3D printing for construction

AM techniques are currently used in a wide range of industries, where many applications are being constantly developed. In the field of construction, some work has been done to be able to use AM for the fabrication of small functional pieces with innovative designs, such as benches, plant pots, and garden lamps; as well as for the large-scale fabrication of pieces with architectural or structural functions such as columns, walls and Arches [3], [4].

The use of hydraulic cement is still the common denominator in most applications, given that its mechanical properties make it an efficient and reliable material. Hence, cement-based materials for construction are not expected to change in the near future [5].

1.1.3 Widespread of "concrete" denomination for all cement-based 3D printing applications

Traditional building uses concrete as a structural material, hence many researchers in the field of cement-based AM have standardized the use of the term Concrete 3D printing (C3DP) even though only a few applications use concrete per se; most of them use mortars instead, which differ from concrete because instead of using coarse aggregates, they use fine aggregates and other materials like micro fillers, additives and rheological agents [2], [6]. This is because cement-based 3D printed materials must have different properties than traditional concrete; they must be able to be pumped and extruded smoothly, but they must retain their shape and gain mechanical strength efficiently [7].

1.1.4 Stages of the cement-based 3D printing process

The process of C3DP consists of three stages: First, in the data preparation, the component is to be designed as a 3D CAD model, which then must be sliced to the desired depth depending on the level of complexity of the design and the resolution that the printer can achieve. Then this sliced model must be converted into a printing path using an adequate programing language (e. g. G-code). The second step is the mortar preparation, where solid and liquid components are to be mixed following a strict order and timing, the mixture will not always be the same if the mixing times and speeds change, or if the materials are added in a different order. Once the mix is ready it must be fed to the printing head. The final step is the component printing, where the printing head is in charge of extruding the mixture through the nozzle using CNC parameters.

1.1.5 Fused filament fabrication approach for cement-based 3D printing

Among common approaches to C3DP, the layer-by-layer extrusion technique seems to be the most attractive for researchers, given that it shares the same principles of FFF, where a great amount of work in the design of machinery and CNC trajectories has been already done. However, unlike FFF, mortar for 3D printing is not a solid material to be fused and deposited, it is rather a fluid that follows a Bingham plastic model where properties like thixotropy, viscosity, and yield stress are responsible for the behavior of the mortar mix, before, during and after the deposition. According to this, during the last few years, there has been a growing interest among researchers for developing mortar mixtures with high specifications for C3DP, where the versatility of the printers would rely less on the mechanical properties of the fresh and hardened mortar and more on the design of the printing machines and the optimization of trajectories and CNC variables [8]–[10].

1.1.6 Challenges for the scaling up of the technology

One of the main challenges of AM for construction is the scaling up of the existing technologies, as most commercially available CNC robots go from the small scale up to the medium scale. They are versatile, precise, and easy to manipulate. Yet, the larger the setup, the more challenging the control and tolerance meeting. Some applications increase the range of printing by using multiple robots [11], others by attaching the robot to tracks or even crawler tracks [12], [13]. Nevertheless, this larger setup involves additional requirements for the construction site such as flatness and ground strength.

The use of Gantry robots, also known as cartesian robots, is the most popular choice among researchers due to their similarity to most FFF printers and their relative ease of being scaled up. They are characterized by simple and precise control of trajectories, positions, and speeds among all three XYZ axes, making them a versatile tool to be used in research work at a laboratory scale [14]. Among other uses, these small-scale gantry robots with a moving base can be used for the development of mixtures for printing; the design and optimization of the components in the printing head, such as the extruding mechanism and nozzle shape, and size; and for the optimization of the CNC variables like material feed rate, nozzle speed, and standoff distance.

1.2 Motivation

Freeform construction using 3d printing has multiple challenges, including the development of printable materials, the optimization of construction techniques, and the development of material delivery systems. In the Mexican context, these challenges must be faced using the tools with the greatest availability in the market. This is why the motivation for this project is as follows.

1.2.1 Development of 3D a printable cement-based mixture

One of the limitations for the development of large-scale machinery for free form construction is the material design, as there is an opportunity for the optimization of the fresh and hardened state properties of high-performance 3D printing mixtures by using mineral micro fillers, fiber micro fillers, and rheological additives; So that the final performance of the mixture allows greater freedom of design and printing speed, thanks to its geometric and mechanical stability [11].

1.2.2 Application of CNC principles in material extruding

From the literature review described in chapter 2, there have been interesting developments in terms of printing techniques and the use of CNC principles applied to the deposition of building materials by extrusion, following the main principles of the fused filament fabrication technique and using different kinds of apparatus like medium to large gantry robots.

1.2.3 Development of proper extrusion for 3D printing

There are also opportunities for improvement in the way the mortars are delivered by the printers, most current application of C3DP use sophisticated high precision concrete pumps to move the cement-based mixture through a hosepipe to the nozzle; In this process, issues like potential segregation, changes of rheological properties and pressure drop can be disadvantageous for the printing quality while increasing energy consumption [15], [16].

1.3 Problem Statement and Context

Traditional construction is an activity that is not only dangerous because it requires a high degree of human labor but also because it is also expensive since the formwork and its respective assembly and disassembly represent high costs for the works. 3D printing appears as an alternative; however, it faces certain challenges that researchers want to face.

1.3.1 Additive manufacturing as an alternative for dangerous and expensive construction.

The construction industry is facing big challenges in terms of cost optimization, environmental awareness, and worker safety conditions. In a construction project, up to 50% of the total cost can be associated with formwork, not only because of the materials themselves but also because of the cost of labor associated with assembly and disassembly [17]–[19]. Also, the costs associated with waste are hard to determine, but it has been estimated that the costs can amount to around 30% of the total building materials [20]. In terms of security, 20% of deaths in private-sector jobs in the US attributed to construction-related activities [21], [22]. Over the last decade, the technologies regarding the so-called fourth industrial revolution (or industry 4.0.) have gained the attention of several industries. One of these technologies is 3D printing (3DP) or additive manufacturing, which has been in the spotlight recently due to the flexibility it has given to the manufacturing process, allowing it to print structures with cost optimization beforehand and no material waste. Also, fully automated construction reduces the need to put workers at risk in the handling and transportation of materials.

1.3.2 Challenges of 3D printing with cement-based materials

Most 3DP techniques can be easily explained and understood as the stacking of 2D printed layers where the building material is deposited layer by layer via extrusion using robotic control. This technique has worked successfully in metals and plastics, because, on the one hand, the printed pieces are small and medium in size, and on the other hand, printing methods for this kind of materials are "fast setting"; meaning that, because of the physical properties of common 3DP metals and polymers, the material hardens almost immediately after extrusion, with no risk of losing its shape or risk of collapsing [23], [24].

Unfortunately, none of the traditional ceramic materials possess such behavior and, in the case of concrete, it must undergo a chemical reaction to achieve its final hardened state. As a result, C3DP has not evolved as fast as in other materials, even though Portland cement (binder used in most concrete mixes) has been used since 1824 [25]. For this matter, industry 4.0. is now being targeted as a way to develop better methods for the implementation of additive manufacturing of cement-based mixtures, which is why this technology is projected to grow by approximately 15% annually by 2021 [26]. Market studies also say that the use of this technology can lead to reductions in construction wastes between 30% and 60%, labor costs between 50% and 80%, and production time between 50% and 70% [26]. However, only a few C3DP technologies have reached the market in small increments, which is why most of the C3DP services offered are limited to small architectural decorative pieces. Large buildings are mostly prototypes, as is the case of companies like XtreeE in France, COBOD in Denmark, CyBe in the Netherlands, ApisCor in Russia, and WinSun in China [1].

1.3.3 Problem statement

According to this, to be able to print complex structures in the construction industry, it is important to design a 3D printable mixture with optimal specifications, meaning that the fresh and hardened state properties must allow the smooth mixing and extruding, while the deposited layers must harden as fast as possible without losing strength or changing their geometry. In the same line of work, it is important to design a mechanism for the adequate delivery of such mixture using a robot. The extruder head must be able to deliver material with the correct feed rate, nozzle size, and distance.

1.4 Research Question

In the Mexican context, can a small-scale extrusion system be developed by the design of a cement-based printable mortar and an extruder for a gantry robot?

1.5 Research Objectives

1.5.1 Main objective

To design and implement a mortar 3D printer capable of creating small structures. It is to be able of delivering material in a controllable way while depositing stable layers of material.

1.5.2 Specific objectives

- To identify the key components and proportions in the design of a 3D printable cement-based mixture.
- To determine the optimal composition of the printable mixture to enhance its fresh state properties.
- To assess the mechanical strength of the hardened mixture.
- To design an extruder capable of extruding material without the use of additional concrete pumps
- To conduct printing tests to optimize printing parameters and speeds in accordance with the developed printable mixture.

1.6 Solution overview

To answer the research question and to achieve the general and specific objectives, this research will be divided into stages:

- In the first stage, there is a literature review, where the aim is to identify the main approaches for 3D printable mixture components, proportions, and characterization techniques. In terms of the extrusion head, the most convenient approach is defined for the scale of this project.

- In the second stage, a design and analysis of experiments will be used to optimize the fresh state, hardened state, rheological and mechanical properties of the printing mixture using the standard characterization techniques.
- Equally important, the extruding head is to be designed to take advantage of the obtained specifications of the designed mixture. In this process, the most important features will be size, weight, energy efficiency, waste minimization, and extruding accuracy.
- The final challenge will be the system integration, the extruding head, and the mixture must be put together in a 3D printer, studies for printing speed, material feed rate, nozzle size, and distance, and trajectories will be employed for the optimization of the CNC parameters.

2 Chapter 2: Literature review

To meet the objectives of this thesis and to be sure that the work to be done with this research generates a contribution to science, it is important that at first, a bibliographic review is carried out to identify which are the currently available technologies, the topics that are being investigated the most and the opportunities for innovation that can be detected and that may apply to the context of the country and the region.

At first, a general approach to cement-based 3d printing will be discussed. On the one hand, from the perspective of research, that is, a review will be made of the most relevant publications that in recent years have set the trend in the development of techniques, equipment, and materials for 3D printing by extrusion of a cement-based matrix. On the other hand, from the perspective of intellectual property, this being the most relevant patents worldwide, in which functional devices and methodologies are described, which are the starting point for future developments.

Later, there will be mentioned the mixture designs that other authors have developed and found to be optimal for this type of application, which will serve as a starting point for the development of a new formulation. In the same way, it is mentioned how researchers have approached the issue of printing conditions and the measurement of the properties of the material in the fresh state and the hardened state. And finally, the most outstanding trends in the subject of laboratory-scale mortar extruder design will be shown.

2.1 General research approaches to cement-based 3D printing.

Several universities, research centers, and private companies are invested in developing C3DP technologies. The main approaches for these developments are the nozzle design, the printing method, the mix design, and the CAD optimization, most of them focused on the flexibilization of printed designs and the scaling up of the equipment and methods.

2.1.1 The use of robotic arms and CAD optimization for printing complex structures.

XtreeE in France is a company dedicated to the development of 3D printing technologies. In their paper “*Large-scale 3D printing of ultra-high-performance concrete- a new processing route for architects and builders*”, Gosselin et al. [17] proposed the use of a 6-axis robotic arm rather than the gantry setup, which, in conjunction with the use of ultra-high-performance concrete, allows the fabrication of complex curved designs with a certain degree of overhanging components. This level of extrusion freedom is achieved by using the tangential continuity method (TCM), rather than the cantilever method, where each layer is extruded perpendicular to the base. As can be seen in Figure 1 (left) the TCM takes advantage of the 6-axis robotic arm and prints every layer perpendicular to the previous one, achieving a better bonding between layers.

The same research showed the importance of CAD in the final result. By optimizing the design, researchers achieved printed models with bioinspired architectural design, structural function, and soundproofing capabilities, as illustrated in Figure 1 (Right). By using the proposed method, they were able to print the structure without the need for temporary supports.

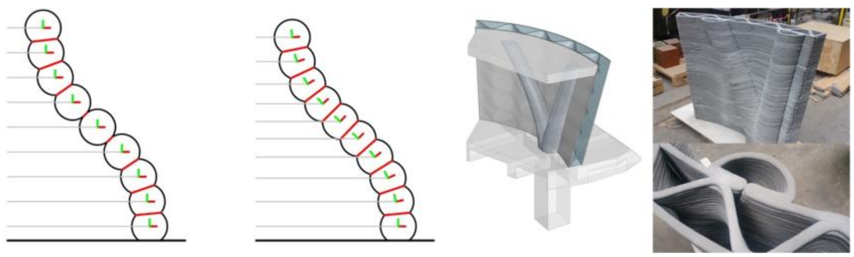


Figure 1. (left) cantilever Method, Tangential Continuity Method (right) structural, bio-inspired soundproofing 3D printed wall [17]

2.1.2 Mixing traditional construction with 3D printing and the use of laboratory-scale robots.

Another relevant work in progress has been carried out at the TU Dresden. They proposed the CONPrint3D concept, which focuses on taking advantage of the existing machinery and architectural designs from traditional building methods to generate on-site, monolithic 3D-printed structures. It also proposes a concrete mix with large 8mm aggregates with outstanding fresh state stability. In their paper "*Large-scale digital concrete construction – CONPrint3D concept for on-site, monolithic 3D-printing"* Mechtcherine et al. [5] discuss the main features of the CONPrint3D:

- It is an adaptation of automated 3D printing to the traditional printing methods, which is why it is focused on printing straight-shaped straight-edged monolithic structures.
- Maximum exploitation of the existing construction machinery by modifying the concrete pumps and cranes (used for filling the formwork) to use it as a large-scale robotic arm. There is also a small-scale industrial robot used for laboratory tests, as shown in Figure 3.
- Standard complying hardened concrete, which does not require the development of new standards for 3D printed concrete as other methods do.
- Printhead able to extrude consistent, smooth, sharp, and large filaments, as illustrated in Figure 2.

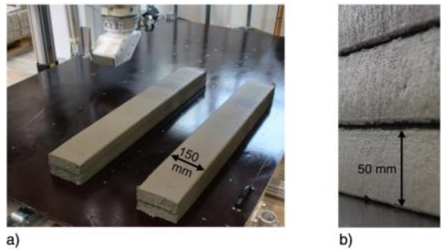


Figure 2. Large printed layers with CONPrint3D method. (a) width (b) height [5].

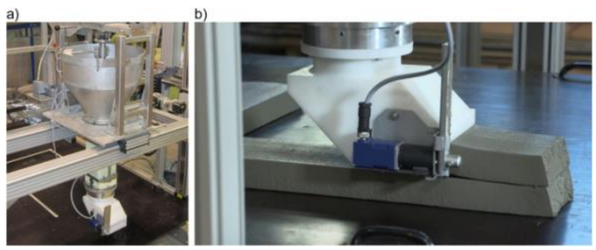


Figure 3. (a) Industrial robot for small structures (b) printing nozzle [5].

2.1.3 Nozzle designs and multiple functionalities of the extruder head.

In the US, Khoshnevis *et. al.* from the University of Southern California have been working in the contour crafting (CC) technique, which uses a set of trowels at the nozzle of the extruding head. These trowels smooth the extruded filament to build aesthetic structures, as illustrated in Figure 4. In their paper "*Automated construction by contour crafting-related robotics and information technologies"* [14], different applications of this technique in construction are discussed:

- The inclusion of utility conduits inside of the structure without affecting the exterior appearance of the structure.
- The trowels allow a smooth printed structure that is ready to paint.
- It allows the inclusion of smart materials like sensors and electrical components.
- The printing robot can also deposit reinforcement materials during printing.
- Robots can also be used to automatically deposit paint and ceramic adhesives.
- Inclusion of embedded wires during printing that can be used later as electrical and communications lining.

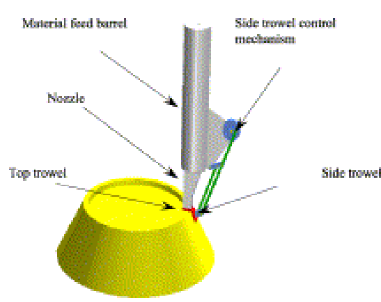


Figure 4. Contour crafting setup [14]

2.1.4 The use of real-time testing for extrusion of multiple material batches.

Loret et. al. from the ETH Zurich worked on a paper called "*Complex concrete structures: Merging existing casting techniques with digital fabrication" [27]*, where they describe the Smart Dynamic Casting (SDC) technique which, in few words, uses the method of the slipping formwork. Slipping formwork is when contractors take a formwork, fill it with concrete, and, after the concrete sets, it is slipped upwards before repeating the process. In the case of SDC, a parallel device is used to test, in real-time, the setting of the mix inside of the formwork, giving feedback to the robot for it to know when to slip it.

2.1.5 Summary of research approaches to cement-based 3D printing

From the research literature and the information summarized in Table 1, it can be pointed out some highlights, which are useful to define the focus of the project developments.

Table 1. Summarized Paper contributions

Autor	Approaches	Results
Gosselin et al. [17]	The use of a robotic arm and a high-performance concrete mix for the building of structures with overhanging components using the TCM and optimization of CAD Design	Printing of bioinspired architectural design, with structural function and soundproofing capabilities. The TCM allowed better geometrical stability.
Mechtcherine et al. [5]	The use of the existing construction machinery and traditional designs for 3D printing. They also propose the use of a small-scale gantry printer for laboratory tests	Printing of cement-based materials with traditional formulations using a laboratory-scale gantry robot.
Khoshnevis [14]	Work with the CC technique, which uses trowels to smooth the surface as it extrudes. They propose the application of the technique in the functionalization of structures while building	Deposition of reinforcement while printing; a nozzle design for hollow cavities and structures with different geometries. They are working in the printing of overhanging components without support
Loret et al. [27]	Development of the smart dynamic casting technic as real-time feedback for automated construction with slipping formwork	Smart dynamic casting can optimize the speed of extrusion and the use of different material batches.

2.2 Patents

Some of the most important research efforts in the field of C3DP have led to important patentable technologies, especially those regarding apparatus and methods for concrete extrusion and reinforcement insertion. Relevant patents in the field of this research can be the guide for future developments.

2.2.1 Method and apparatus for delivery of cementitious material

The patent [28] was granted in 2017 to the Loughborough University by the European patent office but with a worldwide application. It consists of a cement-based matrix 3D printing system that provides cementitious material, extrudes it through a nozzle, and deposits it in a pre-determined path. It can also deposit non-cementitious material as support (with an activator agent) or serve as an interface between cementitious and support material.

It can deliver accelerating or retarding agents, operate one or more vibrating nozzles, and is monitored by a set of cameras to identify defects in texture or deformation. As this project focuses on the design of the extrusion nozzle and the cement-based printing mix, this patent provides important information about the apparatus and techniques that could be used for a better extrusion and deposition of the material, however, it does not have any claims regarding reinforcement material such as fibers or steel bars. Additionally, the patent also has no claims about the use of trowels or other devices for smoothing the printed surface.

2.2.2 Construction material cord extrusion system for additive manufacturing robot of architectural structures comprising a reinforcing fiber insertion device

The patent [11] was granted in 2019 to the French company, XtreeE, by the French Office of Intellectual Property. It claims an apparatus for extruding cords of construction material using a robot, it comprises an extrusion head with material inlet and extrusion outlet and a pump for the extrusion head adapted to the additive manufacturing robot. It works by stacking layers of the extruded cord along a predetermined path. The apparatus is also able to insert reinforcement fibers into the extruded cord. This patent is a good example of the necessary apparatus for the correct orientation of the deposited layers.

2.2.3 Nozzle for forming an extruded wall with a ribe-like interior.

Dr. Behrokh Khoshnevis from the University of Southern California has been assigned several patents for their developments of the CC technique, one of them was granted in 2011 by the United States *[15]*. It claims the design of an extrusion nozzle with three outlets. Two of the nozzle outlets control the extrusion of unhardened material to form the exterior surfaces of the structure where the third outlet goes in-between the other two outlets and can have a width much less than the distance between the first and second outlet. The third outlet can also be configurated to oscillate in a sinusoidal-like way in between the extrusion of the other two outlets, those that form the exterior walls, as illustrated in Figure 5. The system can be configured to extrude from one, two, or three outlets at the same time.

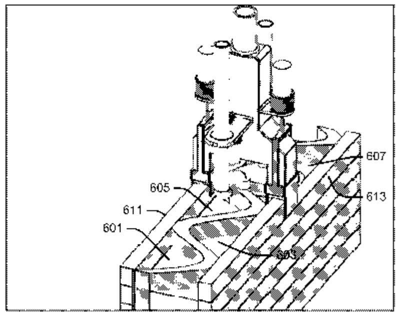


Figure 5. Three outlet nozzle configurations [19].

2.2.4 Apparatus and method for vertical slip forming of concrete structures

This patent [29] was granted to ETH Zurich In Switzerland by the World Intellectual Property Organization. It claims a frame with a formwork inside, which acts as slipping formwork, where concrete is poured, and the formwork is slipped upwards as the mix hardens inside of the formwork. The apparatus has some actuators that receive signals from a control unit to modify the position of the formwork wall as it moves upwards, allowing the manufacture of columns or walls with variable form or diameter. It also has an attached device responsible for automatically monitoring the hardening of each concrete batch that is being poured in the formwork, giving real-time feedback to the system about when the mix inside of the formwork is hard enough for it to be slipped upwards and how different batches of material can be used in the same final piece.

2.2.5 Method of vertical forming of a concrete wall structure and apparatus therefor

This is a patent application by the ETH Zurich [30]. It claims a method for vertical forming of concrete structures, where the contour or shell of the structure is built first by additive manufacturing, and then it is filled with concrete. This method also allows for building a shell around a steel reinforcement structure, acting as a built-in formwork.

2.2.6 Summary

All the patents mentioned above show significant opportunities for improvement by working on the design of the extruding apparatus by making them easier to manufacture. It is also remarkable the opportunity of developing robust printing equipment designed to be used under the roughest conditions and take advantage of the already existing machinery for applications in 3D printing

2.3 Mix design for optimal printing

2.3.1 The use of fillers to improve fresh properties

In the paper “Fresh properties of a novel 3D printing concrete ink” [31] Zhang et. al. from the Southeast University in China showed their development of a thixotropic mix design with fluid behavior during pumping and extrusion, and satisfactory static behavior after deposition. They found that thixotropy, green strength, and hydration are always improved when adding rheological additives and fillers like nano clay, silica fume, or fly ash. Four formulations with different proportions were compared to a mixture containing no additives or binders other than Portland cement. They found that the formulation Table 2, improves the thixotropic behavior and increases the buildability up to 260 mm compared to 75 mm when no additional fillers were used.

2.3.2 Influence of superplasticizers and silica fume

Manikandan et al. [8] described the influence of superplasticizers and silica fume on the printability of a fresh cementitious mixture for 3D printing. They concluded that the formulation for optimum extrudability and buildability is the one shown in Table 2. They found that high contents of superplasticizer make the mix less viscous and less cohesive, while high contents of silica fume make the mix highly cohesive and the curing is delayed.

2.3.3 Influence of sand, binder, and additives

Le et al. [10] identified an optimum mix for C3DP developed by testing proportions of sand between 55% and 75%, binder between 25 and 45%, and rheological additives between 0% and 5%. They report that using the optimal formulation shown in Table 2, they were able to build 61 layers without noticeable deformation, with a shear strength in the range of 0.3 to 0.9 kPa in terms of extrudability and buildability and an open time of 100 min and compressive strength of 110 MPa at 28 days.

2.3.4 Influence of sand content and gradation.

Weng et al. [32] studied the effect of sand gradation in the printability of cement-based mixtures, they compared the performance of natural sand and continuous, uniform, and gapped gradations. As the study is focused on the sand gradation, the mix proportions to the weight of cement were kept the same for all experiments, that is why they used the formulation shown Table 2. The rheological characterization was performed using the mini-slump test and a Viskomat XL, for printing they used a MAI Pictor pump with a 3m length 2.54 cm diameter to extrude a cylindrical column of 10 cm of inner diameter and a layer width and height of 20 mm and 10 mm. For Mechanical characterization, they used ASTM C109/C109M-13. They found that the mix with a continuous gradation < 1.2 mm, has appropriate compressive and flexural strength and significantly higher yield stress and lower plastic viscosity, being able to print 10 layers more than uniform and gap gradation.

2.3.5 Influence of fibers on fresh state properties

Paul et al. [33] evaluated the fresh and hardened properties of different formulations, they found that in fresh-state, the addition of glass fibers in the formulation shown Table 2 increases yield stress and lower plastic viscosity.

2.3.6 Influence of fibers on fresh-state and hardened-state properties

Alyousef et al. [34] studied the use of Saudi sheep wool fibers (SSWF) as reinforcement for the enhancement of mechanical properties of traditional concrete. They prepared eight samples varying the SSWF from 0% to 6% and other four using modified Saudi sheep wool (MSSWF) varying the MSSWF from 0% to 1.5%. The MSSWF was prepared by putting the SSWF in 35% NaCl aqueous solution, at 22-28 Celsius for 24 hours. They found that the increase of fibers slightly reduced workability and compressive strength, but this later value is higher for the MSSWF. On the other hand, tensile and flexural strength were enhanced with the addition of fibers. The authors recommend that the optimum dosage is around 2-3% of MSSWF for the improvement of tensile, flexural strength, ductility, and adhesion to the binder matrix.

2.3.7 Summary

Table 2 summarizes the formulations that each of the articles considered optimal. This information will be useful for the exploration and development of the novel formulation that will be proposed in this Thesis.

Table 2. Summary of formulations expressed as weight proportion of cement. Water/binder ratio (W/B), Sand (S), Cement (C), Fly Ash (FA), Silica fume (SF), fibers, High range water reducing agent (HRWRA), Viscosity modifying agent (VMA), Retarding agent (RA).

	W/B	S	C	FA	SF	Fibers	HRWRA	VMA	RA
Zhang et al. [31]	0.35	1	1	0.021	0.021	-	0.36%	0.0125%	-
Manikandan et al. [8]	0.3	-	1	0.015	0.026	-	-	-	-
Le et al. [10]	0.26	1.5	1	0.286	0.143	1.2 kg/m^3 PP	1% binder		0.5% binder
Weng et al. [32]	0.3	0.5	1	1	0.1		11.3 g/l	-	-
Paul et al [33]	0.98	4.18	1	0.96	0.5	0.047 Glass	0.0311	-	-
Kazemian et al. [9]	0.43	2.26	1	-	0.1	-	0.16% binder	-	-
Tay et al. [35]	0.71	2.43	1	0.29	0.14	-	-	-	-

2.4 Printing conditions:

2.4.1 Influence of nozzle shape and time between layers in printability

Regarding printing conditions, Paul et al. [33] remark that specimens printed with squared nozzles have lower variations in their hardened properties as the printed structures contain fewer voids, however, rounded nozzles are found to be better for printing complex shapes. For optimum printing shape stability and layer settlement, Kazemian et al. [9] reported that the addition of silica fume or nano-clay, together with a time gap of 19 minutes between layers, can reduce deformation to 0.

2.4.2 Influence of material flow rate and travel speed on the printing quality

Tay et al. [36] determined the influence of flow rate and travel speed of the nozzle on the printing quality. They wanted to be able of printing the main structure and a support structure for overhanging components using the same extruding head and material. Instead of using supporting materials or structures for printing overhanging areas, they used low-quality printing parameters to obtain a discontinuous pattern that is rigid enough to keep its shape and withstand the weight of other layers, but after it hardens it is easily broken and removed, leaving hollow spaces below the high-quality overhanging areas of the completed piece.

In the first place, using the formulation designed by Tay et al. [35] shown in Table 2, they performed a test when where they gradually increased the nozzle speed for different values of flow rate, registering the values where the filament started to present discontinuities and the measure the size of this gaps. Then, by performing a gap distance characterization, they were able to determine that 10 mm is the maximum gap that a filament can cross without a slump greater than 2mm. With all this data, they built the contour plot, shown in Figure 6, where they present the optimal speed values for the desired printing quality.

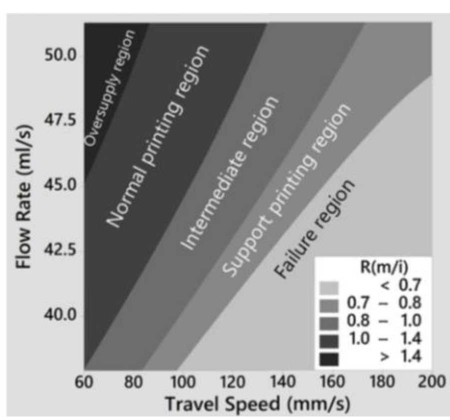


Figure 6. Characterization of different printing regions [36]

2.5 Properties Evaluation:

For the determination of the fresh and hardened state properties of the cementitious mixture, there are not specific standard methods for 3D printed structures, that is why most researchers use their own methods or modified versions of standards.

2.5.1 Fresh-state properties determination

2.5.1.1 Rheometer tests vs. slump and slump-flow

In terms of fresh properties, there is still a feud between empirical fast tests as the slump and slump flow, and quantitative analysis using a rheometer. Some prefer the rheometer because of its repeatability and precision in measuring properties like thixotropy, viscosity, and yield stress using the Bingham plastic model, which is closely related to pumpability, shape stability, workability, open time, among others [31], [37], [38]. Zhan et al. [39], concluded that to print a complete piece without the mix being too stiff or too wet, the viscosity must be between 3.8-4.5 Pa.s, the yield stress between 178.5-359.8 Pa and thixotropy less than 6284.5 Pa/s. Paul et al. [33] recommend thixotropy must be at least 10000 N mm rpm to ensure good pumpability.

Some researchers [40] find the use of a rheometer inconvenient, as its results somehow depend on the type of equipment and the geometry of the spindles. They highlight the advantages of the traditional slump and slump flow tests as a quick, reliable, and field-friendly way to determine fresh state properties. This method uses the flow table and conical mold described in ASTM C230 [41], the procedure described in ASTM 1347 [42] must be followed, the slump is measured as the height of the fresh mortar after removing the conical mold and the slump flow is the diameter after the table is jolted 25 times in 15 s. European Standard EN 1015-3 [43] can also be used but the number of jolts and dimensions of the equipment are different. Tay et al. [40] say that the printable values for slump and slump flow of mortars are 2-4 mm and 150-190 mm respectively. Zhang et al. [39], however, recommend slump flow values between 192.5-269 mm.

2.5.1.2 Extrudability

For extrudability, Le et al. [10] used a 9 mm diameter nozzle for extruding five continuous segments, the first one was a 300 mm row and the fifth were five continuous rows of the same length. The test was evaluated as YES when all the segments could be extruded without blockages or fractures.

2.5.1.3 Buildability

Determination buildability is one of the main concerns for C3DP because it is always important for the printed layers to be able to withstand the weight of subsequent layers. This property can be measured in different but complementary ways. One of them is the Yield stress obtained from the rheological analysis which is the maximum stress load that the static material can withstand before flowing [38], [44]. Another method is the green strength, where a cylinder is filled with mortar, then it is unmolded, and a little container is put on top of the fresh mix. The container is slowly filled with known amounts of sand until the cylinder collapses [45]. However, the most widely used method is the height of layers, an empirical test measuring the maximum number of layers with a geometry defined by the researchers that can be stacked before the structure collapses [10], [31].

2.5.2 Hardened-sate properties determination

For the determination of the hardened state properties like flexural and compressive strength, there is not a standard for 3D printed structures, that is why not all researchers use the same testing methods. some papers on the field like [9], [10], [32] measure these properties on casted samples using the mixture. Others like [33], [39], [46] have evaluated these properties using 3D printed specimens, proving that there is an anisotropic behavior. Both Paul et al. [33] and Zhang et al. [39] agree that compressive strength is higher when the force is applied parallel to the printing direction. However, the first ones found that flexural strength was higher when applied perpendicular to the printing direction and the later ones found that is higher when applied parallel to the printing direction.
Regardless of what type of samples are used, the applicable standards for measuring mechanical properties are as follows:

- European Standard: EN 196-1 [47] describes the testing method for three-point flexural strength and compressive strength of 40 mm X 40 mm x 160 mm hydraulic cement mortar prisms. This test can be performed at different ages: 24 h, 48 h, 72 h, 7 days, and 28 days. The same broken prisms used for flexural strength can be used for measuring compressive strength.

- American Standard:
  - Flexural: ASTM C348-20 [48] Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars test, uses 40 mm x 40 mm x 160 mm hydraulic cement mortar prisms. The test can be performed at 4 ages: 24 h, 3 days, 7 days, and 28 days.
  - Compressive:
    - ASTM C349-18 [49] Standard Test Method for Compressive Strength of Hydraulic-Cement Mortars (Using Portions of Prisms Broken in Flexure)
    - ASTM C109/C109M-20a [50]Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)

2.6 Extrusion system

An extrusion system must have the ability to deposit precise quantities of materials over varying distances and speeds. The accuracy of the printed material depends not only on the extrusion head but on its positioning system.

2.6.1 Extruder for small batches

Albar et al. [16] proposed an extrusion system under a creative commons license. In the design shown in Figure 7, it can be seen that the design consists of a stainless-steel body with three sections welded together. The top section is a hopper where the material is deposited, the middle section is a barrel where the material is forced towards the final section, which is the nozzle. This nozzle is changeable according to the desired shape and size, in this article they used a circular nozzle of 20 mm in diameter. The extruder moves the material through the three mentioned parts with the help of an endless screw, which is attached to a wall scrapper for the hopper, and the assembly is moved by a geared motor.

This article provides important information about the proper dimensions for a cement-based extruder to be linked to a lab-scale gantry printer. In the same way, it explains the advantages of using an endless screw to move the material and the design and operation parameters that they found optimal for the mortar formulation they used.

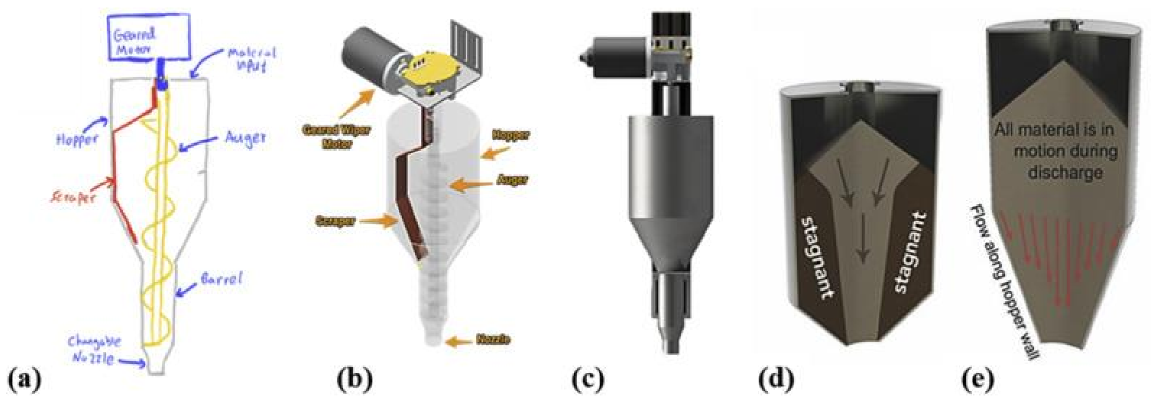


Figure 7. Extrusion head proposed by Albar et al.[16]

2.6.2 Laboratory scale printer with a moving platform

For the evaluation of mixtures designs, Ma et al. [51] use a laboratory-scale printer, which consists of a steel frame of 0.5 m (L) x 0.39 m (W) x 1.1 m (H) where a V-shape storage bin is connected with a vertical steel rod and motion wheels to move it in axis Z. A conical screw is in charge of mixing the material in the V-shape bin while conducting it towards the nozzle which deposits material on a platform that can move in axis X and Y. The sketch of the design is shown in Figure 8.

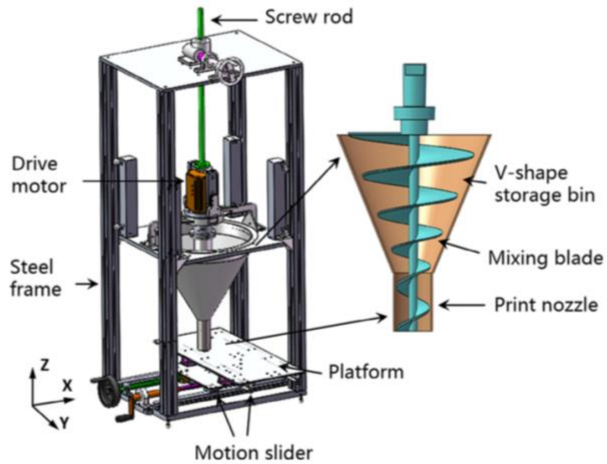


Figure 8. Sketch of the extrusion system used by Ma et al.[51]

This article highlights the use of an endless screw as an optimal choice to move and extrude the material, it also explains the dimensions and the type of movement that the robot-extruder assembly must have to obtain better printing quality.

2.6.2.1 Findings

At the end of the bibliographic review, it appears that there are a series of trends in research that various authors around the world have carried out. In this way, the contributions of the authors can be summarized and the research opportunities to be exploited in this thesis can be identified.

2.6.3 Contributions

Table 3 shows a summary of the contributions made by the different consulted authors, divided into 4 main categories: printing method, extruding apparatus, mix design, and evaluation of properties. In the last column there is an abstract of the main contribution from each author and in the last row are reflected the opportunities that will be explored in this thesis.

Table 3. Summary of contributions

Researcher	Printing Method	Extruding Apparatus	Mix Design	Evaluation of Properties	Main Contribution
Gosselin et al	Tangential continuity method, Round 20 mm diameter nozzle	6-axis robotic arm, medium scale, peristaltic pump + screw	-	Flexural strength estimated compressive strength of extruded samples	Importance of geometrical optimization and the use of silica fume as micro filler
Mechtcherine et al.	Rectangular layer cross-section of 150 x 50 mm2	Machinery from traditional building methods	-	Qualitative Extrudability, Flow table	laboratory-scale extruder, traditional formulations, and machinery
Khoshnevis	Trowels at the nozzle. Three nozzle system with oscillatory movement	XYZ gantry system with a cylinder/piston system	-	-	Deposition of various materials. Smoothing surface while printing
Loret et al.	Formwork that slides as the concrete hardens	Robotic arm, concrete pump	-	Vicat	Real-time estimation of material hardening for printing speed optimization
Loughborough University	Extrusion through one or more vibrating nozzles	-	-	-	Nozzle design for delivering different types of materials and additives
XtreeE	Extrusion through a single nozzle	Robotic arm with concrete pump	-	-	Example of commercial robot for large scale extrusion
Zhang et al.	Round 20 mm nozzle	XYZ gantry system	Evaluation of nano clay, silica fume, and fly ash	Qualitative buildability, flow table, rheometer, Green strength, calorimetry	Qualitative techniques and flow table for printability estimation. Micro fillers as a performance enhancement
Manikandan et al.	Round 3 mm nozzle	-	Evaluation of silica fume and plasticizer quantities	Rheometer (shear stress, shear rate, and viscosity) for printability evaluation	Disadvantages of high contents of micro fillers and plasticizer
Le et al.	Round 9 mm nozzle	Concrete pump	Evaluation of effects of sand, binder, and additives quantities	Qualitative extrudability and buildability. shear vane apparatus for workability	Study of the relationship between buildability and extrudability with open time and workability.
Weng et al.	square 25.5 mm nozzle	Peristaltic pump	Evaluation of sand gradation	Slump, Rheometer, compressive strength	The use of fine sand for printability improving
Paul et al.	rectangular and round nozzles	Robotic arm, concrete pump	Evaluation of fibers effects	slump-flow, Rheometer, Compressive strength	Fiber content for printability and strength optimization. Round nozzles for complex shapes printing
Alyousef et al.	-	-	Evaluation of fibers effects	compressive strength	Workability and compressive strength reduction by the use of fibers
Kazemian et al.	-	XYZ gantry system	Effects of micro fillers	Slump-flow, compressive strength	The addition of micro fillers for deformation reducing
Tay et al.	30 x 15 mm rectangular nozzle, different flow rates, and travel speeds	XYZ gantry system, concrete pump	-	Qualitative filament continuity	Optimal travel speeds and flow rates for the desired printing quality.

2.6.4 Insights

After the bibliographic review and the summary of other author's contributions, it was possible to identify some key points that are found to be important since they represent the greatest research opportunities. Table 4 summarizes the expected contributions of this thesis, and below the final insights from this chapter are discussed.

Table 4. Approaches and expected contributions of this thesis

Printing Method	Extruding Apparatus	Mix Design	Evaluation of Properties	Main Contribution
Round 9 mm to 15 mm nozzles	XYZ gantry system with screw extruder	Use of traditional mortar components and micro fillers	Qualitative extrudability and buildability. Slump-flow, compressive strength	The use of traditional mortar components in the Mexican context for small-scale extruding, and the design of an extruder for such task.

2.6.4.1 The importance of the extrusion system design in the material deposition process and its influence on the final result.

In the first place, it can be seen how important is to take advantage of the robot's capabilities and to use an endless screw for moving the material inside of the extruder for achieving better geometrical stability and to reduce the number of voids in the filament. It is also essential not only to improve the properties of the mortar printing mix but to optimize the CAD design to achieve better strength and functionality.

2.6.4.2 The use of machinery and materials of traditional construction for an easy application to the Mexican context

It is found relevant to develop 3D printing methods by making use of the main advantages of traditional construction, which are in general, the availability of this kind of machinery and the simplicity of the material formulations. The development of the novel formulation that will be proposed in this thesis will be based on the experimental exploration of the effects and advantages of each of the most common raw materials for extrudable mortars used in the literature, and more importantly on the availability, simplicity, and economic advantages of building materials commonly used in Mexico.

2.6.4.3 The development of techniques for evaluating the properties in the fresh state and the hardened state of cement-based mixtures for 3D printing

Given that there are not many standard procedures for testing 3D printable mortars, it will be necessary to use combined qualitative and quantitative methods to assess the fresh-state and hardened-state properties. The most relevant in this case would be consistency, buildability, extrudability, slump, slump flow, and compressive strength.

2.6.4.4 The simplification of methods for evaluating the printability of mixtures

Finally, it can be pointed out the relevance of the fast feedback methods to rapidly assess the process of extrusion when multiple batches of mortar must be used. This can be summarized in the measurement of two main properties: slump and slump-flow. As they are indicators of the appropriate fresh-state properties that give a mortar the ability to be extruded into complex structures with stable geometries.

3 Chapter 3: Research Methodology

This chapter explains the steps to follow in this work to achieve the objectives from chapter one. In this methodology, it is important to highlight that most of the experimental work is carried out in the context of health contingency. This situation demands the search for experimentation and testing alternatives, as well as the exploration of new reference frameworks for the evaluation of the properties of fresh and hardened mortars.

Figure 9 shows a summary of the proposed methodology to achieve the objectives of this thesis. It begins with a literature review in which the trends in cement-based 3D printing technology are explored, and the research opportunities applicable to the Mexican context are detected. Then an exploratory work is followed for the development of a novel mortar where standards for mixing are defined, followed by qualitative tests that will help to define the components for the mortar and the approximate levels of proportion for a printable mixture.

Once the exploratory stage is done, it will be worked on a design of experiments, where qualitative and quantitative methods will be used to assess the performance of different formulations. According to the results, the chosen formulations will be tested in the extruder that will be designed and manufactured in another stage of the project. And finally, the extruder will be attached to a printer robot where small-scale printing tests using the optimal mortar formulation will be performed.

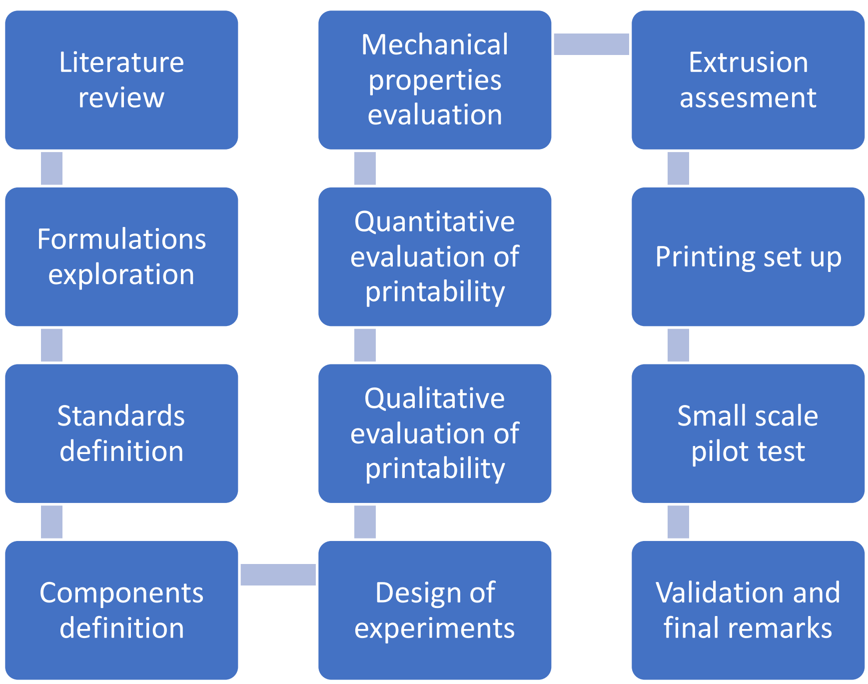


Figure 9. Proposed methodology

The execution of this project cannot be done linearly, since the final result depends on several elements developed independently, and the contingency conditions required looking for backup plans and rethinking processes and scopes. That is why the workflow presented in Figure 10 graphically describes each of the stages and processes of this project and how they merge into the final result.

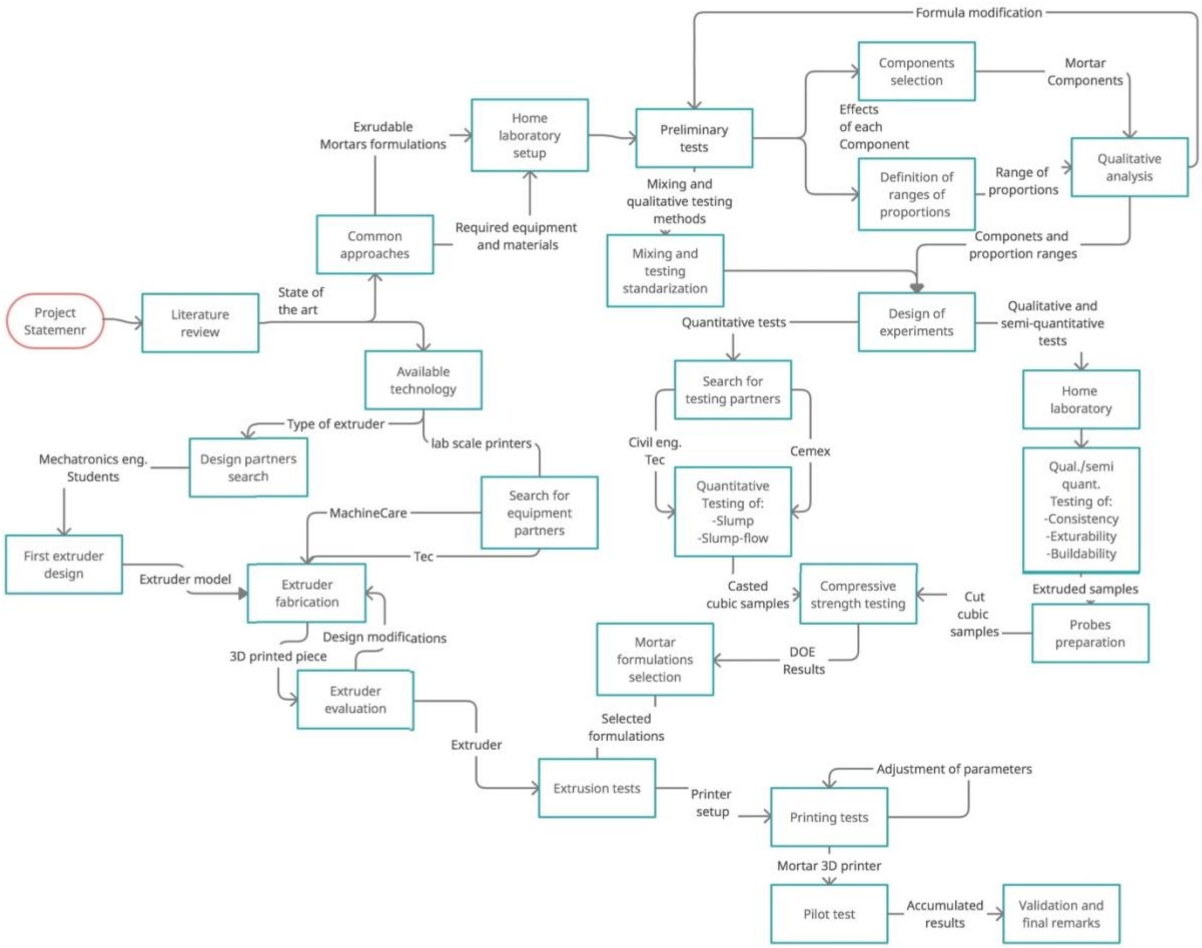


Figure 10. Project workflow

3.1 Common approaches to materials for 3D printing in construction

From the literature review shown in chapter 2, it was found that the common denominator for 3D printing in construction is the use of cement-based printing matrices deposited layer by layer by extrusion. This is why a development process of a new extrudable mortar formulation will be carried out, in which traditional components are used so that it can be easily used in the Mexican context.

3.2 Work plan for the development of the extrudable mortar

The first thing that will be done is the selection of the equipment and tools that will be used in the establishment of a laboratory at home. In the same way, a selection will be made of the materials that are going to be used in the development of the formulations, always keeping in mind that one of the objectives of this development is to simplify the formula as much as possible and to use widely available materials in the Mexican context.

Once this task is completed and knowing what materials are available, it will be proceeded to perform an interpretation and adaptation of the formulations that were found in the literature review.

Subsequently, an exploratory work will be carried out in which, on the one hand, the effects of each one of the components of the mortar and the appropriate proportion levels will be identified. And on the other hand, a standardization of the mixing method and qualitative analysis of the mortars will be carried out. All this information will be the basis for the next stage, which will be a design of experiments for the selection of an optimal formulation for use in 3D printing.

3.3 Home laboratory setup

For efficient and repeatable work, it is important that the same tools and equipment are always used and that the same batches of material are used.

3.3.1 Equipment

The following equipment is required to weigh and mix the materials:

- Beurer brand balance with 5 kg of capacity and readable down to 1 g. It can also measure the room temperature.

- Planetary mixer Kitchenaid professional 600, 575 W of power, and 6L or 3.6 kg of capacity.

3.3.2 Materials

During all the tests that will be carried out for this project, the same batches of the following materials are going to be used:

- Composite Portland Cement as the binder (C) (CEMEX, Mexico) which complies with the Mexican standard NMX-C-414-ONNCCE
- Limestone sand # 5 (S) (Tecno arenas Monterrey) the composition and granulometry provided by the manufacturer are shown in Table 5 and Figure 11 respectively

- Silica fume with a specific surface between 15-35 m^2/g (SF) (Sika Mexico)
- Virgin copolymer fibers for concrete reinforcement with 67700 fibers/g (F) (MasterBuilders, Mexico)
- Lignosulfonates-based plasticizer tablets (P) (Thermotek pro, Mexico).

Table 5. Chemical composition of limestone sand #5 (Tecno Arenas Monterrey)

$CaCO_3$ (%)	SO_2 (%)	R_2O_3 (%)	MgO (%)	S (%)
95.77	2.0	1.0	1.2	0.03

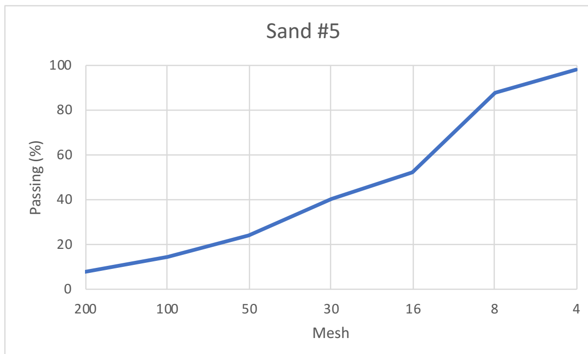


Figure 11. Granulometry of limestone sand #5 (Tecno Arenas Monterrey)

3.3.3 Preparation of the materials

On the first place, according to the required storage conditions, the location of the equipment, raw materials, and tools is to be defined. Also, the raw materials will be labeled with their name and date of opening.

The dry raw materials are put into plastic bags for moisture protection and then located at a dry and clean place, away from direct sunlight. Liquid raw materials are stored in sealed translucent containers, in a fresh and dry place, away from direct sunlight. Tap water is put in a plastic jar to balance its temperature. And finally, for easy dosage, an aqueous solution of P is prepared by putting $175 \pm 1g$ of the tablet, in $672 \pm 1g$ of water, it is left to dissolve for 48h, filtered, and stored as Plasticizer solution (PSol).

3.4 Preliminary tests of extrudable mortars formulations

As previously mentioned in this chapter, an interpretation and adaptation of the formulations found in the literature review must be carried out. With this information, the first round of preliminary tests is planned, where there will be an evaluation of consistency, nozzle size, extrusion of the first layer, extrusion of six layers, and stability. According to the results, other rounds of tests will be carried out, where additionally to the mentioned properties, buildability will be also evaluated.

3.4.1 Formulation planning for the first round of experiments

As the same materials described in the literature review papers are not available or the authors are not clear about the manufacturers, concentration and proportions, it is not possible to exactly replicate their formulations. That is why, given that the reviewed formulations are only considered as the starting point for the development of a novel mortar formulation, the following interpretations are set:

- In the water to binder ratio, only the Portland cement is considered as the binder.
- When not specified, the additives (fibers, high range water reducing agents (HRWRA), viscosity modifying agents (VMA), retarding agents (RA)) are assumed as weight proportion of binder (Portland cement).
- The weight by volume proportions are converted to weight by weight using the average density of a fresh common mortar, which is approximately 2000 kg/m^3 [52].

Besides the interpretations, some modifications and assumptions need to be performed according to the materials and equipment available for the project:

- The fly ash percentage will be added to the silica fume, given that they play a similar role [31].
- Viscosity modifying agents (VMA) and retarder agents (RA) will not be used.
- The scale has an uncertainty of $\pm$ 1g, all weights will be approximated to the closest integer in grams.
- The Plasticizer was originally a solid and based on the preparation mentioned in section 3.3.3 , it has 20.66% of solids. The remaining percentage is water, which must be counted as a fraction of the total water content.

According to the interpretations, assumptions, and modifications during the tests, the formulations shown in Table 2 of section 2.3.7 become the ones shown in Table 6.

Table 6. Proposed formulations for the first tests expressed as weight proportion of cement. Water (W), Sand (S), Cement (C), Silica fume (SF), fibers, Plasticizer solution (PSol)

Name	W	S	C	SF	Fibers	PSol
Test 1 – Zhang et al.	0.34	1	1	0.042		0.017
Test 2 – Manikandan et al.	0.30		1	0.041		
Test 3 – Le et al.	0.22	1.5	1	0.429	0.0017	0.048
Test 4 – Weng et al.	0.24	0.5	1	1.1		0.071
Test 5 – Paul et al	0.86	4.18	1	1.46	0.047	0.151
Test 6 – Kazemian et al.	0.42	2.26	1	0.1		0.008
Test 7 – Tay et al	0.71	2.43	1	0.43		

3.5 Mortar mixing and testing standardization

To ensure the highest possible repeatability in all the tests carried out in this investigation, it is important to define how all the samples are to be prepared, how they are to be mixed, and how the qualitative properties are to be evaluated, given that there are not any procedures defined by international standards organizations for mortars to be used in 3D printing.

3.5.1 Sample preparation

According to the proportions of the formulation and the amount of material that needs to be prepared, the weight in kg of each of the mortar components will be calculated. Subsequently, each of the solid materials is weighed, and at the end, they are placed in the same plastic bag. The bag is closed tightly, leaving a little air, and is mixed manually until it is visually homogeneous. It is important that to avoid clumps, special attention is paid to the dispersion of the fibers. Liquid components are weighted separately from solids.

3.5.2 Mixing procedure

First, the liquid components are placed in the mixer bowl, then the zero time is recorded, and simultaneously, the solid mixture is quickly but carefully added to the bowl while it is manually mixed with the mixer's paddle for 30 seconds. After this time, the bowl and paddle are placed in the mixer and mixed in "stir" mode for 30 seconds. After that, the speed is changed to level 4 for 30 seconds. At this point, if the mixture still looks dry and not cohesive, known amounts of water and plasticizer solution can be added and recorded for adjustments of the final formulation.

Then, the mixer is stopped for 1 minute, during the first 30 seconds, the silicon trowel is used to scrap the material from the walls and the paddle. Next, the mixer is set to speed 4 for 1 minute. After that, the mixer is stopped for 10 minutes; during the first 30 seconds, the silicon trowel is used to scrap the material from the walls and the paddle. Finally, mix in speed 4 for 30 seconds.

3.5.3 Testing standardization

The evaluation of consistency, extrudability, and buildability will be carried out qualitatively. The standards defined for the measurement of these properties in a repeatable manner will be described in section 3.6 as they will be necessary for the evaluation of the novel mortar formulation that is being developed.

3.6 Qualitative analysis of preliminary tests

As mentioned above, the basic properties to be evaluated in preliminary tests are consistency, nozzle size for extrusion, first layer extrusion, six layers extrusion, and stability. In the last round of preliminary tests, the buildability will also be evaluated. The methods used to evaluate these properties are described below.

3.6.1 Consistency evaluation

The consistency evaluation allows getting an idea of how cohesive and manageable the mortar is, and how easy it can be extruded in the next steps of the process. If the mortar is difficult to mix, as the viscosity is too high, this means that it will be difficult to make it go through an extruder. On the other hand, if the mixture has a very low viscosity and there is no cohesion in the mixture, it means that when it is passed through an extruder, it will begin to drip, and the moment the material layer is deposited, it will not retain its shape, nor will it be able to withstand the weight of subsequent layers.

After the mixing procedure, a qualitative consistency test is carried out, which consists of grabbing a portion of mortar with the silicone trowel, placing it in a vertical position, and verifying how much material remains adhered to the trowel and how much it drips. The test is evaluated as OK, if a layer of more than 1 cm of thickness remains adhered to the trowel, without dripping or falling for more than 10 seconds. An example of a passing sample (OK) is shown in Figure 12 (A) and a non-passing test (NOT OK) is shown in Figure 12 (B).

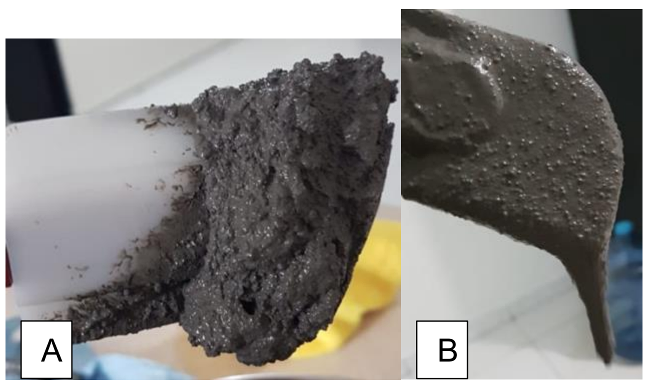


Figure 12. Consistency check (A) Test evaluated as OK (B) Test evaluated as NOT OK

3.6.2 Extrusion, lumps, and stability evaluation

The extrusion test allows the evaluation of how much force is required to make the material flow through a nozzle with a given diameter, and how homogeneous and continuous is the layer that is being deposited. That is, it is evaluated if all the filament that was extruded has the same shape and diameter of the nozzle and if there are no discontinuities in the filament.

Similarly, once the layers of material have been deposited, an evaluation of the stability of the extruded structure must be made. Observing how much the shape of the filament changes when time passes since it was extruded and how much it deforms when other layers of material are put on top of it.

The open side of a disposable pastry bag is folded outwards at least 3 cm, and the tip is cut to the appropriate diameter to fit the nozzle. Then a 9 mm nozzle is fit, and a portion of mortar of about the size of a golf ball is put into the bag. Subsequently, an extrusion attempt is performed; if the mortar extrudes through the nozzle, then the rest of the bag is filled with mortar, otherwise, the tip is changed for a bigger one, until the mortar extrudes through. The diameter of the used nozzle is recorded, and if the mortar does not extrude at all, the biggest diameter attempted is recorded with an asterisk "*".

The first layer is achieved by extruding back and forth a continuous layer of about 150 mm of length until achieving a width of about 50 mm, following the path shown in Figure 13. The first layer extrusion is evaluated as OK if the mortar flows smoothly through the nozzle without clumps and if the filament looks overall continuous.

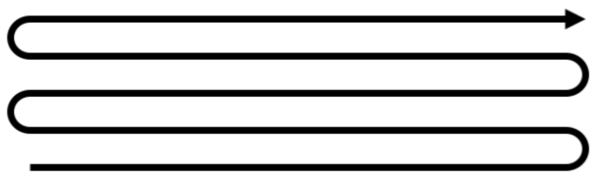


Figure 13. Extruding path for the first layer

After extruding six layers equal to the first one, one on top of the other, a specimen of approximately 150 mm long, 50 mm wide, and 50 mm high is obtained, as can be seen in Figure 14. The six layers extrusion is evaluated as OK if all the layers look overall continuous and with the same dimensions. The stability is evaluated as OK if the specimen does not collapse, tilt, or lose its shape significantly.

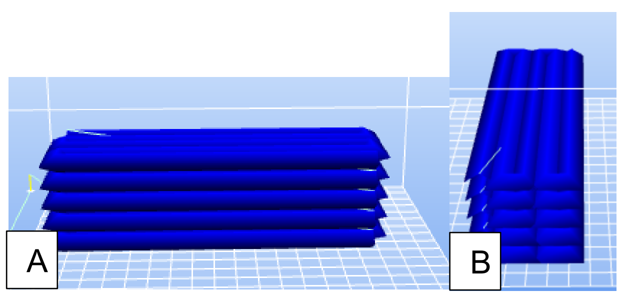


Figure 14. Extrusion and stability evaluation for 6 layers (A) side view (B) front view

As these sets of tests are preliminary and exploratory, after the qualitative tests for each sample, additional layers can be extruded to explore buildability and flow rate.

3.6.3 Buildability test

Buildability is evaluated as the capacity of the material to be continuously extruded in subsequent layers without the collapse of the whole structure.

At the last round of preliminary tests, a simple buildability test is performed by stacking concentric square layers with an approximate size of 60mm x 60 mm for the external square and 45 mm x 45 mm for the internal. The buildability is evaluated as OK if the structure does not collapse before 10 layers and the structure looks overall homogeneous. More layers can be attempted if the first 10 layers are ok.

3.7 Selection of components to be used in the DOE for the mortar formulation.

At the end of the preliminary tests, the key components for a mortar mix to be printable. In this way are identified, those components whose advantages are easily identifiable will be selected, and those that do not provide significant performance improvements or that even generate mixing or extrusion problems will be discarded.

In this way, when performing the design of experiments, the number of tests will be reduced since it is known in advance which are the components that are required for the mortar and only the appropriate proportions must be found.

3.7.1 Criteria for discarding components for the mortar

Any of the components used in the preliminary tests will be discarded for any of the following reasons: their presence or absence does not generate significant changes in the performance of the mix, the component is difficult to incorporate into the mix, or the component generates extrusion problems.

3.8 Identification of levels of component proportions to be used in the DOE for the mortar formulation

During the preliminary tests, formulations with very different proportions among themselves will be evaluated, that is, while some authors use large amounts of certain components, others use few amounts. This is why, after the preliminary tests, it will be identified for each component, which is the highest and the lowest level of proportion in which good performance is obtained. These levels will be used as the upper and lower level in the DOE to be carried out later.

3.9 Design of experiments for the development of the novel extrudable mortar

By defining which are the components that are going to be present in the extrudable mortar being developed; and by having an idea of which are the proportion levels in which these materials provide better performance. It is possible to carry out a small design of experiments for the final formulation to be used for printing.

The response variable will be the printability, which involves fresh state and hardened state properties, that can be more fully evaluated in qualitative tests to be performed at the home laboratory, and quantitative tests to be performed at a cement laboratory.

3.9.1 Factorial Design

A 2^2 factorial with one center point is designed and shown in Table 7, where the two factors are sand (S) and silica fume (SF), expressed as proportions by weight of cement. The levels for each factor are set taking into account the formulations with the better performance in the preliminary tests:

- Sand: 0.4(-) and 3 (+)
- Silica Fume: 0.4(-) and 1.5(+)

Table 7. DOE Week 7

Run	S	SF
1	-	+
2	-	-
3	+	+
4	0	0
5	+	-

The amount of water is set to an initial of 0.5 by weight of cement, but additions can be made at the initial stages of mixing to achieve a visually compliant consistency, according to the method described in 3.6.1 . That is why each run has two replicates, in the first one the water additions are made, and in the second one, the final amount of water obtained from run 1 is used. Table 8 shows the total runs and proportions.

Table 8. Final DOE for mortar formulation.

Name	W (initial)	S	C	SF
1-1	0.5	0.4	1	1.5
1-2	0.5	0.4	1	1.5
2-1	0.5	0.4	1	0.4
2-2	0.5	0.4	1	0.4
3-1	0.5	3	1	1.5
3-2	0.5	3	1	1.5
4-1	0.5	1.7	1	0.95
4-2	0.5	1.7	1	0.95
5-1	0.5	3	1	0.4
5-2	0.5	3	1	0.4

3.10 Qualitative tests for the DOE

As already mentioned earlier in this document, the evaluation of the properties of the printable mortar being developed cannot be entirely evaluated through quantitative tests using international standards, so consistency, extrusion, stability, and buildability must be evaluated by qualitative methods, which in general are the most used by authors who research in this type of application.

The evaluation process for consistency, extrudability, and buildability are described in detail in section 3.6. This time, for each formulation there are two replicates, for the first one there will be water additions, and that same amount of water will be used for the second replicate. Also, the extrusion is performed through both 9 mm and 15 mm nozzles, and extrusion of the first layer will not be evaluated.

3.11 Quantitative tests

3.11.1 Fresh state properties: slump and Slump-flow

As mentioned earlier in the literature review, a quick and easy quantitative way to assess whether a mortar is suitable for printing is by measuring the slump and slump-flow. The slump measures how much the material deforms vertically under its own weight, and the slump flow indicates how much the mixture flows when forces are applied to it, in this case, when it is going to be extruded. This test will be performed every 15 minutes, until achieving 1 hour. This will indicate how much the printability of the mortar changes with time.

The mixes with low slump and slump-flow values have low pumpability and may contain voids after printing, which would result in collapse once a few layers are deposited. The mixes with high slump and slump-flow values would not have enough static yield stress to sustain layers above them.

For this test, the conical mold and flow table are used in accordance with ASTM C1437.

- Put the mold on the flow table and fill half the mold with mortar
- Tamp 20 times evenly over the cross-section of the mortar
- Fill the rest of the mold and tamp again 20 times evenly over the cross-section of the mortar
- Excess material is removed by passing a spatula along the edge of the mold in a saw motion.
- The mold is removed and the height difference (start-end) is measured at the highest point and the lowest point. The percentage of difference from the initial height is recorded as Slump.
- The table is hit 25 times.

- The diameter is measured at two points. Record the average in millimeters as Slump-flow.

3.12 Extruded probes preparation

As explained in section 2.5.2 , there is no standard test method to measure the compressive strength of extruded mortars, that is why the specimens must be prepared to obtain a geometry similar to the 50 x 50 x 50 mm cubes, that are used in the ASTM C109 / C109M-20 standard. The process for preparing, curing, and cutting the specimens is explained below.

3.12.1 Curing process

After completing the evaluation of the fresh state properties of the DOE formulations, explained in section 3.6; for each formulation, 2 prisms with approximate dimensions of 150 x 50 x 50 mm are obtained.

These prisms are left to harden for 24 hours in the environment and then are stored in a container saturated with water.

3.12.2 Cutting of cubic samples

To measure the compressive strength of the specimens extruded by hand, an approach to the ASTM C109/C109M-20 method will be used. Hence, each prism is to be cut transversely to the printing direction into two cubes of approximately 50 x 50 x 50 mm.

3.12.3 Extruded samples cross-section analysis

After cutting the specimens into cubes, a visual evaluation of the cross-section will be carried out. It will be checked if the majority of the filaments are fused to their adjacent filaments, which Is desirable for better compressive strength. Or if on the contrary, there are gaps between adjacent filaments, weakening the structure.

3.13 Compressive strength testing

To know the mechanical strength of each of the mortar formulations in the DOE, the compressive strength in cubic specimens will be measured according to the ASTM C109 / C109M-20 standard. The evaluation of casted samples and extruded samples is going to be performed.

3.13.1 Casted samples

After measuring slump and slump-flow as mentioned on 3.11, each mortar mix is cast into three cubic molds, following the procedure of standard ASTM C109 / C109M-20. The cubes are tested for compressive strength, one after 24 h, the other after 3 days, and the last one after 7 days with appropriate curing conditions.

3.13.2 Extruded samples

After following the specimen preparation process explained in section 3.12, 4 cubic specimens are obtained from each of the formulations in the DOE, which will be evaluated following the procedure indicated in ASTM C109 / C109M-20 for the measurement of compressive strength, as follows:

From the 4 cubes obtained from extrusion through the 9 mm nozzle, two of them will be compressed applying the force longitudinally to the extrusion direction, and the other two applying the force transversely to the extrusion direction.

3.14 Mortar formulation selection

After completing the qualitative and quantitative tests of the design of experiments, there is enough data to select the formulation with the best performance and definitively rule out those that do not meet the basic criteria to be used for 3D printing.

3.14.1 Selection criteria

For the qualitative tests, the selected formulation must be evaluated as OK in the consistency, first layer extrusion, six layers extrusion, stability, and buildability tests. they must also be extrudable through the 9 mm and 15 mm nozzles.

As for the quantitative tests, the selected formulation must have an initial and final slump value (after 60 minutes) of less than 6%. As for the slump flow, its initial and final value must be within the range of 150-190 mm.

Regarding mechanical strength, the one with the best performance in the compressive strength tests will be chosen, both for casted probes and extruded probes.

3.15 Available technology for extrusion systems

After the literature review, one of the most relevant aspects in the selection of material deposition methods for 3D printing for construction is the selection of the type of printer and the type of extruder to be used. For this, it is necessary to take into account what is the scope of the project and what is the scale at which you want to carry out the printing tests. In the same way, the type of machinery available and the ease of manufacture of the designs that are made must be taken into account.

3.16 Fabrication and evaluation of the extruder

The extruder designed by one of the partners is going to be manufactured by 3D printing, which implies an additional challenge, which is the adjustment of the printing conditions that allow the parts to be manufactured with the highest geometric fidelity and avoiding contraction or warping problems.

In this order of ideas, in each manufacturing attempt, it will be verified that the printed parts do not have contraction or warping problems, that they have an adequate thickness so that they are resistant, and that they fit perfectly with each other.

3.17 Extrusion tests using the fabricated extruder and the selected mortar formulations

Having a functional extruder prototype, the next step is to carry out extrusion tests. for this, the formulation with the best performance selected according to the criteria mentioned in 3.14 will be used.

3.17.1 Endless screw movement calibration

The extruder will be coupled to a robot that was originally designed to be a 3D FFF printer, that is why the motor that will be used for the extruder works with the g-code commands that would make a plastic filament towards the hot end of the printer.

To calibrate the movement of the endless screw, the number of motor steps per unit so that one unit in the g-code is one complete revolution of the screw must be found. For this, with the help of the Repetier-Host Software, the steps per unit will be varied until the screw makes one complete turn when asking the printer to extrude a unit.

3.17.2 Mortar feeding and flow through the extruder

Before starting the printing tests, it is important to ensure that the extruder works correctly for the selected mortar. First of all, it must be possible to feed the mortar to the extruder without affecting the operation of the endless screw and the robot. Second, the screw must be able to move the material from the top of the extruder towards and through the nozzle, without overflowing or jamming. Third, the movement of the screw must make the extruded mortar filament come out continuously and homogeneously. And fourth, the extruder’s motor must have enough torque to work without any problem.

3.17.3 Mortar extruding

To test the repeatability in the extrusion of the mortar, some tests will be carried out in which it will be visually checked how different the lengths of several extruded filaments are for the same number of revolutions of the endless screw. So multiple segments will be extruded for 1, 2, 3, 4, and 5 revolutions.

3.18 Setup of the printer and printing tests

Once it is ensured that the extruder works correctly with the selected mortar, it is proceeded to adapt the extruder to the printing robot that the partners finally provide.

With this, flow rate and travel speed selection tests will be performed to obtain the best possible print quality. This being the one in which completely continuous filaments are obtained, with minimum gaps or irregularities in the diameter.

3.18.1 Printing parameters

To find the most suitable printing parameters for the extruder and the mortar mixture, it must be known the appropriate combination between the extruder's displacement feed rate in XY and the revolutions of the endless screw per millimeter of deposited filament.

As an initial exploration, a 5^2 factorial design will be made with 5 levels of feed rate, 5 levels of revolutions, and 3 repetitions. The tests will be done in order, in incremental feed rates and revolutions, as shown in Table 9.

Table 9. Order for the tests in the initial exploration of printing parameters (Incremental)

	Feedrate				
Revolutions	**500**	**1000**	**1500**	**2000**	**2500**
4	**T1**	**T2**	**T3**	**T4**	**T5**
6	**T6**	**T7**	**T8**	**T9**	**T10**
8	**T11**	**T12**	**T13**	**T14**	**T15**
10	**T16**	**T17**	**T18**	**T19**	**T20**
12	**T21**	**T22**	**T23**	**T24**	**T25**

The feed rate levels will range from 500 to 2500 in increments of 500, the revolutions levels will range from 4 to 12 in increments of 2. Each test consists of a continuous, straight extrusion 200 mm long, using a 9 mm nozzle and a standoff distance of 9 mm.

The response variable is the printing quality, according to the qualitative criteria mentioned in section 3.6, which are the continuity and homogeneity of the extruded filament. In the end, the necessary information will be found to carry out more exhaustive tests at the levels where the best results are found.

With the results of the initial exploration, the levels of feed rate of displacement and revolutions of the extruder will be defined, in which the best results are expected to be achieved. These will undergo additional extrusion tests in which the quality and continuity of extrusion will be verified in longer segments.

The number of tests will be defined according to the results of section 3.4. Each test consists of extruding 5 continuous segments 200 mm long, following the path shown in Figure 13 of section 3.6.2 . A 9 mm nozzle will be used, and the standoff distance will be 9 mm.

With the results obtained, a single value of feed rate will be defined for the displacement of the extruder, and with the number of revolutions per segment of 200 mm, the required revolutions per printed millimeter will be calculated.

3.19 Multilayer printing

After setting the feed rate of displacement of the extruder in the XY directions and the revolutions of the endless screw per millimeter of extruded filament, it is ensured that all layers extruded under those conditions will have the same dimensions. However, the optimal standoff distance between the nozzle and the surface must be found, that is, the layer height.

For each test six subsequent layers will be extruded, each of them following the path shown in Figure 13 of section 3.6.2 . Three standoff distances will be tested: 8, 9, and 10 mm. The printing quality will be evaluated according to the criteria mentioned in section 3.6.

3.20 Pilot test for the printing of a complex structure

Once it is ensured that the selected formulation can be extruded correctly, that the travel speed and flow rate parameters are correct for the expected printing quality, and also that material can be freely extruded in the X and Y directions and layer by layer in the Z direction. Final tests will be performed in which the objective is to print a complex structure on a small scale based on a CAD model.

3.20.1 First pilot test with simple trajectory

The structure shown in Figure 15 will be printed. It is composed of a 100 mm x 100 mm solid base, and a double filament shell of 10 layers.

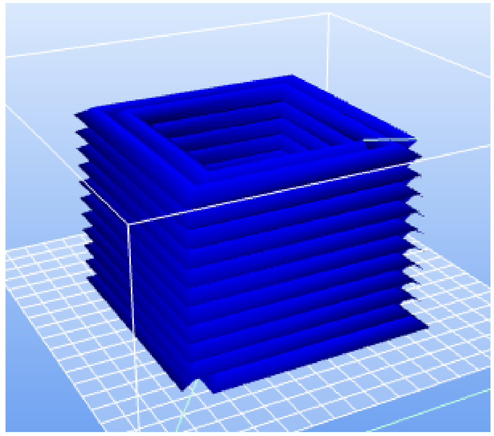


Figure 15. Model for pilot test

The trajectories for the first layer and the next layers are shown in Figure 16.

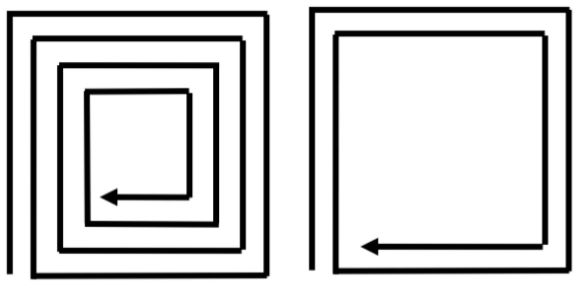


Figure 16. Printing trajectory for pilot test, first layer (left), next layers (right)

3.20.2 Second pilot test with complex trajectory

Based on the same structure of the first pilot test, a second test with a different trajectory will be performed, as shown in Figure 17.

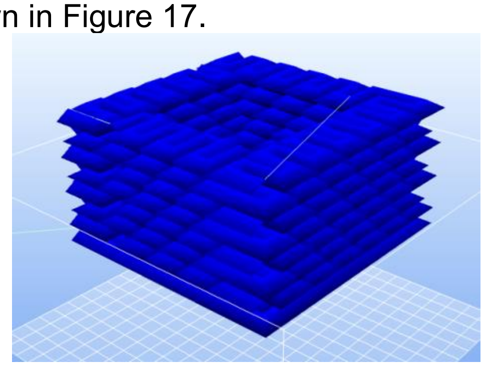


Figure 17. Model for complex trajectory for pilot test

The trajectory for the first layer will be the same as in the first pilot tests, but for the next layers, a complex trajectory will be used, as shown in Figure 18. As there are many changes in the direction of the movement. It will help to see how the printer can move in any direction, even when the printed piece is heavy, and to validate if the nozzle drags the filament and affects the printing quality.

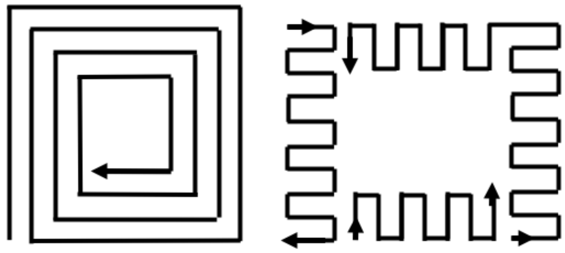


Figure 18. Complex trajectory pilot test. First layer (left), next layers (right)

3.20.3 Third pilot test for hollow wall

To show one of the advantages of cement-based 3D printing for construction, a small-scale wall will be printed, where it will be shown that this technique has great potential for material optimization. The model and trajectory are shown in Figure 19 and Figure 20 respectively.

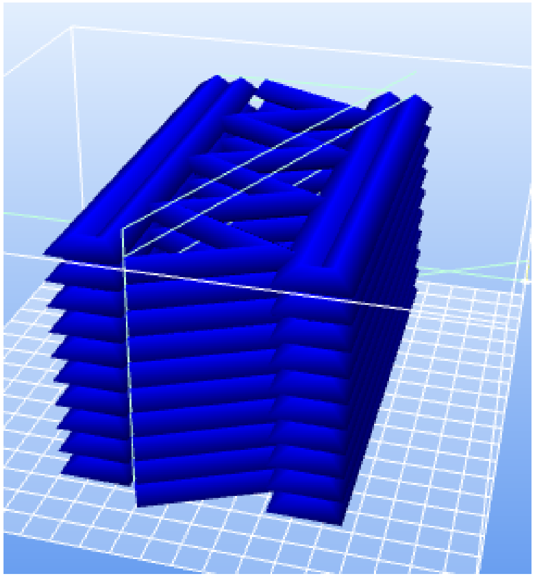


Figure 19. Hollow wall model

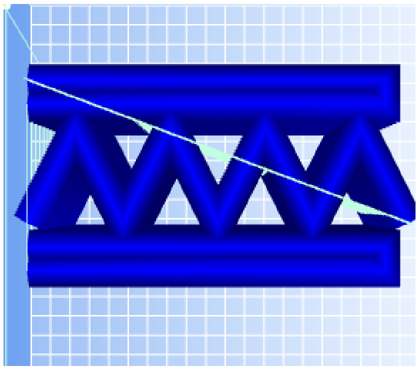


Figure 20. Hollow wall trajectory

4 Chapter 4: Results and Discussion

This chapter is primarily focused on making a chronological and sequential report of the results of all the activities that were carried out according to the methodology described in the previous chapter.

These activities can be classified into four main stages. The first was an exploratory work on mortars, their components, proportions, preparation standards, and properties evaluation. The second was a DOE for the development of a new printable mortar formulation. The third was the design and manufacturing of a mortar extrusion system linked to a printing robot. And finally, the fourth stage consists of using the formulation developed in the second stage in conjunction with the robot developed in the third to test printed structures on a small scale.

4.1 Preliminary tests of extrudable mortars formulations

The preliminary tests began with the first round of experiments using the formulations outlined in 3.4.1 . Subsequently, according to the additions that were made, and the results of the qualitative evaluation, modifications were made to the formulations and the second round of preliminary tests was carried out. Finally, it was decided to do a third round of experiments making some adjustments and using only those formulations with the best performance in the previous round.

The formulations for each round, before and after the modifications, are shown below

4.1.1 First round of experiments

4.1.1.1 Final Formulations after additions

To achieve the expected consistency, additions of water and Psol were made in each of the tests. In this way, the formulas in Table 6 become those shown in Table 10.

Table 10. Final used formulations after additions in the first round of experiments. Proportions by weight of cement.

Name	W	S	C	SF	Fibers	PSol
Test 1 - (Zhang et al.)	0.35	1.00	1.00	0.04		0.10
Test 2 - (Manikandan et al.)	0.30		1.00	0.04		
Test 3 - (Le et al.)	0.52	1.50	1.00	0.43	0.0034	0.14
Test 4 - (Weng et al.)	0.65	0.50	1.00	1.10		0.14
Test 5 - Paul et al.	1.25	4.18	1.00	1.46	0.02	0.46
Test 6 - (Kazemian et al.)	0.54	2.26	1.00	0.10		0.08
Test 7 - (Tay et al)	0.71	2.43	1.00	0.43		0.05

4.1.2 Second round of experiments

4.1.2.1 Initial Formulations based on the modifications proposed after round 1

After the first round of preliminary tests, the second round of tests was proposed, in which Test 2 was eliminated, the use of PSol was eliminated and some proportions of the other formulations were modified. The details of the modifications can be seen in section 4.3.1.3.

In this way, the formulas of Table 10, used in the first round, become those shown in Table 11.

Table 11. Modified formulations for the second round of preliminary tests. Proportions by weight of cement.

Name	W	S	C	SF	Fibers
Test 1.2	0.45	0.50	1.00	0.54	
Test 3.2	0.66	1.50	1.00	0.43	0.0034
Test 4.2	0.65	0.50	1.00	1.10	
Test 5.2	1.46	4.19	1.00	1.46	0.0078
Test 6.2	0.52	2.19	1.00	0.54	
Test 7.2	0.81	2.24	1.00	0.62	

4.1.2.2 Final formulations after additions

After performing the qualitative tests for this round of experiments, water additions were made to achieve the desired consistency, the final used formulations are shown in Table 12

Table 12. Used formulations after additions. Proportions by weight of cement.

Name	W	S	C	SF	Fibers
Test 1.2	0.57	0.50	1.00	0.54	
Test 3.2	0.66	1.50	1.00	0.43	0.0029
Test 4.2	0.65	0.50	1.00	0.57	
Test 5.2	1.78	4.19	1.00	1.46	0.0067
Test 6.2	0.80	2.19	1.00	0.54	
Test 7.2	0.90	2.24	1.00	0.62	

4.1.3 Third round of experiments

4.1.3.1 Formulation planning for the Third round of experiments

The third round of experiments was carried out, based on the 3 formulations with the best performance in the previous round: Tests 1, 6, and 7. Slight modifications were made to the water content.

Also, an additional version of Test 5 is done, this time without using fibers, which in previous rounds generated clumps and discontinuities. These formulations can be seen in

Table 13. This time there are not additions as the desired consistency was achieved with the specified water amount.

Table 13. Formulations for the third round of preliminary tests. Proportions by weight of cement. Water(W), Sand (S), Cement (C), Silica fume (SF)

Name	W	S	C	SF
Test 1.3	0.60	0.50	1.00	0.54
Test 5.3	1.72	4.19	1.00	1.46
Test 6.3	0.82	2.19	1.00	0.54
Test 7.3	0.88	2.24	1.00	0.62

4.2 Mortar mixing and testing standardization.

During the three preliminary test rounds, the mixing and qualitative evaluation methods described in sections 3.5 and 3.6 of the methodology were used. It was found that these methods are adequate to be used in the rest of the experiments of this thesis, therefore no modifications were made.

4.3 Qualitative analysis of preliminary tests

4.3.1 First Round

4.3.1.1 Consistency test

In this round, the most significant observation was that PSol was not working as a plasticizer, since very significant amounts of it had to be added for the mortar to lower its viscosity, which indicated that what was influencing the viscosity was the water. For this reason, it was decided not to use Psol in the following rounds of tests.

Most samples were evaluated as OK given that this property could be estimated beforehand, and additions of water were made before the end of the mixing process. Figure 21 (B) shows Test 7 as a passing sample.

Test 2 did not pass because, after the additions of Water and Psol, it was workable but looked dry and detached from the pallet, it had a consistency similar to kinetic Sand. On the other hand, Test 5 did not pass because the mortar dripped from the trowel, as can be seen in Figure 21 (A).

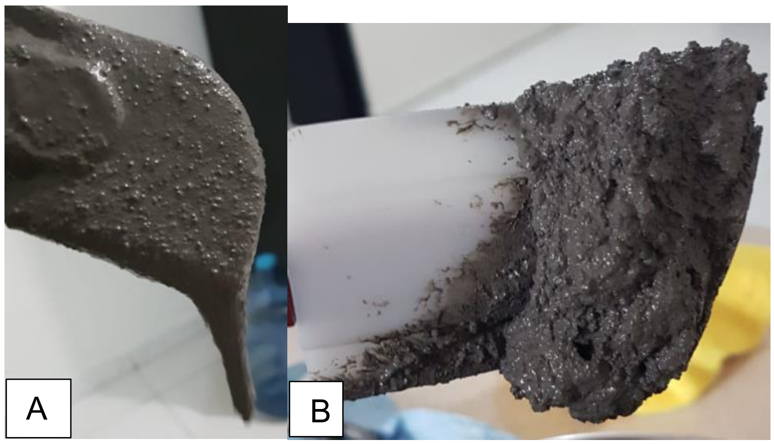


Figure 21. Consistency tests for first round of preliminary tests, (A) Test 5 - NOT OK, (B) Test 7 - OK

4.3.1.2 Extrusion, clumps, and stability evaluation

In general, all the formulations had issues either in the extrusion process or in the final result.

4.3.1.2.1 Nozzle size

Tests 1, 6, and 7 passed through the 9 mm nozzle with no drips or blockages. Test 3 passed through the 9 mm nozzle but was then blocked by the fibers. Test 4 did not pass through the 9 mm nozzle; it did pass through the 15 mm nozzle but required a lot of pressure. Tests 2 and 5 could not be extruded, not even through the 15 mm nozzle; Test 2 because it required a lot of pressure, and Test 5 because the mixture was dripping, and the fiber clumps blocked the nozzle.

4.3.1.2.2 First layer

Only Tests 3, 6, and 7 were evaluated as OK, because as can be seen in the examples shown Figure 22 (B) and (C), the filament is mostly continuous, without significant gaps or diameter variations. Also, the extruding process was smooth. Test 1 was extrudable but as can be seen in Figure 22 (A), it had significant changes in the filament diameter and some discontinuities. On the other hand, Tests 2 and 5 were not extrudable at all.

Figure 22. First layer extrusion of first round of preliminary tests (A) Test 1, (B) Test 3, (C) Test 7

4.3.1.2.3 Six layers

Only Test 6 was evaluated as OK for the extrusion of six layers, because it was the only sample that was easily extrudable, without overall discontinuities or filament diameter variation. However, as it can be seen in Figure 23 (C), The specimen was not stable at all; after a while, the layers lost their shape and the intermediate layers collapsed.

As it can be seen in Figure 23 (A) and (D), tests 1, 4, and 7 were stable after extrusion, they did not exhibit significant deformation after extruding; contrary to the rest of the samples, where the specimens tilted or collapsed or after extrusion, as shown on Figure 23 (B) and (C).

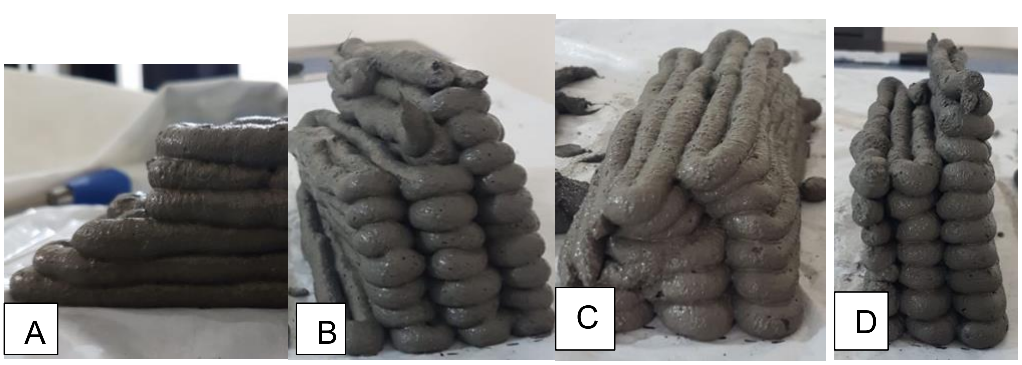


Figure 23. Extrusion of 6 layers first round of preliminary tests (A) Test 1, (B) Test 3, (C) Test 6, (D) Test 7

4.3.1.3 Insights

Table 14 compiles all of the results of the qualitative evaluation of this round of experiments.

Table 14. Qualitative evaluation of first round of preliminary tests

Name	Consistency test	Nozzle (mm)	Extrusion first layer	Extrusion six layers	Stability
Test 1 - (Zhang et al.)	OK	9	NOT OK	NOT OK	OK
Test 2 - (Manikandan et al.)	NOT OK	15*	NOT OK	NOT OK	NOT OK
Test 3 - (Le et al.)	OK	9	OK	NOT OK	NOT OK
Test 4 - (Weng et al.)	OK	15	NOT OK	NOT OK	OK
Test 5 – (Paul et al.)	NOT OK	15*	NOT OK	NOT OK	NOT OK
Test 6 - (Kazemian et al.)	OK	9	OK	OK	NOT OK
Test 7 - (Tay et al)	OK	9	OK	NOT OK	OK

Table 15 shows a summary of the observations for each test and the suggested modifications for the formulations and a general insight for this round.

Table 15. Observations from the first round of preliminary tests and modifications for the next round

Test	Main observation	Modification
Test 1 (Zhang et al.)	Extrudable but loses the property with time.	Increase SF content to 0.54 and decrease S to 0.5. for extrudability improvement
Test 2 (Manikandan et al.)	Hard to extrude even through a 15 mm nozzle	Formulation is dismissed, it would require many additions.
Test 3 (Le et al.)	Low extrusion pressure without dripping but had many clumps that fully blocked the nozzle.	Same formulation taking care of fiber dispersion
Test 4 (Weng et al.)	Non-extrudable through 9 mm nozzle because it required much pressure for extruding	Reduce SF content to 1.1 and increase water to improve extrudability
Test 5 (Paul et al.)	The mortar was dripping from the nozzle and fibers formed clumps that blocked the extrusion	Reduce the amount of water to 1 and use the same number of fibers as Test 3
Test 6 (Kazemian et al.)	Was extrudable and continuous but deposited layers lost their shape after few minutes	Reduce water to 0.44, increase SF to 0.54 and decrease S to 2.19 for Thixotropy improvement.
Test 7 (Tay et al)	Good extrusion and stability but had few discontinuities.	Increase SF to 0.62 and water to 0.82
General	Psol did not work as a plasticizer, the water in it was the one lowering the viscosity of the mortars. Fiber dispersion is important to avoid clumps.	PSol is dismissed for the following round of tests.

4.3.2 Second Round

4.3.2.1 Consistency test

All samples were evaluated as OK, given that, after the first round of tests, it was known beforehand the most likely amount of water that needed to be added to achieve the desired consistency.

4.3.2.2 Extrusion and stability evaluation

4.3.2.2.1 Nozzle size

Tests 6.2 and 7.2 passed through the 9 mm nozzle with ease. However, test 1.2 was hardly extrudable through both 9 mm and 15 mm nozzle, it required much pressure. Test 4.2 did not pass through the 9 mm nozzle and hardly did through the 15 mm one.

From the formulations using fibers, Tests 3.2 hardly passed through the 9 mm nozzle due to fiber clumps and did pass through the 15 mm nozzle but with sudden blockages. Test 5.2 passed through the 9 mm nozzle but with sudden blockages.

4.3.2.2.2 First layer

Only tests 6.2 and 7.2 had a good extrusion, the layers were continuous, smooth, and homogeneous. Even though Tests 1.2 and 4.2 had an appropriate consistency, they were hard to extrude, therefore the first layer had discontinuities and the filament diameter was uneven.

As for the formulations with fibers, Test 3.2 and 5.2 had extrusion problems even when special attention was put into the dispersion of the fibers. The mortars were extrudable, but they still had clumps that caused sudden changes in the pressure required for extruding, which generated discontinuities and lowered the quality of the extruded filament.

4.3.2.2.3 Six layers

Most samples had the same behavior as in the extrusion of the first layer. Test 7.2 improved the extrusion after the first layer but there were still discontinuities. Tests 1.2, 3.2, 4.2, and 5.2 were extrudable, but the layers looked discontinuous and the filament diameter was not even, as can be seen in Figure 24.

Regarding the stability, all formulations kept their shape after the extrusion, without tilting or collapsing, this can be seen in Figure 24.

Figure 24. Six layers extrusion at the second round of preliminary tests

4.3.2.3 Insights

Table 16 compiles all of the results of the qualitative evaluation of this round of experiments.

Table 16. Qualitative evaluation of second round of preliminary tests

Name	Consistency test	Nozzle (mm)	Extrusion first layer	Extrusion six layers	Stability
Test 1.2	OK	15	NOT OK	NOT OK	OK
Test 3.2	OK	15	NOT OK	NOT OK	OK
Test 4.2	OK	9	NOT OK	NOT OK	OK
Test 5.2	OK	9	NOT OK	NOT OK	OK
Test 6.2	OK	9	OK	OK	OK
Test 7.2	OK	9	OK	OK	OK

Table 17 shows a summary of the observations for each test, the suggested modifications for the formulations, and a general insight for this round.

Table 17. Observations from the second round of preliminary tests and modifications for the next round

Test	Observations	Modifications
Test 1.2	The extrusion is hard at the beginning but then with constant pressure it gets, better. The extruded structure is stable	Increase the amount of water (0.6) for better workability
Test 3.2	Only extrudable through the 15 mm nozzle, fiber clumps blocked the nozzle, and the extrusion was uneven but stable	This formulation is dismissed due to the clumps generated by the fibers
Test 4.2	Workable but hardly extrudable. The extrusion was uneven but stable	This formulation is dismissed because it is hard to extrude
Test 5.2	Fiber clumps blocked the nozzle, and the extrusion was uneven but stable	Fibers will be dismissed, water increase to 1.72
Test 6.2	Did OK in all tests	Increase of water to 0.82
Test 7.2	Did OK in all tests	Increase of water to 0.88
General	Fiber dispersion is hardly achievable. Higher sand and SF contents increase the water demand	Only the Three formulations with the best performance are going to be used for the next round. Fibers will be dismissed

4.3.3 Third round

4.3.3.1 Consistency test

Given that the formulations for this round of experiments did not change in proportions of dry materials, the water demand should not have changed, that is why no water additions were made, and all samples were evaluated as OK for this test.

4.3.3.2 Extrusion and stability evaluation

4.3.3.2.1 Nozzle size

For this round, all mortars went through the 9 mm nozzle. However, Test 1.3 was the only one that required a significant amount of extrusion pressure.

4.3.3.2.2 First layer

Only Test 1.3 had extrusion problems, the mortar was hard to extrude and the deposited layer looked very discontinuous and the filament was uneven. The other 3 samples were easily extruded.

4.3.3.2.3 Six layers

As it can be seen in Figure 25, all samples had the same behavior as in the first layer test, hence only Test 1.3 was hard to extrude and looked uneven and discontinuous. Regarding stability, all samples kept their shape after extruding, without tilting or collapsing.

Figure 25. Six layers extrusion at the third round of preliminary tests

4.3.3.3 Buildability

For this test, all samples were extrudable for ten layers; Test 1.3 was the hardest to extrude and presented discontinuities. As it can be seen in Figure 26, for tests 5.3 and 6.3, layers looked continuous and stable, the final structure looked asymmetric because of the inaccuracy of manual extrusion.

As Test 7.3 had the best extrusion and stability in this round of tests, after the ten layers of the buildability test, successive layers were extruded until the structure collapsed at 21 layers. The extruded structure at 20 layers can be seen in Figure 27.

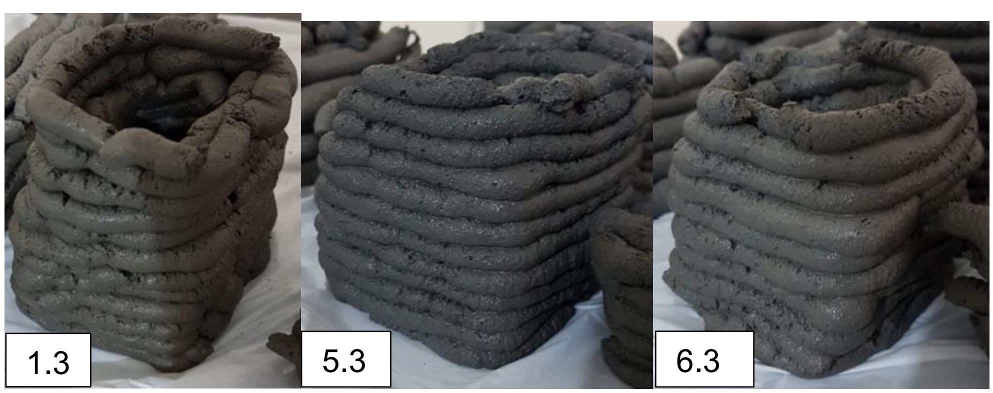


Figure 26. Buildability test for 10 layers, Third round of preliminary tests

Figure 27. Buildability of Test 7.3 after 20 layers

4.3.3.4 Insights

Table 18 compiles all of the results of the qualitative evaluation of this round of experiments.

Table 18. Qualitative evaluation of Third round of preliminary tests

Name	Consistency test	Nozzle (mm)	Extrusion first layer	Extrusion six layers	Stability	Buildability
Test 1.3	OK	9	NOT OK	NOT OK	OK	OK
Test 5.3	OK	9	OK	OK	OK	OK
Test 6.3	OK	9	OK	OK	OK	OK
Test 7.3	OK	9	OK	OK	OK	OK

Table 19 shows a summary of the final observations for each test.

Table 19. Observations from the second round of preliminary tests and modifications for the next round

Test	Observations
Test 1.3	The formulation was extrudable and stable, but the deposited layers were discontinuous and uneven
Test 5.3	The consistency feels low but did not drip from the nozzle and the extrusion and stability were ok
Test 6.3	The formulation did OK in all tests
Test 7.3	Had the best performance in this round of experiments, it achieved 20 deposited layers.
General	Besides Test 1.3 all formulations passed the qualitative tests, and they will work as a starting point for the DOE

4.4 Selection of components to be used in the DOE for the mortar formulation.

In section 4.3, Initially, there were two liquid components, water and PSol; and four solid components, Sand, Cement, SF, and fibers. After the first round of tests, the use of PSol was ruled out; since, as it was not a high-performance plasticizer, it was not contributing to lower the viscosity of the mortars, it was the water present in it that was improving the plasticity.

In the first round of tests, the plastic fibers added to two of the formulations were forming clumps in the mortars, blocking the nozzle and generating poor quality in the extrusion. At first, it was thought that this problem could be solved by improving the dispersion during the mortar preparation and mixing process; however, in the second round of tests, the problem persisted, so it was decided to discard the use of the fibers.

Based on the above, it was decided that only five components were to be used for the DOE: water, sand, and Portland cement, as they are the main components of the mortar. And silica fume, as it improves the stability and extrudability of the mortars.

4.5 Identification of levels of component proportions to be used in the DOE for the mortar formulation

After being clear about the components of the formulations for the DOE, it was observed which were the proportions of each of them in which the mortars had a better performance in the preliminary tests.

Since all the formulations are expressed in proportion by weight of cement, it was clear that the proportion of cement was always going to be 1. and on the other hand, the water demand of each mortar depends on the proportions of the dry materials, it is that is why it should not be fixed.

This left with two components, sand, and SF. In the preliminary tests, it was found that the mortars had a better performance when the proportion of sand was at a minimum of 0.5 and a maximum of 2.24. And when the proportion of SF was at the minimum 0.54 and the maximum 1.46.

4.6 Qualitative tests for the DOE

4.6.1 Consistency test

As can be seen in the images shown in Table 20, all formulations passed the consistency test. It can also be seen how the consistency looks the same for both runs of each formulation, taking into account that, in the first run, water additions were made during mixing, and for the second run the additions were already included in the total water, as it can be seen in Table 21.

Table 20. Consistency evaluation for DOE

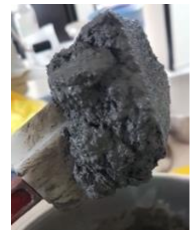
Formulation	Run 1	Run 2
1		
2		
3		
4		
5		

Table 21. Water demand as a proportion by weight of cement

Name	1-1	1-2	2-1	2-2	3-1	3-2	4-1	4-2	5-1	5-2
Initial W/C	0.5	1.1	0.5	0.5	0.5	1.5	0.5	1.0	0.5	0.8
Addition	0.6	-	-	-	1	-	0.5	-	0.3	-

4.6.2 Extrusion, clumps, and stability evaluation

All samples in the DOE were extrudable through the 9 mm nozzle, without clumps or stability issues.

The main differences among formulations were regarding extrusion; 2 and 3 were the easiest to extrude, they did not require much pressure for extrusion, minimum discontinuities were detected, mostly caused by human error. Formulations 1 and 4 required significant amounts of pressure to start flowing, but once the mortar started to come out of the nozzle, the pressure decreased, and it got easier to extrude. Formulation 5 had a fair extrusion, but the layers looked discontinuous and rough. Table 22 shows the final extrusions for each formulation.

Table 22. Extrusion and stability of DOE formulations through 9 mm nozzle

Formulation	Extrusion
1	
2	
3	
4	
5	

4.6.3 Buildability

All formulations achieved more than 10 consecutive layers, however, as it can be seen in Figure 28, formulation 2 was the one that looked more homogeneous and stable, mainly because it was easy to extrude and that made it easier to manually deposit even layers. The other formulations had sometimes discontinuities and uneven layers, on the one hand, because of the extrudability of the mortar and on the other hand because of human error.

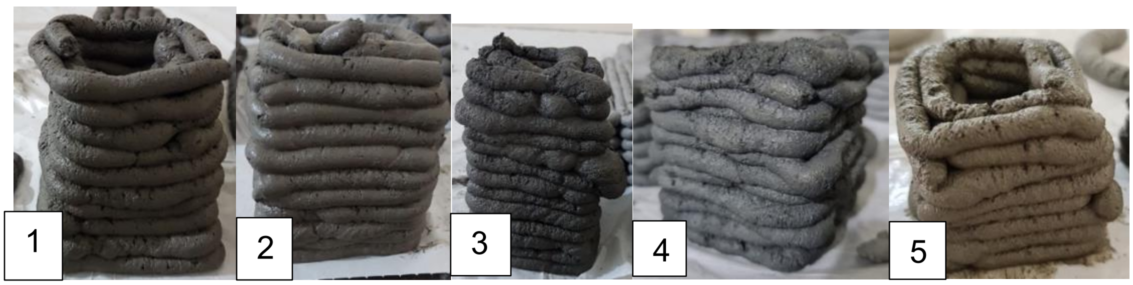


Figure 28. Buildability in DOE

4.6.4 Insights

Table 23 summarizes the observations of the qualitative tests performed at the home laboratory for the DOE formulations.

Table 23. Qualitative evaluation of mortars from the DOE

Name	Consistency test	Pass through 9 mm nozzle	Extrusion six layers	Stability	Buildability
Run 1-1	OK	OK	OK	OK	NOT OK
Run 1-2	OK	OK	OK	OK	NOT OK
Run 2-1	OK	OK	OK	OK	OK
Run 2-2	OK	OK	OK	OK	OK
Run 3-1	OK	OK	OK	OK	NOT OK
Run 3-2	OK	OK	OK	OK	NOT OK
Run 4-1	OK	OK	OK	OK	NOT OK
Run 4-2	OK	OK	OK	OK	NOT OK
Run 5-1	OK	OK	NOT OK	OK	NOT OK
Run 5-2	OK	OK	NOT OK	OK	NOT OK

In terms of the formulations, samples with a higher amount of sand, demand more water for an extrudable consistency and also looked more discontinuous.

Findings from these qualitative evaluations will be later compared and discussed with the results of the qualitative tests for the fresh mortars, described in section 4.7

4.7 Quantitative tests

4.7.1 Fresh state properties: slump and slump flow

Measurements of slump and slump-flow were taken for each sample as described in section 3.11.1 and shown in Figure 29

Figure 29. Slump test (left) and slump-flow test (right)

4.7.1.1 Results

4.7.1.1.1 Slump

Figure 30 shows the results of the slump test performed every 15 minutes on each of the 5 formulations. In the first place, it can be noticed how only test 3 increases the percentage of slump over time, which is not desirable for this case, in which it is wanted that the mixture deforms under its weight as little as possible, and it can be an indicator that the low amount of cement delays the initiation of nucleation in the hydration process.

The other samples have little variation in their slump value, which is desirable in this case as it indicates that for at least 60 minutes, the mortars can retain their shape and support their weight without hardening. Sample 2 begins with a slump value of 6%, but after 15 minutes and for the remaining time, it remains with a constant value of 4%, this can be an indicator of the beginning of the nucleation process in the hydration of the cement. The other samples, 1, 4, and 5, have a constant slump value during the 60 minutes of 4%.

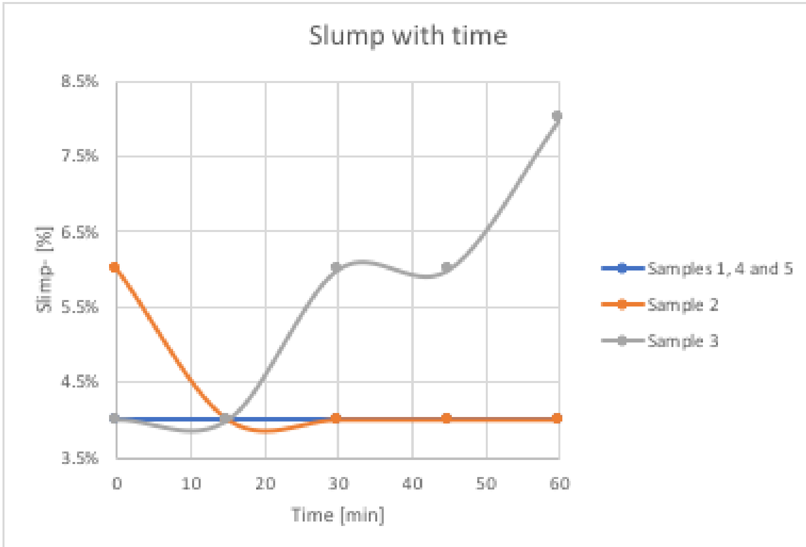


Figure 30. Change of the slump value with time for samples of the DOE

4.7.1.1.2 Slump-flow

Figure 31 shows how the value of slump-flow changes in a range of 1 hour from the preparation of the mortar. It was to be expected that the samples would lose fluidity over time since the cement hydration processes begin from the moment it comes into contact with water, that is why except for sample 3, all samples lose fluidity over time or remains constant, however, they remain in the range of 150mm to 184mm.

Sample 3 has the highest fluidity and ranges from 187mm to 195mm. the fact that its value increases and decreases over time might be because the nucleation processes in hydration are mild due to its low quantity of cement.

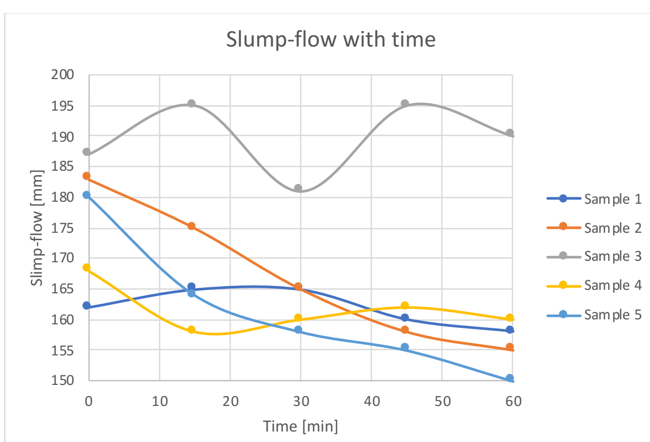


Figure 31. Change of the slump-flow value with time for samples in the DOE

4.7.2 Comparison of qualitative tests with quantitative tests

The results of the qualitative evaluation of consistency, extrudability, and stability, shown in section 4.6.4 , can be compared with the quantitative results of the slump and slump flow tests since both are intended to measure the ability of each mortar to be extruded and retain its shape under its weight.

Specifically, when comparing consistency and stability with the slump test, it can be noted that although in the qualitative tests, all mortars were evaluated with OK, in the quantitative test it can be seen how sample 3 has deformations greater than the others, which would imply that the greater the number of layers deposited, the greater the deviation of the height with respect to the diameter of the filament.

Formulation 5 was the only one that was evaluated as NO OK in the qualitative extrusion tests, and in the slump-flow test, it was also the one that reached the lowest flow levels. On the other hand, Formulations 2 and 3, which were the ones with the smoothest extrusion, obtained the highest flow values. This is an indication that the flow test is a quick indirect way of knowing the extrudability of a mortar.

4.8 Extruded probes preparation

4.8.1 Cutting of the specimens

To be able to measure the compressive strength of the extruded samples in section 4.6. Each prism was cut transversely to the extruding direction to obtain two cubes with approximate dimensions of 50 x 50 x 50 mm, however, given the complex shape and irregular surface, they were measured using a caliper to obtain the average area for the compressive strength tests.

4.8.2 Extruded samples cross-section analysis

After cutting the specimens into cubes, a visual evaluation of the cross-section was carried out. Table 24 shows the cross-section of the extruded samples for each formulation and nozzle diameter.

It is important to mention that since the samples are manually extruded, there are important variations in the homogeneity of the arrangement of each of the layers, however in this case the focus is seeing how well each of the filaments retain their shape after being deposited. and how well they fuse when they come into contact with adjacent filaments.

For all cases, there are empty spaces present, in some cases due to how the layers were deposited and in other cases due to the geometric stability of the filament. It can be noted that formulations 3 and 4 are the ones with the least number of voids, and 1, 2, and 5, despite having voids, the filaments that are in contact are also well fused.

Table 24. Longitudinal and cross-section of cubes cut from extruded probes

Formulation	Cross-section
1	
2	
3	
4	
5	

4.9 Compressive strength testing

4.9.1 Extruded samples

From the process mentioned in 4.8, two cubes were obtained for each pair of prisms, for two of them the force was applied parallel to the printing direction, and for the other two, it was applied perpendicular to the extruding direction. This can be seen in Figure 32. The applied force area for each cube was calculated with the average dimensions measured with a caliper.

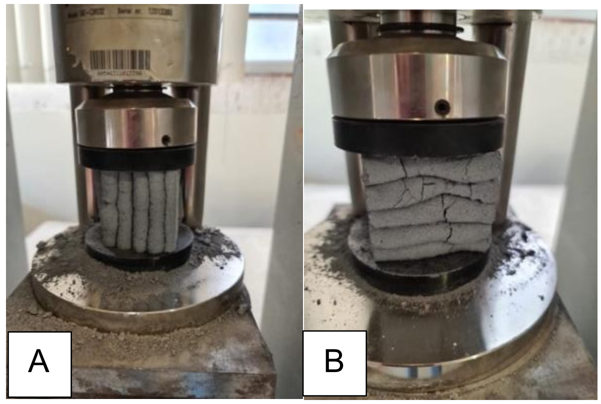


Figure 32. Compressive strength tests for extruded samples (A) longitudinal applied force (B) Transversal applied force

4.9.1.1 Longitudinal applied force

The compressive strength in MPa for specimens where the force was applied in the longitudinal direction of the extrusion can be found in Table 25.

Table 25. Compressive strength of extruded samples with longitudinal applied force

Longitudinal applied force			
Sample	**Run 1 (MPa)**	**Run 2 (MPa)**	**Average (MPa)**
1	4.983	5.125	5.054
2	12.095	12.203	12.149
3	1.997	1.351	1.674
4	10.937	11.101	11.019
5	8.235	7.583	7.909

As it can be seen in Figure 33, sample 2 was the one with the highest strength in both diameters, and sample 3 was the one with the lowest strength. In most cases, the strength was higher when the sample was extruded through a 15 mm nozzle, as the test specimen contained a lower number of voids. However, as was the case of sample 4, discontinuities in the extruded layers reduce the strength as they represent weak spots.

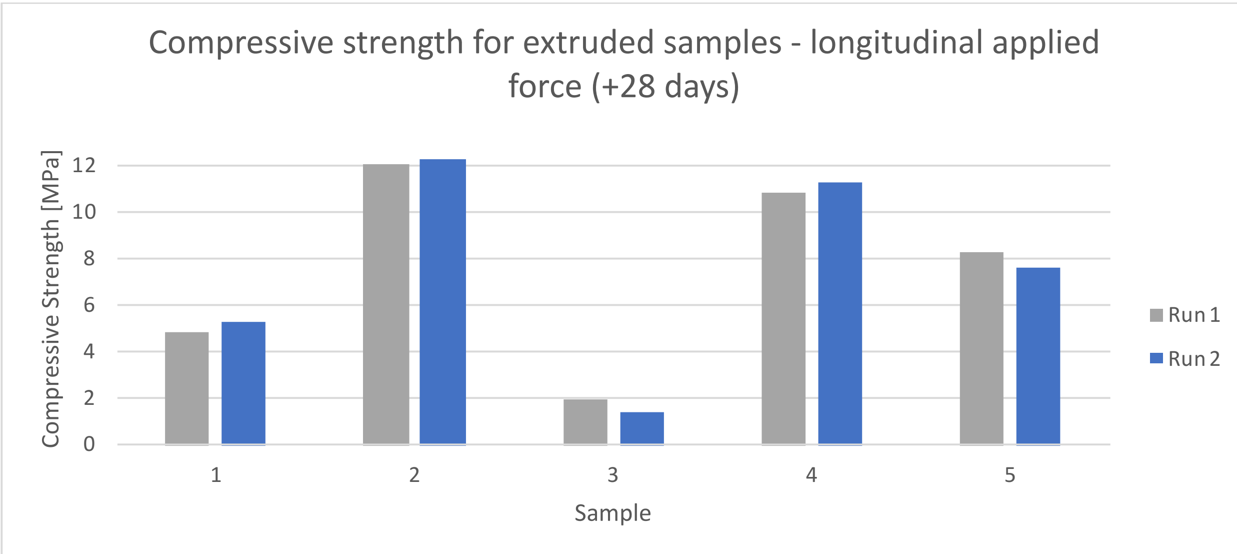


Figure 33. Compressive strength for extruded samples with longitudinal applied force

4.9.1.2 Transversal applied force

The compressive strength in MPa for specimens where the force was applied in the transversal direction of the extrusion can be found in Table 26.

Table 26. Compressive strength of extruded samples with transversal applied force

Transversal applied force			
Sample	**Run 1 (MPa)**	**Run 2 (MPa)**	**Average (MPa)**
1	1.187	1.485	1.336
2	4.286	4.792	4.539
3	0.542	0.529	0.535
4	2.947	2.793	2.870
5	3.750	3.396	3.573

As it can be seen in Figure 34, sample 2 was the one with the highest strength, while sample 3 had the lowest. Only for sample 5, the strength was significantly higher when extruded through the 9 mm nozzle.

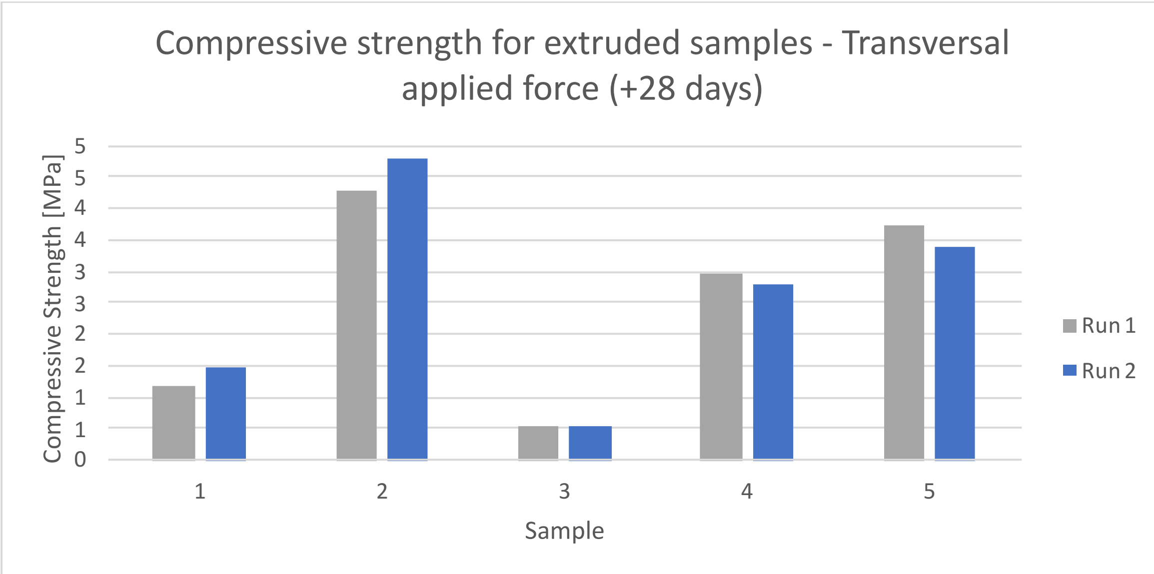


Figure 34. Compressive strength for extruded samples with transversal applied force

4.9.2 Casted samples

4.9.2.1 Civil engineering lab

After the first measurement of the slump and slump flow (at 0 minutes), part of each mixture was cast into cubes, as shown in Figure 35. After the demolding and appropriate curing, following the ASTM C109 standard, each cube was tested in the compression machine until failure, as shown in Figure 36.

Figure 35. Casted samples for compressive strength

Figure 36. Compressive strength test of a casted sample

The compressive strengths in MPa for each formulation at 24 h, 3 days, and 7 days are shown in Table 27.

Table 27. Compressive strength for samples of the DOE (Tec Laboratory)

Sample	24 h (Mpa)	3 d (Mpa)	7 d (Mpa)
1	2.3	7.8	14.9
2	16.7	28.3	40.1
3	1.8	5.5	10.3
4	6.0	12.9	21.8
5	7.1	14.3	19.1

4.9.2.2 CEMEX laboratory

The compressive strengths in MPa for each formulation at 24 h, 3 days, and 7 days are shown in Table 28.

Table 28. Compressive strength for samples of the DOE (CEMEX Laboratory)

Sample	24 h (Mpa)	3 d (Mpa)	7 d (Mpa)
1	2.2	8.3	13.8
2	17.8	30.3	39.7
3	1.9	5.9	9.8
4	6.3	13.8	20.3
5	7.2	14	19.1

4.9.2.3 Interlaboratory comparison and results.

4.9.2.3.1 Variation

Table 29 shows the variation for the compressive strength for Tec and CEMEX laboratories, where none of the samples has a variation greater than 7.4%. According to the ASTM C1437 standard, results from two different laboratories on similar batches should not differ by more than 19.2% for cubes at 3 days of age, and 18.1% at 7 days of age. It does not specify the permissible range for younger ages, but it mentions that it is larger than for 3 days. This means that the results are comparable.

Table 29. Interlaboratory variation for compressive strength

Sample	24 h	3 d	7 d
1	4.3%	-6.4%	7.4%
2	-6.6%	-7.1%	1.0%
3	-5.6%	-7.3%	4.9%
4	-5.0%	-7.0%	6.9%
5	-2.1%	2.2%	0.0%

4.9.2.3.2 Average results.

As there is not significant interlaboratory variation, the results from both laboratories were averaged and can be seen in Table 30.Table 30. Average results for compressive strength of casted samples

Table 30. Average results for compressive strength of casted samples

Sample	24 h (Mpa)	3 d (Mpa)	7 d (Mpa)
1	2.3	8.1	14.4
2	17.3	29.3	39.9
3	1.9	5.7	10.1
4	6.2	13.4	21.1
5	7.1	14.2	19.1

As it can be seen in Figure 37, for all cases, the strength of the mortars increases with their age, as the hydration reactions of the Portland cement slowly occur. However, formulation 2 has the greatest compressive strength at all ages and formulation 3 has the smallest.

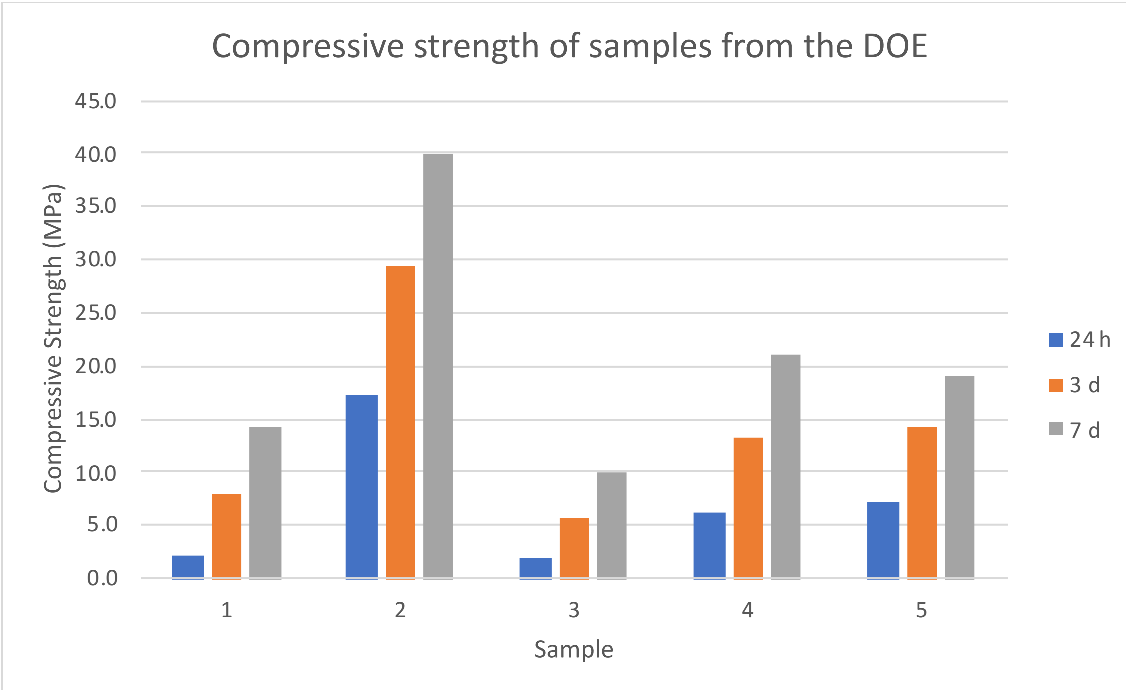


Figure 37. Compressive strength results for casted DOE samples

4.9.3 Findings

4.9.3.1 Extruding direction

It is notable that extruded mortars are anisotropic materials, so their compressive strength changes significantly when the direction of force is changed. Figure 38 shows the difference in compressive strength for each sample and each direction. In this case, the samples show less strength when the force is applied transversely to the printing direction. This is mainly because the structure is not completely solid, and the voids present between the filaments generate weakness in the material. That is why it is important to try to reduce the number of voids when defining the printing parameters for the printer.

In the case in which the force is applied in the extrusion direction, these voids do not affect in the same way since the path of the force inside the specimen is through the filaments. however, when there are discontinuities in the filaments, the path of force is interrupted, and the strength drops.

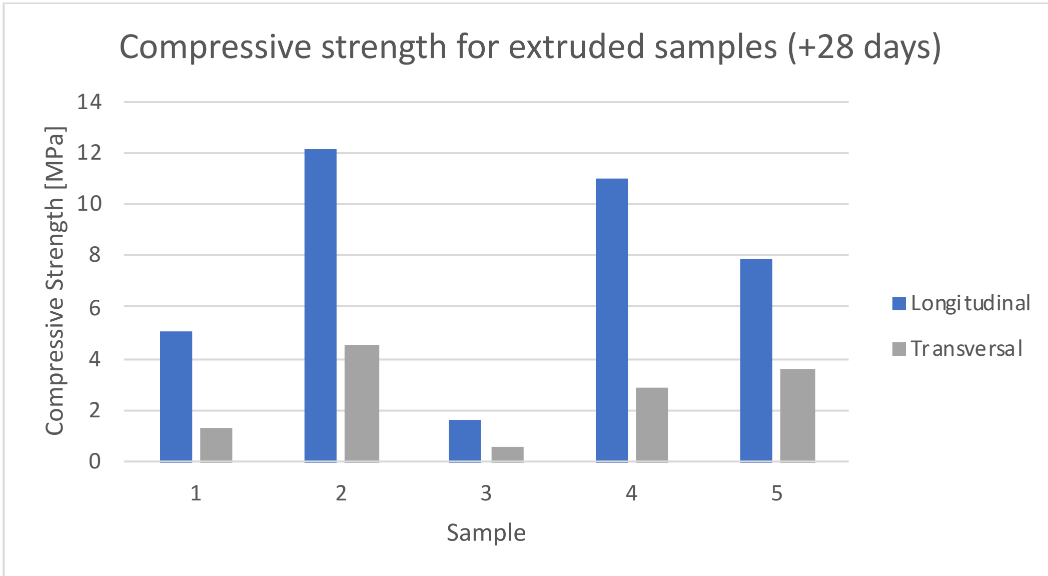


Figure 38. Compressive strength with direction

4.9.3.2 Formulation

Formulation 3, which is the one with both high levels of sand and SF, is the one with the lowest compressive strength in both directions, this is because it has a lower amount of cement, which is the material that provides the most of the strength to a mortar. In the same vein, the formulation, with both low levels of sand and SF, has the highest compressive strength in both directions.

Formulation 5, which has a high level of sand and a low level of SF, has a higher strength than formulation 1, which has a low level of sand and a high level of SF. This is an indication that sand has a less negative effect on strength than SF. This is corroborated with the result of formulation 4, which has intermediate levels of sand and SF and has strength similar to when there is a lot of sand and little SF.

4.9.3.3 Casted samples vs. Extruded samples

The results obtained for extruded samples and casted samples are not strictly comparable since they were tested at different ages, the extruded samples were more than 28 days old, so they had already reached their maximum strength. However, it is notorious how all the casted samples have a greater strength after 7 days than the same extruded formulations after more than 28.

As mentioned above, extruded mortars have the disadvantage of containing voids in their structure and of being anisotropic, however, the compression strength ranking is the same for both types of specimens; Formulation 2 has the highest strength in all cases and all ages, while Formulation 3 has the least strength in all cases and all ages.

4.10 Mortar formulation selection

The mortar formulation to be chosen for the tests with the extruder was chosen according to the results obtained in the qualitative tests in the home laboratory and the quantitative tests at the laboratory at Tec.

4.10.1 Qualitative criteria

In the qualitative tests for the fresh mortars, only formulation 2 obtained the desired consistency after mixing, it was extrudable through the 9 mm nozzle, both the first layer and the six layers were continuous and smooth, and the extruded structures were stable and maintained stability when stacking more than 10 layers. Formulations 1, 3, and 4 passed most of the tests except for buildability since when stacking more than 10 layers, the structures tilted and looked unstable.

4.10.2 Quantitative criteria

4.10.2.1 Fresh state properties

In the quantitative tests, only formulation 3 could not maintain its slump value below 6%, because 60 minutes after mixing, it reached 8%. Since the goal of mortar formulation is to be able to retain its shape after being extruded, the chosen mortar is expected to have a low slump value. In the case of slump flow, an extrudable mortar is expected to have a value between 150 and 190 mm for at least 1 hour. All formulations meet the criteria, except for 3, which reaches 195 mm at 15 and 45 minutes.

4.10.2.2 Hardened state properties

Regarding the mechanical strength of hardened mortars, it is clear that the extruded samples have lower compressive strength than when they are cast, and specifically, it is lower when the force is applied transversely to the extrusion direction. However, all the formulations had the same strength ranking in all the tests, that is, formulation 2 obtained the highest strength in all cases, then 4, 5, and 1, and finally, that 3 was the one that had the lowest strength.

4.10.3 Chosen formulation

According to this analysis, formulation 2 was chosen, given that it was the one that succeeded in all qualitative tests, had maximum slump values of 6% and slump flow between 155 and 182 mm; and additionally, it had the greatest compressive strength when cast and extruded, and when measured in both longitudinal and transversal directions. The components and the proportions by weight of cement of said formulation are water (0.5), sand (0.4), silica fume (0.4), and Portland cement (1).

4.11 Design of the extruder

The design approach was carried out in different ways, on the one hand, due to the pandemic situation and on the other hand due to the importance of taking into account various design perspectives. The first design was made by students of the last semester of Mechatronics Engineering of the Tec. Based on that, it was worked in collaboration with the partner MachineCare to arrive at a second design in which the manufacture was facilitated. A third design was developed, taking into account the advantages and shortcomings of the previous two designs.

4.11.1 Mechatronics engineering students

According to the requirements, the students designed the extruder shown in Figure 39. It consists of 3 parts: The endless screw, the “Y” shaped body, which is attached with 4 screws to the nozzle. It is 30 cm tall and has an internal diameter of 4 cm.

It has a cylindrical body with an endless screw inside. Additionally, it has an entrance on the side to let the cement in, either by connecting a hose coming from a pump or a funnel to manually feed the mortar. On one of the sides, it has the corresponding supports and holes for attaching it to a robot. At the bottom, it has a removable nozzle that can be exchanged for any other shape or size.

Figure 39. Render of the Extruder design

4.11.2 MachineCare

The design provided by the mechatronics students had some geometric inconsistencies and needed modifications in size, thickness, and location of the screws, to attach it to the motor and the robot.

After multiple modifications to the length, internal diameter, screw design, and the addition of a funnel for feeding the material, the final design is shown in Figure 40 is 16 cm high, has an inside diameter of 2 cm, and a 4-revolution worm screw to be adapted to a NEMA 17 motor.

The motor, the body, the funnel, and the nozzle are attached to each other and to the robot with M4 screws. The motor shaft is inserted into the endless screw and tightened with screws.

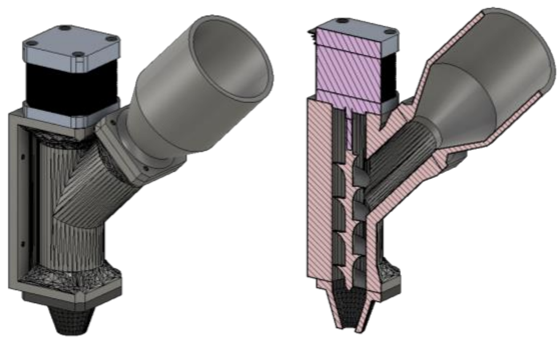


Figure 40. Final extruder design in collaboration with MachineCare

4.11.3 Own design

As an additional option and based on the key points learned from the other two designs, another design was proposed, taking into account what was found in the literature review.

The design shown in Figure 41 consists of 4 parts: the body, the interchangeable nozzle, the motor holder, and the worm.

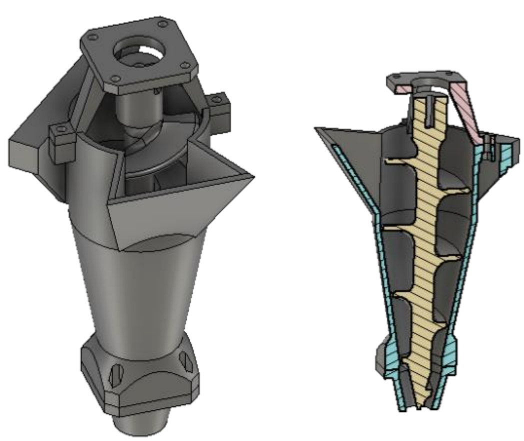


Figure 41. Own extruder design

The body is 13.5 centimeters high; it works as a hopper and an extruder. That is why the upper part is a 5 cm diameter cylinder and the lower part is a cone with a 2.5 cm end opening that connects with 4 M4 screws to the interchangeable nozzles.

As can be seen in detail in Figure 42, the body has a side inlet with a wide opening to facilitate the feeding of the material. In the same way, the extruder attaches to the robot without the need for screws, as it hangs on the robot stand (from the attachment pointed with an arrow in the figure) and is held in place by its weight. this is convenient since it facilitates the assembly and disassembly of the extruder from the robot when cleaning.

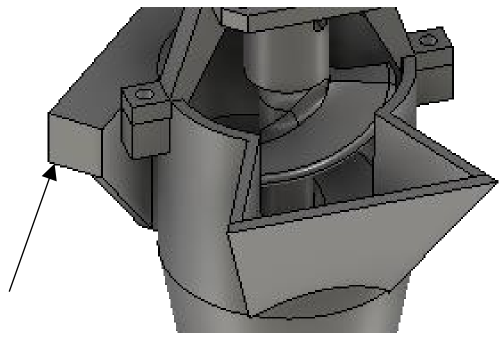


Figure 42. detailed view of the material input and the attachment to the robot.

The motor holder is fixed to the NEMA 17 motor through 4 M4 screws and is then placed on the upper part of the extruder body in the corresponding recesses, where it is fixed with 3 M4 screws. This design prevents mortar from entering the motor, at the same time that it allows a visual view of the screw and facilitates disassembly for cleaning.

The endless screw has 4 revolutions and a clearance of 1.5 mm with the body of the extruder, to avoid that the grains of material jamming it. The motor shaft is inserted into the screw through a thigh hole with the same shape as the shaft, so it does not need screws for fastening.

4.12 Fabrication and evaluation of the extruder

The extruder was manufactured in two ways, initially, it was in charge of MachineCare, which made several attempts of 3D printing; that led to several modifications, up to a final prototype that was delivered to the home laboratory, together with the robot for testing. After evaluating its performance and testing it with mortar mixtures, its advantages and weaknesses were noted, and it worked as a starting point for the design that was manufactured on the printer at the home laboratory.

4.12.1 Machine Care

MachineCare manufactured the design mentioned in section 4.11.1 , which was designed by the mechatronics students. Then modifications were made that led to a second and third manufacturing attempt, to finally get to a fourth prototype which was the one that was delivered with the robot to the home laboratory.

4.12.1.1 First fabrication attempt

In Figure 43 It can be seen that as the walls of the extruder have just 1 mm of thickness, the piece was not strong enough to even support its weight. The thickness had to be increased to 5 mm and the design had to be modified to be able to attach a NEMA 17 stepper motor.

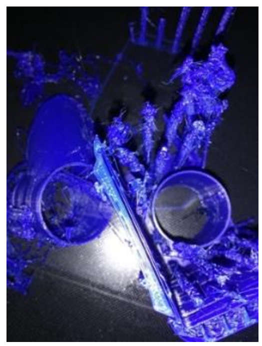


Figure 43. First fabrication attempt of the extruder

4.12.1.2 Second and third fabrication attempts

After the modifications mentioned in the previous paragraph, the quality of the printed piece was improved and allowed the attachment of a commercial motor; however, at a second fabrication attempt, it still has warping problems, as it can be seen in Figure 44, hence the size of the piece and the printing parameters needed to be modified.

Figure 44. Second fabrication attempt of the extruder

Due to the size of the piece, at a third fabrication attempt, warping kept happening, as can be seen in Figure 45. It was decided to reduce the size of the piece to avoid this issue and to decrease the printing time.

Figure 45. Third printing attempt of the extruder.

4.12.1.3 Fourth printing attempt

By reducing the size of the extruder, the inside diameter was also reduced, however, the warping problems in the printing were solved, so that the endless screw could also be manufactured, and all the pieces fell into place, as can be seen in Figure 46. This was the extruder that MachineCare delivered in conjunction with the cartesian robot.

Figure 46. Fourth printing attempt of the extruder

4.12.1.4 Evaluation

When assembled, all parts align properly, and the extruder was able to move the endless screw in both directions without significant friction. When attached to the robot, it is strong enough to withstand the weight of the empty extruder and move in XYZ directions.

However, when tested with mortar, some issues appear. The first one is the feeding of the material to the extruder; the input is very narrow, and the mortar easily blocks it and does not flow towards the extruder. The second issue is that sand particles get stuck between the screw and the walls, jamming the motor. The third issue is that as the screw spins, part of the wet mortar flows towards the motor. And the final issue is that, after use, it is hard to detach from the robot and disassemble for cleaning, as many screws have to be removed.

4.12.2 Home Laboratory

With the PLA printer from the home laboratory, several attempts were made to manufacture each of the parts of a new extruder, the final design shown in section 4.11.3

was reached. In each of the attempts, design flaws were identified, and an attempt was made to improve some of the characteristics. The main drawbacks were the friction of the screw with the body walls, the coupling of the motor shaft with the screw, and the coupling of the motor holder with the body.

4.12.2.1 First fabrication attempt

In the first manufacturing attempt, the printing parameters were still not clear, that is why when trying to print the body and the nozzle, there were adhesion problems between layers as shown in Figure 47, where it can be seen that in the case of the body, the fabrication was not even finished.

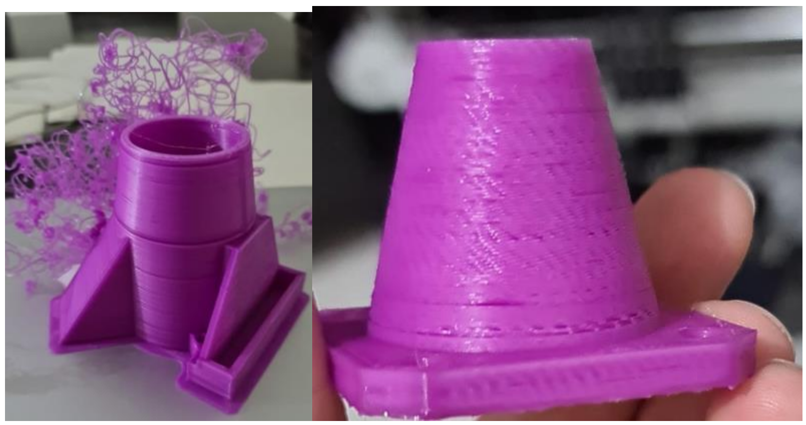


Figure 47. First fabrication attempt of own body and nozzle.

By modifying the printing parameters, it was possible to print the motor holder with good quality; however, there were errors in the dimensions and location of the holes for the screws, so it was not possible to screw it to the motor or the body.

As for the endless screw, in the first manufacturing attempt it did not have enough filling, so part of the screw broke when it was separated from the printing support. Additionally, at first, a scrapper was attached to the screw, it was intended to remove the material adhered to the walls of the extruder when it rotated, however, in the end, it was more an obstacle than an aid. Figure 48 shows the broken screw with the scrapper.

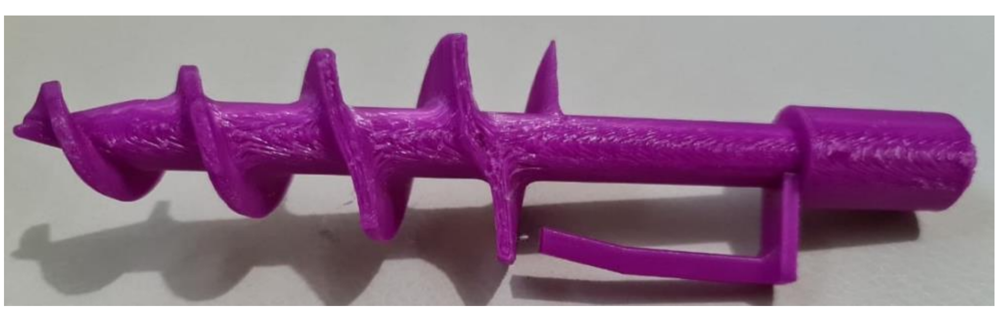


Figure 48. First fabrication attempt of the endless screw

4.12.2.2 *Second fabrication attempt*

In the second attempt, the extruder could be completely fabricated, this time the dimensions of the holes for the screws and nuts were modified, for the motor to be screwed to the motor holder.

In addition, some grooves were added to the body for placing the motor holder, so that it does not necessarily have to be screwed to de body for the screw to be able to rotate freely. Said modifications can be seen in Figure 49.

Likewise, the endless screw could be correctly manufactured and separated from the support material. However, when looking at Figure 49, three disadvantages can be noted in this design. The first one is that the input of the material is very narrow, it is even smaller than a kitchen spoon, which makes it difficult to feed the material to the extruder. The second one is that the screw begins very low in the extruder body, which makes it difficult to move downwards the material that is fed through the inlet. And the third one is that the screw is very close to the walls of the body, which would cause grains of material to get stuck between the screw and the wall.

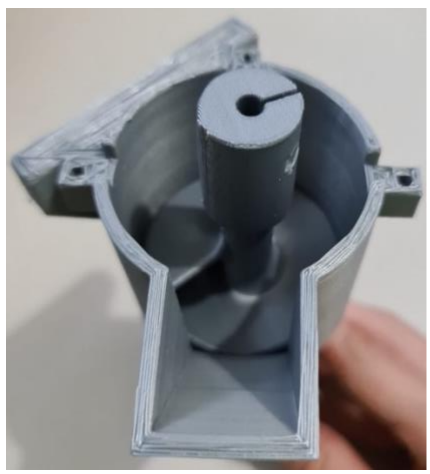


Figure 49 Second fabrication attempt of the own extruder

As for the endless screw, it can be seen in Figure 50 that a nice-looking result was obtained. However, besides the problems of being too short and rubbing against the body walls, it has 5.5 turns of the screw, which would require a higher motor speed to extrude the material. Furthermore, as can be seen in Figure 51, the hole for inserting the motor shaft is circular in shape, which means that if it is not tight enough, there is a risk that the motor shaft would slip.

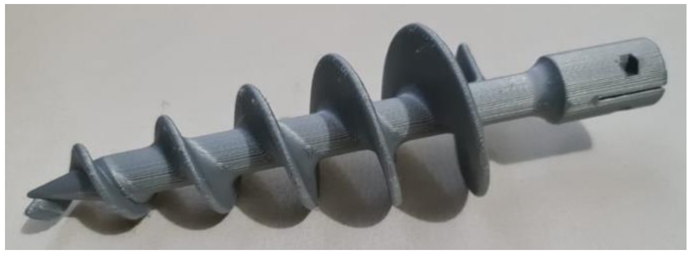


Figure 50. Second attempt of screw fabrication in own design.

Figure 51. Hole in the screw for the motor shaft, second fabrication attempt of own design.

4.12.2.3 Third fabrication attempt

In this last attempt, all the parts could be manufactured and worked as expected. To the body of the extruder, only the material inlet was extended, as can be seen in Figure 52. In the same figure, it can also be seen how the new screw design reaches the top of the extruder body, which facilitates the feeding of material. Figure 53 shows the new screw with only 4 turns so extrusion does not require very fast motor movement.

Figure 52. Final design of the extruder body and endless screw

Figure 53. Final design of the endless screw

Figure 54 shows the new hole design in the endless screw. It has the same shape as the motor's shaft, so it prevents the shaft from slipping when turning. The nozzle to be used has a diameter of 9 mm and it is shown in Figure 55.

Figure 54. Hole in the endless screw for motor shaft attachment

Figure 55. Nozzle for the final extruder

The motor holder was made taller to increase the distance between the motor and the body, allowing the coupling between the motor shaft and the endless screw to be outside of the body. The final fabricated extruder can be seen in Figure 56, where the nozzle is attached to the body, the endless screw is attached to the motor, the motor base is keeping the motor and the screw in place, and the complete assembly is attached to the cartesian robot.

Figure 56. Final fabricated extruder

4.12.2.4 Evaluation

The final design shown in Figure 56 is easily assembled, all 4 parts fit properly. When empty, it moves freely without friction or jams. When used with mortar, the input is wide enough to feed the material with a kitchen spoon and it easily flows towards the endless screw that pushes it downwards towards the nozzle without significant jams.

The extruder is easy to mount and unmount from the robot as it does not have any screw, and only three screws need to be removed for cleaning after use.

4.13 Extrusion tests using the fabricated extruder and the selected mortar formulation

To assess the performance of the extruder, the selected mortar from section 4.10.3 was used, and the movement of the extruder motor was controlled used G-code in the software Repetier-Host.

4.13.1 Endless screw movement calibration

A mark was drawn at the initial position of the screw, and with the M92 command, the number of steps per unit of the extruder was incrementally modified until it was found that 3200 steps/unit allowed the screw to make one complete revolution for one unit.

4.13.2 Mortar feeding

As it can be seen in Figure 57, an extrusion could be achieved. The mortar could be fed through the inlet using a kitchen spoon, this operation did not impair the operation of the extruder, as it does not jam the screw. Also, the motor has enough torque to move the material even when full of mortar. The endless screw can move the material from the inlet towards the bottom of the extruder and through the nozzle, without overflowing or jamming.

Figure 57. Extrusion tests

4.13.3 Mortar extruding

For the evaluation of the repeatability of the extrusion, at least three filaments were extruded for each quantity of revolutions of the screw, Table 31 shows the results and observations.

Table 31. Extrusion tests with the extruder

Revolutions	Results	Observations
1		From 7 extrusions only two of them look significantly shorter than the rest
2		From 9 extrusions only 1of them looks significantly shorter
3		From 7 extrusions, only 4 of them look straight and they are pretty similar in length.
4		The 3 extrusions look almost the same length
5		The 4 extrusions look almost the same length.

In general, each number of revolutions extrudes almost the same mortar length every time. This means that the extrusion has good repeatability, for one revolution as well as for five. Therefore, g-code can be used for programing the extruder on the printer, and the extruder parameters can be set and the same printing results every time can be expected.

4.14 Setup of the printer and printing tests

4.14.1 Printing parameters

4.14.1.1 Initial exploration

Due to the size of the printer bed, the 25 tests of each run were divided into three batches, two with 10 tests each, and another with the other 5. Table 32 shows the observations for all the 200 mm segments extruded for each of the feed rate and revolutions combinations, according to the order shown in Table 9.

Table 32. Observations of incremental order DOE for printing parameters

Run 1

Run 2

Run 3


Table 33 shows the qualitative results of each of the tests performed. According to the color code, the tests marked in red failed in all 3 runs, those marked in orange failed in 2, those marked in yellow failed in 1 and those marked in green failed in any.

Table 33. Qualitative results for DOE for printing parameters

	Feed rate				
Revolutions	**500**	**1000**	**1500**	**2000**	**2500**
4	**T1**	**T2**	**T3**	**T4**	**T5**
	OK	NOT OK	NOT OK	NOT OK	NOT OK
	NOT OK	NOT OK	NOT OK	NOT OK	NOT OK
	NOT OK	NOT OK	NOT OK	NOT OK	NOT OK
6	**T6**	**T7**	**T8**	**T9**	**T10**
	NOT OK	OK	OK	NOT OK	NOT OK
	OK	OK	OK	OK	NOT OK
	OK	OK	OK	NOT OK	NOT OK
8	**T11**	**T12**	**T13**	**T14**	**T15**
	NOT OK	OK	OK	OK	NOT OK
	OK	OK	OK	NOT OK	NOT OK
	OK	NOT OK	OK	OK	NOT OK
10	**T16**	**T17**	**T18**	**T19**	**T20**
	OK	OK	OK	OK	OK
	OK	OK	OK	OK	NOT OK
	OK	NOT OK	NOT OK	NOT OK	OK
12	**T21**	**T22**	**T23**	**T24**	**T25**
	NOT OK	NOT OK	NOT OK	NOT OK	NOT OK
	NOT OK	NOT OK	NOT OK	NOT OK	OK
	NOT OK	NOT OK	NOT OK	OK	OK

Several important observations were made that helped to make decisions regarding the conditions for the following experiments. First of all, it is clear that a slight initial extrusion must be allowed, so that the extruded filament touches the surface before the extruder begins to travel, and thus the extruded layer has the desired length.

Secondly, it was possible to observe how when the extruder moves very fast, that is, with feed rates of 2000 and 2500, the screw does not have time to extrude the amount of material necessary to obtain a continuous and homogeneous filament.

Third, regarding the screw revolutions, it can be seen that when they are lower (4 revolutions), not enough material is extruded for the feed rate in which the extruder moves, generating discontinuities.

On the other hand, when the revolutions are high (12 revolutions) at a low feed rate, too much material is extruded, generating very thick filaments, and at a high feed rate, the screw rotates very fast and it is difficult to feed the material to the extruder.

According to the above, for the following experiments only the levels were to be explored at which it was considered that for longer segments a good print quality could be obtained. these being 6, 8, and 10 revolutions; and 500, 1000, and 1500 feed rates.

4.14.1.2 Printing parameters definition

Table 34 shows the results of the extrusion tests of 5 continuous segments of 200 mm long for each of the combinations of revolutions and feed rate. The tests were evaluated as "OK" and "NOT OK" according to the qualitative criteria mentioned in section 3.6, those marked in green were those that had a good result and in red those that did not.

Table 34. Results of tests for printing parameters definition

	Feed rate		
Revolutions	**500**	**1000**	**1500**
6	**T1**	**T2**	**T3**
	NOT OK	NOT OK	NOT OK
8	**T4**	**T5**	**T6**
	OK	NOT OK	OK
10	**T7**	**T8**	**T9**
	OK	OK	OK

Figure 58 shows the observations for each of the tests according to the order shown in Table 34. It can be noticed that when the feed rate is lower, the filaments look thicker and there is a better fusion with the adjacent filaments. However, in the case of the T1, so much material comes out that the dimensions of the filament are much larger than those of the nozzle. On the other hand, in the case of the T2, T3, and T5 tests, there is no homogeneity in all the segments.

Even though the conditions of any of the tests evaluated with "OK" could be chosen as the printing parameters, as they all produce a good printing quality, it is important to consider the advantages and disadvantages of each combination of feed rate and revolutions. T6 and T9 have the advantage of a shorter printing time, which for bigger printing works, could save time; the disadvantage is that they demand the mortar to be fed to the extruder very fast, and as the material is manually fed, it could potentially cause issues. In the same way, T4 and T5 have the advantage of a slower feeding to the extruder but the printing takes more time. Therefore, T8 is an appropriate balance, the screw does not move so fast to be hard to feed the material, and the extruder does not move so slow for the printing works to take much time.

Figure 58. Extrusion tests for printing parameters definition

According to the observations and results, it was decided that a feed rate of 1000 will be used for all displacements of the extruder during extrusion operations; during displacements without extrusion, the feed rate will be 5000. As for the revolutions of the endless screw, the best results were obtained for 10 revolutions per segment of 200 mm, which means 0.05 rev/mm. Figure 59 shows single layer extrusions using the selected parameters

Figure 59. Single-layer extrusions with selected printing parameters

4.14.2 Multilayer printing

Table 35 shows the results of the extrusion tests of 5 layers of 5 continuous segments 200 mm long for each nozzle standoff distance. The tests were evaluated as "OK" and "NOT OK" according to the qualitative criteria mentioned in section 3.6, those marked in green were those that had a good result and in red those that did not.

Table 35. Results of tests for nozzle standoff distance definition

Nozzle standoff distance	Six layers extrusion
10 mm	NOT OK
9 mm	OK
8 mm	OK

Although it would be expected that the layer height would be the same as the nozzle diameter, it would be inconvenient; on the one hand, because the layer loses height as it settles on the surface; and on the other hand, because there is a small contact surface between adjacent filaments and the most exterior ones collapse because they are not properly fused with adjacent filaments. That is why only the 10 mm standoff distance failed the extrusion test, as can be seen in Table 36.

The printed structure with the 9 mm standoff distance is the one that looks more homogeneous and the filament geometry looks pretty much always round. However, the greater the roundness of the filament, the smallest the contact area with adjacent filaments, and the poorest the fusion between them. That is why 8 mm was chosen as standoff distance, as it allows a better fusion with adjacent horizontal filaments and creates a flat surface for the extrusion of the next layer.

Table 36. observations for nozzle standoff distance definition

10 mm
 
9 mm
 
8 mm
 

4.14.3 Insights

4.14.3.1 Factors that influence printing

In the process of defining the printing parameters, several factors were identified that significantly influence the process. First of all, it is emphasized that in G-code the speed of the motors cannot be controlled independently, meaning that there cannot be set different speeds for the motors of the extruder and the axes.

This is why the optimal combination between the feed rate of displacement and the number of revolutions of the screw for defined lengths must be found. That is, the speed at which the extruder must move and the number of turns that the screw must make per unit of extruded distance.

Also, it is important to mention that when using the Anet 8 printer, in which the bed moves in the Y direction, there is a vibration caused by said movement, which causes the elements being printed to deform.

4.14.3.2 Feed rate of displacement for the extruder

It was hoped that a high speed could be used so that the printing time would be shorter. However, it made the quality decrease; on the one hand, because of inertia, as it is more likely that the extruded filament remains attached to the extruder than to the surface.
And, on the other hand, because when the extruder suddenly changed its direction, the deposited filament did not have enough time to settle, and the nozzle pulls the filament towards the new direction.

When very low feed rates were used, the mortar had a longer time to settle, and sudden changes in the direction of movement did not affect the deposition of the filament; however, the printing time was significantly increased.

4.14.3.3 Rotation of the extruder's endless screw

It was found that for low displacement feed rates and low revolutions per millimeter, the printing time was high, and the amount of extruded material was not enough for there to be a good fusion between filaments.

For high displacement feed rates and high revolutions per millimeter, printing was faster, but it made it difficult to feed the mortar to the extruder since it had to be done very frequently.

4.14.3.4 Nozzle standoff distance

Several tests were carried out in which it was found that for a distance equal to the diameter of the nozzle, the filament sat completely circular and there was a little contact surface to fuse with adjacent filaments, so the exteriors are more likely to detach from the structure.

For small standoff distances, the extruded filament deformed significantly, obtaining low and wide filaments, which decreased the level of detail of the prints and would increase the number of layers required to print a structure.

4.14.3.5 Final printing parameters

According to all the mentioned considerations, the chosen printing parameters are those shown in Table 37.

Table 37. Printing parameters

XYZ displacement feed rate	Extrusion (rev/mm)	Nozzle standoff distance (mm)
1000	0.05	8

4.15 Pilot test for the printing of a complex structure

As a final step in the development of the cement-based extrusion system for application in 3D printing, two pilot printing tests were carried out, in which all the elements that make it up were tested: the selected mortar formulation, the designed and manufactured extruder, and the robot configuration and printing parameters. In both tests, the same model was printed with different trajectories, the second one more complex than the first one.

4.15.1 First pilot test

Figure 60 shows the result of the first printing pilot test, in which the simple trajectory was used. It can be seen how the base and the next 10 layers were correctly printed. In general, the structure looked homogeneous and there was no deformation in the lower layers due to the weight of the upper layers, nor during or after printing.

The bed could withstand the weight of the 1.5 kg piece and it could easily move in the Y direction, even for the last layers. However, the vibration of the bed caused slight deformations; and as it was difficult to control the amount and frequency with which the material was fed to the extruder, because it was done manually, at certain times, when the extruder did not have enough material inside, the filament lost diameter and that caused the next layers to deform.

Figure 60. First pilot test with simple trajectory

4.15.2 Second pilot test

Figure 61 shows the result of the second pilot test, in which the same model as the previous one was used but using a more complex trajectory for the walls. It was possible to normally print the base, and 10 additional layers. Layer 11 could not print well as there was not enough material left to feed into the extruder and the process had to be stopped.

What stands out from this test is that it is shown that it is possible to print with trajectories in which the nozzle changes direction frequently and the layers are deposited correctly.

Figure 61. Second pilot tests with complex trajectory

4.15.3 Third pilot test

For the third pilot test, a hollow wall was printed, as can be seen in Figure 62. It is remarkable how the zig-zag layer between both walls has a good resolution and it is stable even though it is only 1 layer wide.

Figure 62. Hollow wall printed structure

This kind of structure shows the potential for material savings using this technique, as walls could be printed as wide as casted walls but using less amounts of materials. Also, the acoustic and thermal insulation properties could be improved.

4.15.4 General insights

From both tests, it stands out that all the elements that make up the printing system worked correctly. The extruder fulfilled its function of depositing the material in a controlled way, the robot moved easily in the XYZ axes regardless of the weight of the material, the selected printing parameters allowed an acceptable quality, and the material could be extruded with the chosen trajectories.

It was also possible to identify some disadvantages of the system that are not relevant for the project's scope but are presented as opportunities for improvement for the future. One of them is the type of material used to manufacture the extruder, PLA is susceptible to wear due to movement and constant contact with the abrasive mortar. Another disadvantage is the movement of the printing bed, which generates vibration in the piece and causes it to deform little by little as it is printed. And finally, the fact that the material is fed manually to the extruder, induces human error that affects the quality of the print.

5 Conclusions

5.1 Conclusions and final remarks

With this work, the basic components could be identified to allow a mortar to be used for 3D printing and the proportions of these components that allow a better balance between the properties in the fresh state and the hardened state. The components and the proportions by weight of cement of said formulation are Water (0.5), sand (0.4), silica smoke (0.4), and Portland cement (1).

A relationship could be found between the qualitative and quantitative measurement of the properties in the fresh state. According to the results obtained, those formulations that passed all the qualitative tests carried out in the laboratory at home were also those that obtained the best performance in the slump and slump-flow tests.

Regarding the mechanical strength, it was found that there is a reduction of the compressive strength when the samples are extruded compared to when they are cast. According to the results obtained, the presence of voids within the printed structures generates the loss of strength, which is also why mortars have higher strength when the force is applied in the same printing direction than when applied perpendicular to the printing direction.

A small-scale extruder could be designed and manufactured by 3D printing, which allows the extrusion of mortar filaments in a controllable way and without the need for additional mortar pumps. It has an inlet for manual material feeding and a hopper-shaped body through which the material flows into the interchangeable nozzle with the help of an endless screw powered by a NEMA motor. The extruder is designed so that the mortar does not come into contact with the electrical parts of the printer, and so that assembly and disassembly for cleaning is easy since it is not anchored with screws to the robot and only 3 screws need to be removed to disassemble and wash it.

Additionally, it was possible to join the three elements studied in this work: an Anet A8 robot, the designed and manufactured extruder, and the developed mortar formulation. It was identified that the printing parameters that allow a better balance between quality and speed are: Extruder displacement feed rate of 1000, 0.05 screw revolutions per millimeter of extruded filament, and 8 mm standoff distance from the nozzle.

It is highlighted that only the quantitative tests of slump, slump flow, and compressive strength were carried out in a laboratory. the other tests and developments, both of the mortar formulation and the extruder and the printer, were carried out completely at home during confinement by the pandemic.

Finally, it is important to mention that even though the printer developed in this project has a small scale and cannot be used for large-scale constructions, the applications are innumerable, and they could be hardly achievable through traditional methods. For example, pieces can be printed that can be used as decorative elements, such as flower pots, lamps, vases, and sculptures.

If this work were to be scaled up, the methodologies proposed in this thesis for the development of the printable mortar and the definition of the printing parameters are important contributions to facilitate this task.

5.2 Future work derived from the project

After all the results and findings during the development of this project, they suggest ideas that would allow to deepen in certain aspects of the technology and would allow reaching more outstanding results.

In the first place, a way must be found to work with a printer without a bed, that is, that prints directly on any surface, on the one hand, to avoid vibrations that affect the printing, and on the other hand to make its use more flexible since this would allow print parts directly where they are needed and move the printer without waiting for the part to harden before removing it from the bed.

In the same vein, it would be important to work on the scaling of the printer, although the one developed in this thesis allows multiple applications on a small scale, it would be relevant to explore the medium and large scale.

On the side of the mortar for printing, with access to a specialized laboratory, the implementation of high-performance additives that improve the properties of the mortar could be explored.

Regarding the extruder, in the first place, it is important to explore materials and manufacturing methods that allow the manufacturing of a more resistant and durable extruder. And on the other hand, a way to manage to feed the material to the extruder automatically must be explored.

And finally, there is a great area of opportunity in the development of optimal print paths to improve print speed and mechanical strength.

6 Abbreviations and acronyms

6.1 Abbreviations

C: Cement
FA: Fly Ash
HRWRA: High range water reducing agent
P: Plasticizer
Psol: Plasticizer solution
RA: Retarding agent
SF: Silica fume
VMA: Viscosity modifying agent
W/B: Water to binder ratio

6.2 Acronyms

AM: Additive Manufacturing
CAD: Computer Aided Design
CC: Contour Crafting
CNC: Computer Numerically Controlled
C3DP: Concrete 3D Printing
FFF: Fused Filament Fabrication
MSSWF: Modified Saudi Sheep Wool Fibers
SDC: Smart Dynamic Casting
SSWF: Saudi Sheep Wool Fibers
TCM: Tangential Continuity Method
3DP: 3D Printing

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Curriculum Vitae

Chemical Engineer with deepening in new materials and nanotechnology from UPB Colombia (2017), during that time, I participated in research projects in biotechnology and materials regarding the recovery of heavy metals from mining effluents. I was sponsored by DAAD for scientific divulgation in Germany (2016). I also worked for Cementos Argos as an R&D trainee for six months, where I participated in projects related to the characterization of new cement formulations and achieved some degree of automation in laboratory reports using UiPath.

In Mapei Colombia (2018-2019), as a quality control analyst, I participated in different plant modernization projects, implementation of performance improvements, automation of production processes, among others. Some of the great achievements that I was part of in the company were in the standardization of the quality control and production process in the plant, achieving reductions in production times and QC greater than 60%. In the same way, we managed to implement the quality management system within the laboratory, including some automation in the handling of data and formulations, facilitating the production process, and the generation of indicators and quality reports.

After that, I was accepted for the program of Master of Sciences in Manufacturing Systems (2019).

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