3D Printing on a Large Scale for Construction

Master degree in Product Design Engineering

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escola superior de tecnologia e gestão
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Dissertation under the supervision of Professor Florindo José Mendes Gaspar, and Professor Fábio Jorge Pereira Simões

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Dedication

I dedicate my dissertation work to my fiancé, who has been a constant source of support and inspiration during the challenges of this course during these crazy days. I am truly grateful for having you in my life. This work is also dedicated to my parents, who always encouraged me to pursue my dreams and finish this thesis.

It is with great tenderness that I remember the words of motivation from my grandfathers (*in memoriam*) Amauri and João, who gave me strength to always seek knowledge and, of course, the love from my grandmothers Angela and Vera, who always root for my success.

I cannot forget all my friends that cheered me up when I needed to and always believed in me. Thank you all for not letting me give up.

To all my teachers, from school to university, you all helped and guided me to get here, and I will never forget.

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Abstract

The efficiency of the construction process is directly linked to the characteristics of the materials used. The low productivity performance and the amount of waste produced are issues that most negatively affect the construction sector. Therefore, alternative materials and technologies are to be considered since they represent a solution to such issue. Additive Manufacturing (AM) is growing fast in the construction sector, as it allows enlarging the range of construction. The benefits of using the AM technology with concrete strongly relies on the advantages over the traditional construction techniques. Among such advantages, reduced material waste, the 24/7 operations, the ease of operation and the freedom in design are the most relevant that can lead to the choice of this technique. There are, however, big challenges, mostly related to the materials properties, since their composition must be suitable for printing but also with good properties for construction.

The main objective of this work was to study the parameters for AM printing with concrete and optimize the mix composition, incorporating industrial waste and assessing the printing performance. It was implemented by using a robotic arm with an extruder. This dissertation presents the work carried out to study the mix composition, evaluating the influence of the binder/aggregate ratio, cement/fly ash ratio and quantity and type of admixtures on the results. Mechanical tests were performed to analyze the mechanical properties of the mixes on the fresh and hardened state. Printing tests were executed to evaluate the printability and buildability of the mixes.

Keywords: 3D printing, Cementitious material, Printability, Filler

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List of Acronyms

3D	Three-dimensional
AM	Additive Manufacturing
AP	Set accelerator
CDRSP	Centre for Rapid and Sustainable Product Development
CTM	Compression testing machine
ESTG	School of Technology and Management
FA	Fly Ash
SC3DP	Shotcrete 3D Printing
SP	Superplasticizer
SRF	Shape retention factor
TOT	Thixotropy open time
VMA	Viscosity Modifying Admixture
W/C	Water / Cement

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1. Introduction

Within the wide range of materials consumed in civil construction, up to 75% are from natural resources [1]. The efficiency of the construction process is directly linked to the characteristics of the materials used [2], but it is well known that one of the biggest issues of civil construction is the low productivity and the big volume of waste produced [3]. In such context, alternative materials and technologies can represent a solution to such issues.

According to Tessari [4], sustainable development does not deny the need for technological progress. However, the great nations have focused on the isolated progress of nature, through the unrestrained exploitation of its finite resources, which are rapidly being depleted. This is a negative *modus operandi*, considering that civilization still depends on nature for energy generation, obtaining materials and essential processes for the maintenance of life.

The challenges of sustainable development are mostly related to carry on the economic growth and, simultaneously, preserving the nature and social justice [5].

Additive Manufacturing (AM), also known as 3D printing, allows expanding the range of construction by printing large scale buildings and structural components [6]. The technology is growing fast in several fields, but there’s a lot of work and study to be carried out in the construction industry. Still, AM can be a solution for some difficulties in construction: high production time and cost, safety of workers, low productivity, high waste generation and need for special skilled labours [7].

The Center for the Rapid and Sustainable Product Development of the Polytechnic of Leiria (CDRSP) has developed research in 3D printing with large-scale concrete for construction. This work aims to evaluate the possibility of printing a variety of mortars and further evaluate its structural performance.

Mortars were used on experimental work involving the study of cementitious materials for 3D printing using waste from industries. Using waste materials helps to solve some of the environmental issues mentioned above and can also improve the performance of the mortar [5]. For that, a robotic arm with an extrusion printing system was used. The goal is to evaluate the structural performance of the mortars and find practical applications with 3D printing of developed materials.

The influences of the binder/aggregate ratio, the cement/fly ash ratio and the type and quantity of admixtures used were assessed. One the biggest challenges are the properties of the materials, since it is important that their composition is suitable for printing but also resistant enough. Compressive and flexural strength tests were performed to analyze the mechanical properties of the mixes. Printing tests were executed to evaluate the printability and buildability of the mixes.

1.1. General Background

A few decades ago, it was unthinkable that in the upcoming future anyone would be able to have a digital printer at home or at the office. Although this is our current reality, it can be confusing to choose between laser printers and a commercially available inkjet. AM was mainly adopted in commercial sectors due to expensive technology and raw materials [8] but it is growing fast from past 25 years, especially because the traditional methods are labor dependent and require formwork, as opposed to AM [9].

Small printers are currently available on the market for use at home or at the office, with the use of simple plastic materials to print 3D objects. This new additive manufacturing technology brings many possibilities and advantages, with great potential, mainly due to its ability to quickly produce objects with complex geometry. These qualities are important in all industries and the construction industry is no exception.

Construction is defined as the process of creating high or large structures, i.e. Houses, buildings, and bridges, involving small elements. Although many new technologies have no application in construction, AM is considered an attractive solution by adapting the cementitious materials used in construction. In contrast, large scale building construction has been a challenge for the application of additive manufacturing in construction works.

According to Gosselinab [8], additive construction is related to AM, and it is described as "the process of joining materials to create constructions from 3D model data". It allows processes, like design and production, through digital means.

1.2. Objectives

The main objective of this work was to study cementitious mixes for 3D printing, which involves preparing samples, testing, and analysing the obtained results. The extrusion process was used, as this technology allows complex designs and the utilization of waste materials, contributing for a sustainable construction.

This research aims to achieve the above mentioned objects and also:

- Accomplish continuous printing
- Understand the parameters, compositions, to improve the printing process
- Improve the hardening of the mixture
- Accomplish autonomous construction
- Eliminate the need of formwork in the construction industry
- Reduce waste of material
- Incorporate industrial waste

1.3. Structure of the Report

The research carried out can be classified, in terms of its purposes, as applied research, as it seeks to find an improvement for 3D printing on a large scale for the construction. As for its means, it is laboratory research, carried out in a controlled environment. This paper is divided into five main chapters.

The first chapter is “Introduction”, it gives a general idea about the concept of work and its objectives. Then, “Literature Review” provides a review about 3D printable concrete, and mortar and cement properties.

On chapter 3, “Materials and Methods”, the materials used in the work are detailed, as well as the methodology, the performed tests and the equipment used. In the fourth chapter, “Results”, the test results are discussed and analyzed separately. Finally, the conclusion of the research and future work recommendations are placed in the chapter named “Conclusion”.

2. Literature Review

This chapter discusses and analyses published works in civil engineering academics using mortar and concrete with AM in construction.

2.1. 3D Printable Concrete

The steam and waterpower brought the first transformation in production and automation (Industry 1.0), then there was electrification (Industry 2.0), after that the digital computer (Industry 3.0). Industry 4.0, the fourth industrial revolution, states that the enterprise processes become more digitized and toward a smart, connected, and highly efficient supply chain ecosystem, based on digital technologies – 3D printing, big data, the internet of things, and others [10].

The development of 3D printing technologies in the construction industry was led due to the high demand for low-cost solutions and has potential applications by using a robotic arm with nozzle jet to build concrete structures layer by layer. Layer-based extrusion of concrete is the most extensively researched and widely used 3D printing process for the fabrication of large-scale concrete components [11]. This technology allows work 24/7, increasing speed and minimizing human error, has geometric freedom, does not require formwork and it is considered an environmentally friendly solution [12]. Despite all that, there are a few challenges, the concrete must have sufficient workability and stay fluid while inside the nozzle, but also enough buildability to remain in its position, and solid enough to support the layers above, but should not harden too fast to avoid cold join between layers [13]. Portland cement concrete was found to be the most viable choice for 3D printed concrete because of the properties of fresh and hardened concrete, also since there's a wide range of admixtures available to improve its performance [14].

Natanzi and McNally [13] studied the effect of superplasticizer and nanoclay on six different shear strength-based printing mixtures. The result showed that the use of nanoclay improved the buildability and the initial shear strength, but decreased the flowability, while the superplasticizer increased the shear strength.

2.2. Mortar Properties

The traditional construction method, i.e. brick and mortar to bond layers, can be considered an additive manufacturing before 3D printers even existed [15]. Unlike the conventional cast-in-place concrete, the quality of the final printed product is significantly affected by fresh properties of cementitious materials. Buildability, pumpability, extrudability, and open time are considered the main properties of fresh state printing materials [16].

Buildability is the ability of printable concrete to retain the extruded shape and sustain the load of the following layers without collapse. It depends on structural build-up rate. Higher buildability means construction of tall sections in less time [17]. Flowability and extrudability are the critical parameters to evaluate the flow behavior during printing. Pumpability, or flowability, is the material's ability to flow from the mixer to the nozzle and extrudability is the fresh paste's extrusion with constant thickness and width without cracks.

Equation 1 shows the calculation for extrudability, buildability, and printability. Extrudability is directly proportional to flowability and inversely proportional to rest time, while the buildability is directly proportional to penetration resistance and increases with time. It means that extrudability and buildability are inverse, and the balance between them is the key to optimizing design [18].

$$Extrudabilidy(Pe) = \frac{Flowability(Ds)/Time(t)}{Max(Ds)/Min(t)} \times 100\%$$

$$Buildability(Pb) = \frac{Stiffness(Pr)/Slump(Hs)}{Max(Pr)/Min(Hs)} \times 100\%$$

$$Printability(Pp) = F_{Optimal}(Pe, Pb) \tag{1}$$

P_e = extrudability

D_s = spreading diameter

t = time

P_b = buildability

P_r = penetration resistance

H_s = slump

P_p = printability

Open time is the amount of the time that fresh mixed materials maintain consistency with good workability for printing [6]. The time interval that takes the material to lose its extrudability is called thixotropy open time (TOT) [19].

A long open time is helpful for continuous extrusion, but the biggest challenge is that the paste must be fresh enough to be transported through the printing system and extruded through the nozzle, but it also must be stiff and have buildability to maintain the shape after extrusion [6].

To print the mortar some tests are needed to measure those parameters. Flowability can be examined by the flow table test [20], fresh concrete will flow under action of shear stress and its behavior is represented by the Bingham model (Eq. 2),

$$\tau = \tau_0 + \mu\gamma \tag{2}$$

where the parameter τ_0 is yield stress, the critical shear stress required to initiate the flow. The slope of the line is the plastic viscosity (μ), it affects the resistance to flow and relates shear stress (τ) to shear rate (γ). The lower is the material yield stress and viscosity, higher is its fluidity [21].

The Deborah Number (Eq. 3) indicates if the specific material behaves solid-like (elastic) or liquid-like (viscous). The material is said to be viscoelastic if t_r is similar to t_0, it means it exhibits both types of behavior simultaneously [22]. It is important to remember that for cementitious materials, long time-scale measurements are irrelevant because they set before the measurement is completed.

$$De = t_r/t_0 \tag{3}$$

t_r = relaxation time
t_0 = time characteristic of the experimental measurement

During the remolding of cementitious materials, the liquid-like behavior is more important, but there are other situations where the solid-like behavior is the principal. Cement-based materials can stand unsupported without flowing under their own weight, they develop stiffness and strength during setting [22]. The Bingham model (Eq. 2) can be used to analyze the material behavior, and a controlled stress rheometer can indicate the yield stress.

Rheology is the science of deformation and flow of matter, it is related to the relation between stress, strain, rate of strain, and time [23]. Flow is about the relative movement of adjacent elements of liquid, in shear flows liquid elements past each other while in extensional flows the same elements towards each other.

The rheometer test can be used to characterize the static yield stress, the plastic viscosity, and the dynamic yield stress. There is another challenge here: for a higher resistance to segregation of the materials, a high static yield stress is required, but for ease of placement, self-consolidation, and pumping, a low dynamic yield stress is needed. After determining the dynamic flow curves for different mixture proportions and using different types of admixtures, an optimum balance can be achieved to determine the best mix [21].

Yield stress and viscosity of the material both depends on particle size, surface area, and paste/aggregate volume ratio. Some standards tests, such as flow table test, have been used by researchers to quantify the flow behavior. According to Panda and Tan [19], shape retention factor (SRF) is also a crucial factor for 3D printing concrete, and it can be calculated by Eq. 4.

$$SRF \equiv {}^{S_{bd}}/_{S_{ad}} \tag{4}$$

SRF = shape retention factor
S_{bd} = cross sectional area of 3D sample before demolding
S_{ad} = cross sectional area of 3D sample after demolding

A high SRF is desired, as it means the material must have low slump characteristics to remain stable under its own weight, i.e., high yield stress. The higher is the yield stress, the more difficult it is to extrude the material, resulting in discontinuous filament, which means the SRF should not cross a certain value as it will not be extrudable.

In cement systems, the proximity of particles results in strong interactions. The strength depends on the shape of the particles, their size distribution, their concentration, and their surface properties. It is common that there is a net attraction, causing flocculation. The size and architecture of the flocs interferes in the rheology of the dispersion. The rheology of cement system is better studied in experiments where the shear rate is constant [24].

The rheology of fresh cement paste is dominated by the interaction between cement particles, and it may absorb superplasticizer (SP) molecules. Mikanovic and Jolicoeur [25] explained that SP in cement is used to increase the mortar workability, the same workability could also be obtained in a plain cement but with a huge water reduction. SP can have positive effects but can be unpredictable, the hydration reactions causes stiffening and this can be a problem [26].

2.3. Hardening of Concrete and Mortars

There are numerous technologies for improvement of hardening of concrete and mortars. The buildability can be improved by applying different types of admixtures into the mix. Bhattacherjee and Santhanam [27] tested spraying an alkali-free aluminum sulfate accelerator on the post-printed surface. It was tested for 0%, 1%, 2%, 4% and 8% accelerator. For higher dosages the setting time is faster, the flow reduces drastically, and the yield strength increases. It also enhanced the yield strength of the outer layer and increased the rate of flocculation and hydration.

A common method for 3D printable concrete is to add the accelerator at the nozzle [17]. Shotcrete 3D Printing (SC3DP) uses high kinetic energy to apply the concrete. In this technique the material is torn up by pressured air and sprayed at the nozzle, causing a good interlocking effect because of the increase of contact surface between the layers. The effect of the accelerator was tested for 0%, 2%, 4% and 6% [28]. Since the components are produced directly from the digital model and without human intervention, the method reduces material waste, construction time and labor. But in order to ensure that the technology will work properly, the process parameters, yield stress, geometry and rheological properties of concrete need to be comprehended [29].

Hack and Kloft [11] used a built-up strategy with five steps (Figure 2.1), including structural reinforcement in both horizontal and vertical direction. To increase the buildability, 5% of shotcrete accelerator was applied at the nozzle. Every six layers, the robot stopped to place the horizontal rebars until the full height of the wall was attained, and after the wall was fully printed, the vertical rebars were threaded in place. Once the rebars were inserted, a second layer was applied, and a rotating steel disc was used in the surface finishing process. The second layer is not only for aesthetic, but also essential for the structural integrity. Good layer bonding properties, automated surface finishing and capacity to integrate reinforcement were observed and the research showed the technique is viable.

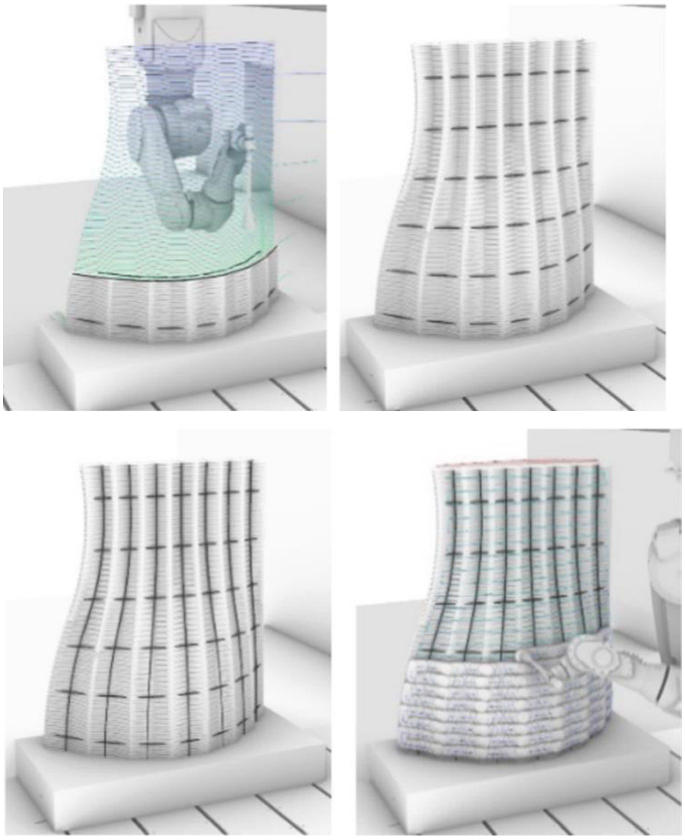

Figure 2.1: Built-up strategy [11]

To examine the effect on the strand geometry, the traverse speed, volume air flow, and nozzle to strand distance are varied and penetration resistance, yield stress, strand geometry and expansion angle during production are measured on a study from Dressler *et al.* [29]. The results showed an increase in yield stress over time for all specimens, also that applying the accelerator increase the strand height, decreases the width, and reduces the concrete stiffening time. When increasing the nozzle to strand distance, the strand width increases and the height decreases. For the traverse speed, its increase leads to a decrease in strand height and width. The setup used is shown on Figure 2.2.

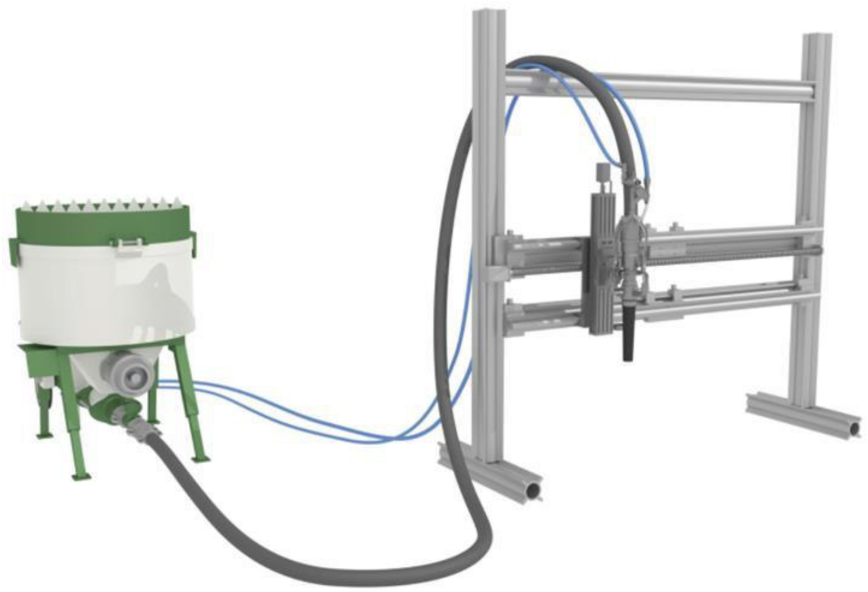

Figure 2.2: Smart additive material investigator to produce shotcrete 3D printed strands [29]

Blaakmeer and Lobo [30] combined a well-known binder system with shear thinning. With this concept it's possible to obtain monolithic objects without the printing direction influence. The pre-requisites are the bottom layer must carry the layers on top without collapsing, and the mortar must be pumpable. Because the mortar was based on a traditional system, there's a good availability of the raw materials but the water dosage had to be controlled when mixing the mortar since some modifications were made. To print larger objects (4 to 5 tons), a robust system with constant properties of the fresh mortar and continuous yield of the pump are needed to run smoothly and provide a good quality printing.

For the design and fabrication of an ultra-thin, 3D printed formwork, the eggshell process is used by Burger *et al.* [31]. Eggshell allows printing a ultra-thin formwork with no additional support, good surface quality and wide range of geometric possibilities [32]. Optimized concrete geometry can increase material savings up to 70% when comparing with traditional components. There are a few challenges: scale up the printing process, establish the design space for the formwork, and integration reinforcement. A thin formwork was 3D printed, then combined with a prefabricated reinforcement cage and filled with concrete to produce the final column, the first example of a full-scale building element using the eggshell process. The design parameters for the column model tested are shown on Figure 2.3, the parametric model could be used to generate fabrication data, excluding the need of an additional step of slicing the geometry [33].

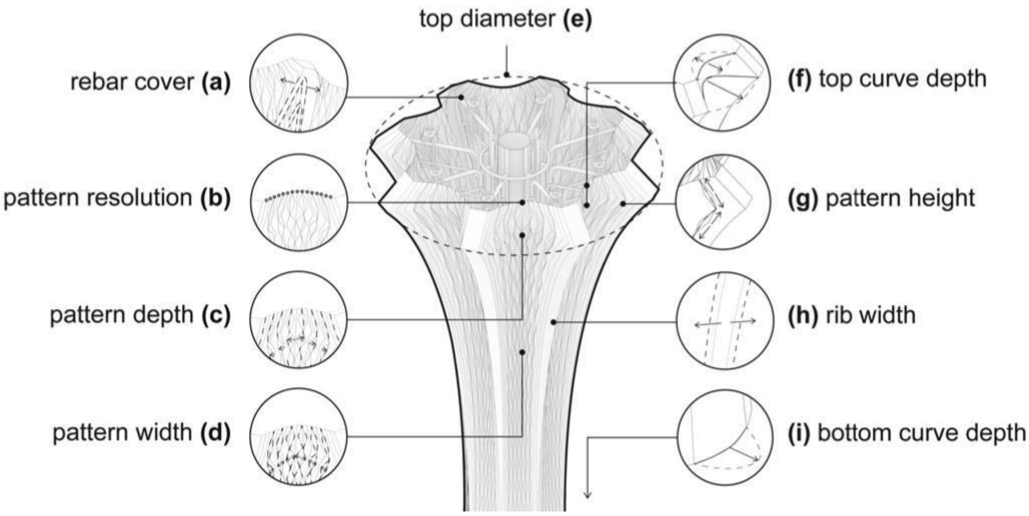

Figure 2.3: Design parameters [33]

3. Materials and Methods

This chapter describes the materials used, mixes composition and preparation, the tests and its procedures, the equipment used and all the arrangement for printing.

3.1. Equipment

The equipment used for each of the performed tests are listed. The experiments are discussed and described individually later on this chapter.

Grain size analysis:

- Automatic sieve shaker
- Sieves with diameters: 2mm, 1mm, 0,5mm, 0,3mm, 0,2mm, and 0,1mm
- Oven
- Digital Scale

Density analysis:

- 100 ml volumetric flask
- Digital Scale

Compactness test:

- Metallic cup (with known volume and weight)
- Digital scale
- Metallic tamper

Admixture analysis:

- Manual flow table and metallic mold
- Metallic tamper
- Caliper

Mechanical tests:

- Automatic mixer
- Manual flow table and metallic mold
- Metallic tamper
- Caliper
- Automatic vibrator

- Metallic mold for mechanical tests
- Curing tank
- Compression testing machine (CTM)

Printing analysis:

- KUKA Industrial Robots model KR150
- KRC2 ED05 controller
- Printing head and nozzle
- Electric pumping motor
- Pipe
- Concrete mixer
- 50l storage tank

Compressive strength test on fresh mortar:

- Instron 4505, universal tensile machine
- PVC cylindric mold
- Nylon lids
- Automatic mixer
- Digital scale
- Ruler
- Photographic camera
- NI Vision Builder software

3.2. Materials

The materials used were chosen to optimize the 3D printing mix, referring to works that have been carried out at CDRSP in the past few years. The cement type CEM II A/L 42.5 R and limestone filler act as a binder, fly ash (FA) was also added to improve the fresh properties.

Biomass FA (Figure 3.1a) is a fine residue transported by flue gasses and its use is conditioned by its physic-mechanical properties. During the biomass combustion process bottom ash and FA are formed [35]. It is a pozzolanic material with benefits for the fresh mixture, as it increases cohesion, viscosity and plasticity while reducing bleeding and segregation. Replacing a percentage of cement with FA enhances the ductility, resistance to cracking and dynamic properties [36].

Limestone filler (Figure 3.1b) is one of the wastes generate in huge quantity during cutting and polishing stones at quarries. The waste of the quarry comes in two forms: powder and sludge. Powder is generated while blasting and griding, and sludge is produced while cutting and polishing. Incorporating waste materials reduces the volume of waste in landfills and saves natural resources [37]. Also, replacing a percentage of sand with limestone filler improves the fluidity and strength of the mortar, due to the pore-filling effect.

a) b)

Figure 3.1: a) Biomass FA and b) limestone filler

To improve the printing properties, the following admixtures were examined:

- Woerment FM 422 is a superplasticizer/strong water reducer specially developed to produce low viscosity ready-mixed concrete. Due to a strong water reduction, the concrete has a low water/binder ratio and maintains its consistency without delay in setting and initial resistance. The benefits of using this admixture include concrete viscosity reduction and control, better rheology, less pressure on the pump and better pumping, reduction of mixing times, greater ease in laying and compacting the concrete, flexible to environmental condition changes, and better behavior with variations in the cement chemical composition. Recommended dosage: 0,2-4% of the weight of cement.

- Woergunit SA 160 is a set accelerator specially designed for wet shotcrete, free from alkalis, chlorides and non-alkaline. Suitable for applications where fast hardening and high initial rather than final strength is required. The fast-curing property allows to optimize the feed cycles and the ability to apply large thicknesses of concrete at once. It also allows to obtain fast hardening with continuous development of initial and final resistance, improving the durability of the shotcrete. It minimizes dust generation during application and therefore improves the working environment. Recommended dosage: 6-10% of the weight of cement.
- Plast V70 is a water reducing plasticizer with secondary effect of a viscosity agent, designed for fluid mortars or self-compacting concrete. It enables to reduce the risk of segregation and bleeding for fresh concrete, it can produce a mortar which is less sensitive to formulation or water variations. Contains a dispersant which makes pumping easier and when coupled with superplasticizers it enables to obtain a very fluid mortar which can be maintained over a long period of time. Recommended dosage: 0,2-0,6kg for 100kg of cement.
- Plast V90 is a VMA developed for producing flowing and self-compacting concrete and mortars. It increases resistance to segregation and bleeding, reduces sensitivity to water and fines variations in concrete formula, and reduces segregation and bleeding when added on fresh concrete. It is recommended to add this admixture to the mixing water. Recommended dosage: 0,2-1% of the weight of cement. The typical dosage is between 0,4% of the product to the weight of cement.
- Frioplast® P facilitates the placement of concrete by extrusion machines owing to its viscosity regulation action. The main advantages of its use are greaser effect, which makes extrusion easier, impermeability, good mechanical resistance, reduces segregation, increase the homogeneity of the concrete, and decrease the water needed while maintaining the workability. Recommended dosage: 0,5% of the weight of cement.

3.3. Grain Size Analysis

The aggregates had to have a maximum size of 1 mm to be suitable for printing. The sand grain size analysis was performed according to NP EN 933-1 2000 [34], the purpose is to derive the particle size distribution of soils. An automatic sieve shaker was used for sand grain size analysis, as shown on Figure 3.2.

Figure 3.2: Automatic sieve shaker

Before the test, a sample of the sand was maintained in an oven at 110°± 5° C for 24h. 6 sieves were used, with diameters: 2 mm, 1 mm, 0,5 mm, 0,3 mm, 0,2 mm, and 0,1 mm. The sieves were placed in an ascending order from bottom to top. The dried sand removed from the oven and weighted and then placed on the top of the sieves. The automatic sieve shaker is turned on for 5 minutes. After the procedure is done, the particle size distribution is determined by weighing the material retained on each of the sieves to calculate the percentage of grains for fine size (*f*), in this case it means the percentage of sand that pass through the 1 mm sieve, by dividing these weights by the total weight of the sample (Eq. 5).

$$f = \frac{(M_1 - M_2) + P}{M_1} \times 100$$

(5)

f = fine grain size sand (%)

M_1 = dry mass (kg)

M_2 = dry mass > 1 mm (kg)

P = dry mass that pass through all sieves (kg)

3.4. Density Analysis

To find the best proportion of sand and filler to be used on the experiments, the first step was to determine the density of the materials. A 100 ml volumetric flask was used. The flask was weighted with some of the material inside and then distilled water was added until the volume reached the 100ml mark, as shown on Figure 3.3. Knowing the total weight and assuming that the distilled water density is 1g/cm^3, it's possible to calculate the sand and filler bulk density. The procedure was performed twice for each material and the average value was taken.

Figure 3.3: Density analysis

3.5. Compactness Test

The compactness test was done to evaluate the aggregates used to find the best proportion to replace sand by limestone filler. The results from the bulk density analysis were considered. For the test, a metallic cup was used, it was weighted and then filled with water and weighted again to discover its volume capacity.

Fine sand and limestone filler were mixed for 0%, 10%, 15%, 20%, 25% and 30% substitution, then using the recipient with known volume and weight, the mixtures were weighted one by one with the goal to find the most compact. Since the volume was the same for all mixes, the most compact mix will be the mix with higher bulk density value.

3.6. Set Accelerator Analysis

For this test 30 different compositions were tested with the purpose of studying the effect of the set accelerator on the consistency of fresh paste. No waste material was used at this stage to avoid external influence on the result.

Figure 3.4: Flow table test

The flow table test was performed according to EN 1015-3 [20]. Before running the test, all the equipment was cleaned with a cloth and dried. The mold was placed on the center of a manual flow table and filled with mortar in two layers, it was compacted by a tamper ten times after each layer was placed to guarantee it was homogeneously filled (Figure 3.4). The mold was removed carefully, then the flow table was jolted 15 times at a constant speed, once per second. The diameter of the mortar was measured in two perpendicular directions with a caliper, and the average was taken to calculate the consistency in mm.

To evaluate the effect of the admixtures used and choose the best dosage, the flow table test was performed every five minutes until a diameter reduction of 30 mm was reached. The quantities for the admixtures are calculated based on the weight of cement used. The Woerment FM 422 percentage added was the same for all mixes, 1%.

The mixes were divided into two groups, for the first group the admixtures were added in the beginning (Table 3.1).

Table 3.1: Mixes composition for admixtures analysis

Mix	Material Composition (weight proportions)			Woergunit AS 160 (%)
	Cement	Sand	W/C	
M1	1	2	0,32	0
M2	1	2	0,43	4
M3	1	2	0,41	6
M4	1	2	0,44	8
M5	1	2	0,50	10
M6	1	2	0,34	2
M7	1	2	0,34	6
M8	1	2	0,44	8
M9	1	2	0,40	6
M10	1	2	0,36	0
M11	1	2	0,37	2
M12	1	2	0,37	8
M13	1	2	0,52	8
M14	1	2	0,46	10
M15	1	2	0,46	4

For the second group (Table 3.2), to understand if the order influences on the result, the materials were added in this order: sand, cement, water, superplasticizer and set accelerator.

Table 3.2: Mixes composition for admixtures analysis

Mix	Material Composition (weight proportions)			Woergunit AS 160 (%)
	Cement	Sand	W/C	
M16	1	2	0,39	2
M17	1	2	0,34	0
M18	1	2	0,38	0

3.7. Mechanical Tests

Two types of tests were performed on hardened mortar to evaluate the strength: bending test and compression test.

3.7.1. Mix preparation

The mix preparation for the mechanical tests was done according to EN 1015-2 [38]. The quantity of the material was calculated in agreement to the mold dimensions of 160x40x40mm. The cement, sand, filler, and admixtures were weighted and then added to the automatic mixer (Figure 3.5). The water quantity was initially estimated using Feret formula (Eq. 6), it was slowly added to the mix while it was analyzed to achieve the required consistency and plasticity. The actual amount of water used was recorded.

$$W_{Feret} = 0{,}235 \times C + 0{,}23 \times F + 0{,}09 \times M + 0{,}03 \times G \tag{6}$$

W_{Feret} = water quantity (l)
C = cement quantity (kg)
F = quantity of fine sand – 0 to 0,5 mm (kg)
M = quantity of mean sand – 0,5 to 2 mm (kg)
G = quantity of gross sand – 2 to 5 mm (kg)

Figure 3.5: Mixer used to prepare mortar for mechanical tests

Table 3.3 shows the materials quantity for each mix. The AP was not added to the mixes because it caused low workability, the paste was too dry too fast, and the specimens had too many air gaps, which lower its resistance. For this reason, it was decided not to use AP on the mixes for this test. The consistency was tested by flow table method, according to EN 1015-3 [20].

After the consistency test was performed, the mix was poured into the mold, and an automatic vibrator was used to remove the air bubbles and make sure it was properly compacted. It was left air drying in the mold for 24 hours, then demolded (Figure 3.6) and placed in a curing tank at a 20°C temperature for 28 days. This procedure was then followed for all mixes.

Table 3.3: Mixes for mechanical tests

Mix	**1**	**2**	**3**	**10**	**18**	**21**	**31**	**42**	**44**
Sand (%)	100	85	80	100	90	80	90	90	90
Filler (%)	0	15	20	0	10	20	10	10	10
Cement: agregate	1:2	1:2	1:2	1:1	1:1	1:1	1:1	1:1	1:1
Cement (%)	100	100	100	100	100	100	80	80	90
Fly ash (%)	-	-	-	-	-	-	20	20	10
VMA 70 (%)	-	-	-	-	-	-	0,5	0,5	0,5
Frioplast (%)	-	-	-	0,5	0,5	0,5	0,5	0,5	0,5
SP (%)	2	2	2	2	2	2	2	2	2
W/C	0,25	0,27	0,27	0,23	0,21	0,24	0,26	0,31	0,31
flow table avg. (cm)	20,3	17,8	-	24,3	19,8	-	17,6	15,5	-

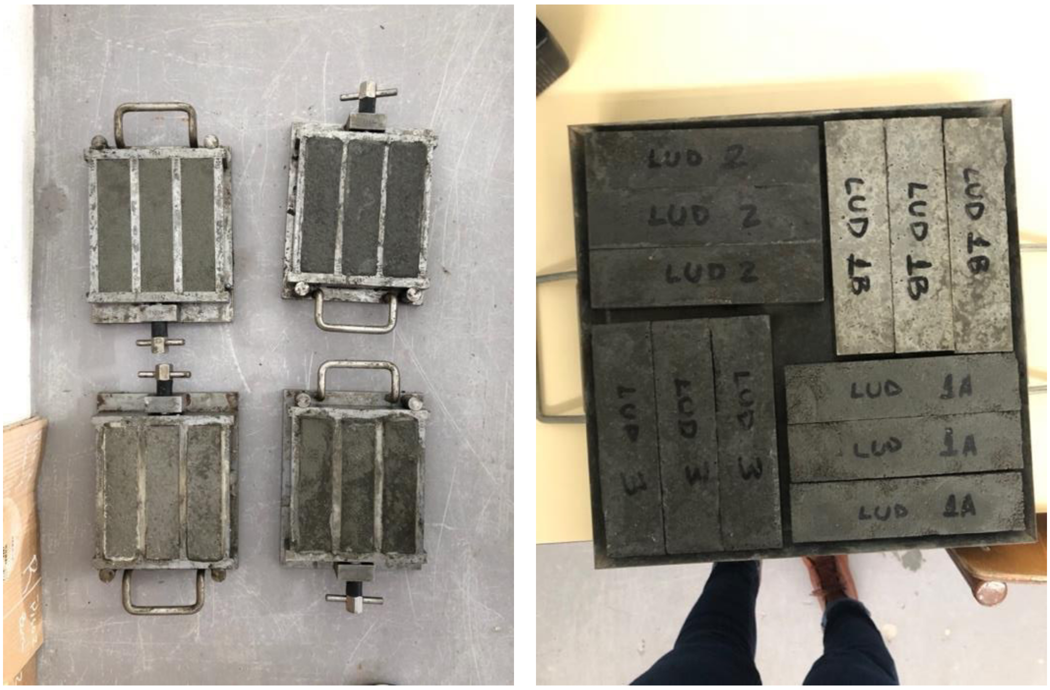

Figure 3.6: Specimens for mechanical tests

3.7.2. Flexural Strength Test

The cured samples were taken out of the curing tank after 28 days (Figure 3.7), dried with a cloth and had its dimensions and weight recorded. Bending tests were performed according to EN 1015-11[39]. A compression testing machine (CTM) was used for this purpose.

The specimens were placed on top of two steel rods 100 mm apart and the load is applied from above, as shown on Figure 3.8. They were carefully placed so that the load was applied evenly through the whole area in contact with the machine. The load was applied at a 20 N/s constant speed.

Figure 3.7: Cured samples

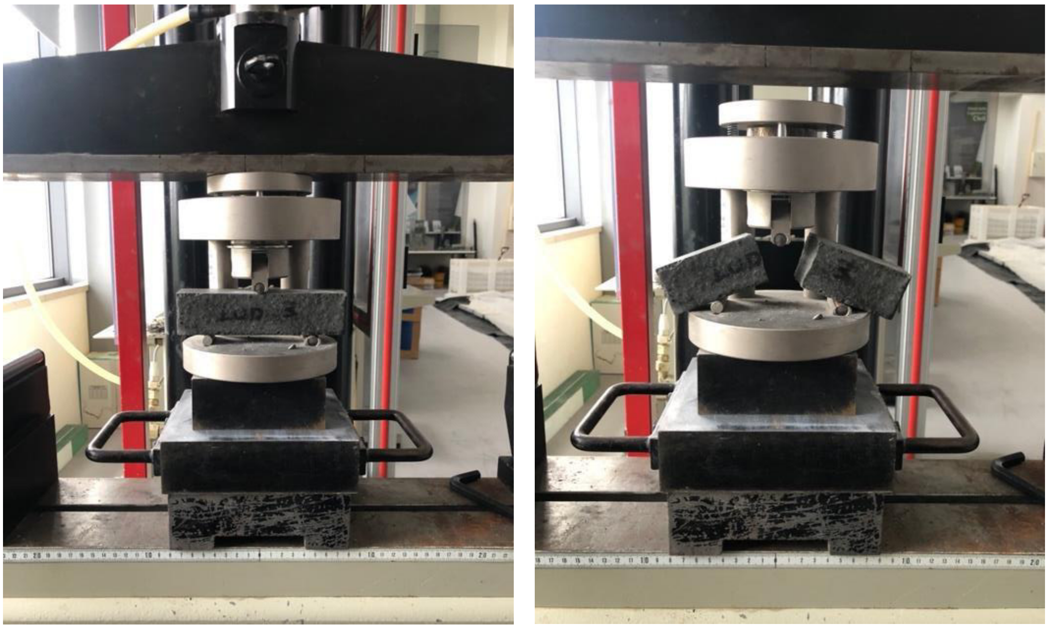

Figure 3.8: Bending test

The maximum load for each specimen was recorded to calculate the flexural strength (Eq. 7), and then the average was taken. The procedure was repeated for all specimens, three samples were tested for each mix.

$$f_s = \frac{3 \times F \times l}{2 \times b \times d^2} \tag{7}$$

f_s = flexural strength (MPa)
F = load (N)
l = support length, the distance between bars (mm)
b = with (mm)
d = depth (mm)

3.7.3. Compressive Strength Test

The specimens were broken in two in result of the bending test, the pieces were then used for compression test. It was used the same CTM used to perform the bending test, but since the load capacity was insufficient, a different configuration was used instead. The test was performed according to EN 1015-11 [39], the load was applied at a 40mm x 40mm area at a

400N/s speed. Figure 3.9 shows the test being performed and how the specimen looks after the test.

The maximum load supported for each specimen was recorded to calculate the compressive strength (Eq. 8) and then the average was taken. The procedure was repeated for all the specimens, 6 for each mix.

$$f_c = \frac{F}{A} \tag{8}$$

f_c = compressive strength (MPa)
F = load (N)
A = area (mm^2)

Figure 3.9: Compression test

3.8. Printing System

This test phase aims to test the printing. The results obtained were examined visually, observing the surface quality, and the presence of deformation, failure, tearing and splitting on fresh specimens. Flow table test was performed to assess the consistency of the mortar.

For the 3D printing tests a robotic arm from KUKA Industrial Robots model KR150 with a payload of 150 kg and 6 axis was used. The robotic arm is a mechanical device that resembles the human arm, it is used to perform tasks that are either unsafe, unpleasant, or highly repetitive. A KRC2 ED05 controller with special software was used to program the tasks and a printing head was attached to the wrist of the robot. The robot is space-saving and installed on the floor, its technical details are shown on Figure 3.10. The dimensions, in mm, are: A=1100, B=3050, C=4625, D= 3100, E=1876, F=976, G=1575.

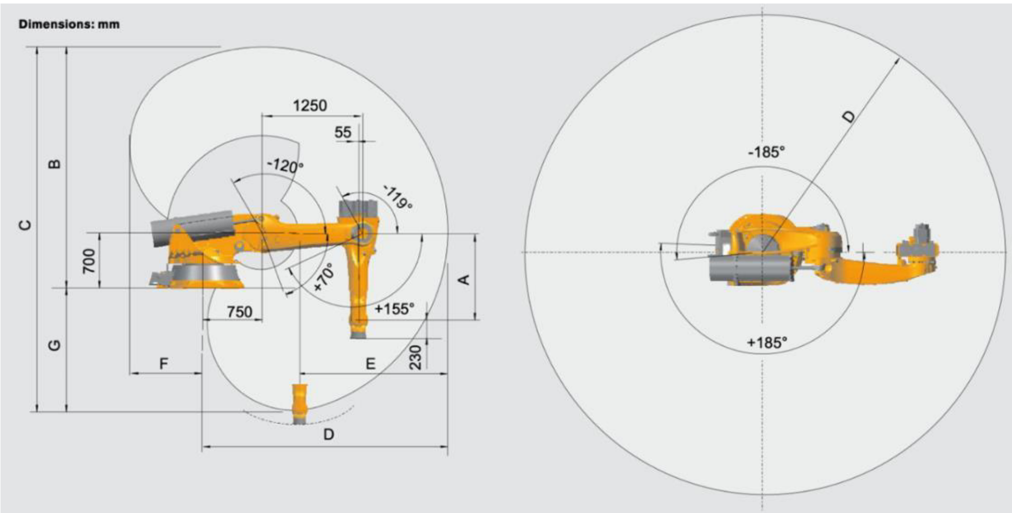

Figure 3.10: Technical details KR 150-2 K [40]

Also, a mixer and a 50l storage tank with an electric motor to pump the concrete through air pressure are connected to the printing head by the pipe, allowing continuously printing through the screw extruder, as shown on Figure 3.11. The printing head and nozzle were developed by CDRSP and the extruding pipe is custom made for printing cementitious material.

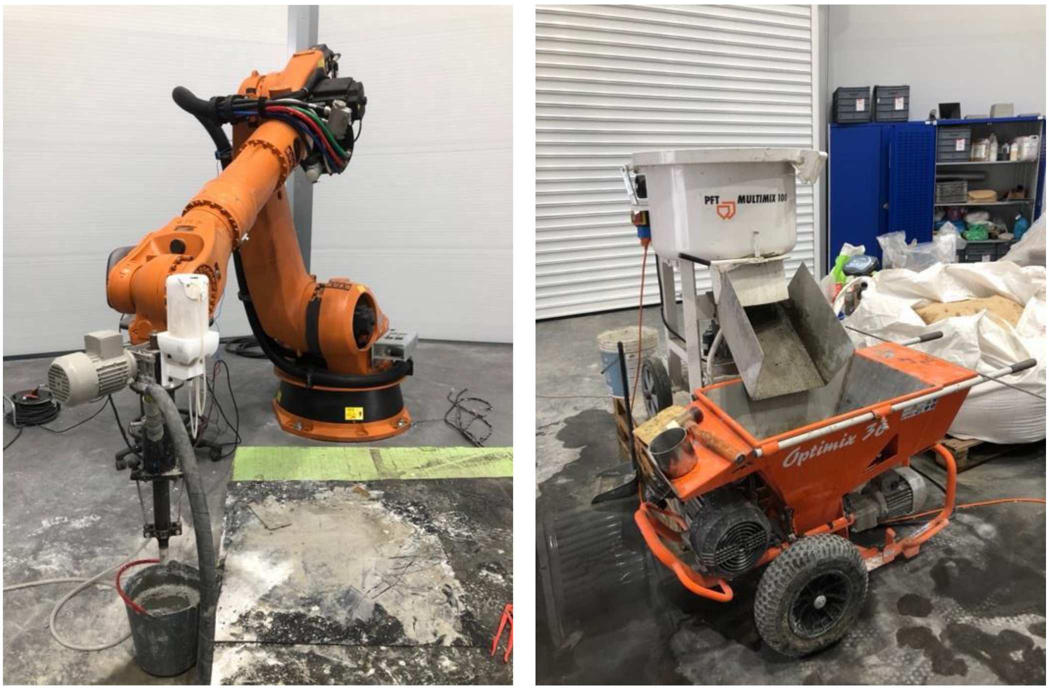

Figure 3.11: Printing equipment

The experimental testing for the 3D printable material followed the chart on Figure 3.12. All the parameters were tested and checked until the best model was found.

The printing tests were performed with 54 mixes, they were analyzed for printability, shape retention and buildability. The flow table test was also performed for all mixes to assess the consistency to assure the printing head best operating conditions.

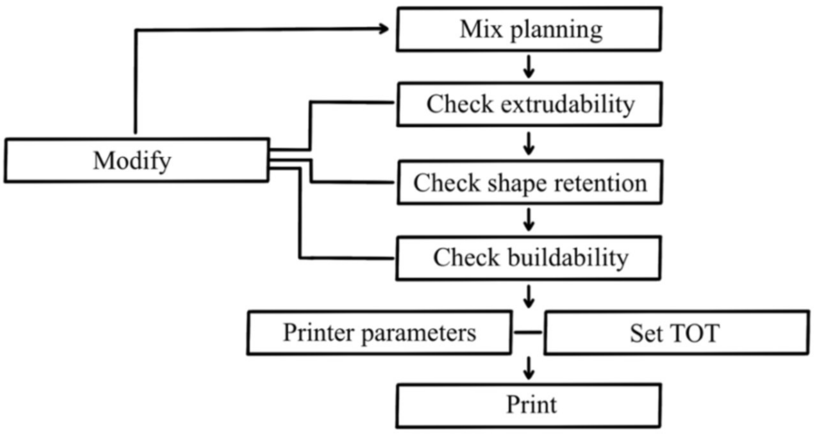

Figure 3.12: Flow chart of experimental testing for 3D printable material.

3.8.1. Extrudability

The first phase of the printing test was to test the extrudability. Some mixes were prepared with a different type of sand to find the better option considering the printing nozzle, the SACT 0-1 has smaller grain size, so it was pondered to be the best choice. The mixes composition is shown on Table 3.4, the cement:aggregate ratio used was 1:2.

Table 3.4: Mixes composition for printing tests

Mix	1	2	3	4	5	6	7	8	9
Filler (%)	20	15	15	10	0	0	0	5	0
FA (%)	0	0	0	0	0	0	0	0	0
Sand type	0-200						SACT 0-1		
SP (%)	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0
Frioplast (%)	-	-	-	-	-	0,5	0,5	0,5	0,5
W/C	0,32	0,31	0,28	0,31	0,29	0,30	0,29	0,26	0,28

The 1:2 ratio for cement and aggregates is used in 3D printing concrete by companies, universities, and individuals [41], because of that it was initially chosen to use this ratio for the mixes. But the machine was not able to extrude the mortars successfully and this could damage all the equipment, so it was tried with a 1:1 ratio instead.

3.8.2. Printability and Buildability

The mixes 10 to 47 were analyzed for printability and buildability, analyzing which mix could support more layers without collapsing. Filler and FA were used to substitute sand and cement, respectively. The quantity varied, and four different admixtures were tested to increase the performance.

For the mixes on Table 3.5, the sand was replaced by filler by 10% and 20%, it was also tested with 0% substitution to compare de results. The mixes 10, 18, 21, and 31 were tested for mechanical performance to decide the best mix to continue the printing trial.

Table 3.5: Mixes composition for printing tests

Mix	10	12	18	20	21	26	27	28	31	32
Filler (%)	0	0	10	20	20	10	10	10	10	10
FA (%)	0	0	0	0	0	0	0	20	20	20
Cement: Aggregate	1:1	1:1	1:1	1:1	1:1	1:1	1:1	1:1	1:1	1:1
SP (%)	2,0	2,0	2,0	2,0	2,0	0,0	1,0	0,0	1,0	1,0
VMA V70 (%)	0	0	0	0	0	0,5	0	0,5	0,5	0
VMA V90 (%)	0	0	0	0	0	0	0,4	0	0	0,4
Frioplast (%)	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5
W/C	0,22	0,21	0,21	0,23	0,24	0,31	0,26	0,36	0,25	0,28

The mixes on Table 3.6 had 10% filler substitution and were examined with and without FA to understand its influence on printing. Only Frioplast, VMA V70, and SP were used as admixtures. The mixes 42 and 44 were tested for mechanical performance.

Table 3.6: Mixes composition for printing tests

Mix	36	40	41	42	44	46	47
Filler (%)	10	10	10	10	10	10	10
FA (%)	0	0	20	20	20	20	20
Cement:Aggregate	1:1	1:1	1:1	1:1	1:1	1:1	1:1
SP (%)	2,0	2,0	2,0	1,0	2,0	2,0	2,0
VMA V70 (%)	0	0	0	0,5	0	0	0
Frioplast (%)	0,5	0,5	0,5	0,5	0,5	0,5	0,5
W/C	0,23	0,24	0,25	0,34	0,23	0,23	0,23

3.8.3. Consistency

After analyzing the mixes printability, buildability, and examining the mechanical tests results, the mixes on Table 3.7 were evaluated based on the consistency. The materials proportions were the same for all mixes, the only change was the water quantity, flow table test was performed to assess the consistency. It was chosen to work with 140 mm, 160 mm, 180 mm, 200 mm, and 300 mm diameter according to the flow table test. The goal was to find the mix that could support more layers without failing. For mixes 52 and 54 it was prepared 2 mix batches to test the extrusion until failure or until it reaches the maximum height according to the robot program.

Table 3.7: Mixes composition for printing tests

Mix	51	52	53	54
Filler (%)	10	10	10	10
FA (%)	20	20	20	20
Cement:Aggregate	1:1	1:1	1:1	1:1
SP (%)	2,0	2,0	2,0	2,0
Frioplast (%)	0,5	0,5	0,5	0,5
W/C	0,23	0,23	0,21	0,22
Consistency avg. (mm)	210	135	182	155

3.9. Compressive Strength Test on Fresh Mortar

The mixes 18, 52 and 54 were tested for compressive strength on fresh mortar. The mix preparation followed the proportions from Table 3.8.

Table 3.8: Mixes composition for compressive strength test

Mix	18	52	54
Filler (%)	10	10	10
FA (%)	0	20	20
Cement:Aggregate	1:1	1:1	1:1
SP (%)	2,0	2,0	2,0
Frioplast (%)	0,5	0,5	0,5
W/C	0,21	0,23	0,22

The quantity of materials was calculated in agreement with the mold. A cylindric mold was specifically made for this test using a PVC tube and 3D printed nylon lids, as shown the sketch on Figure 3.13.

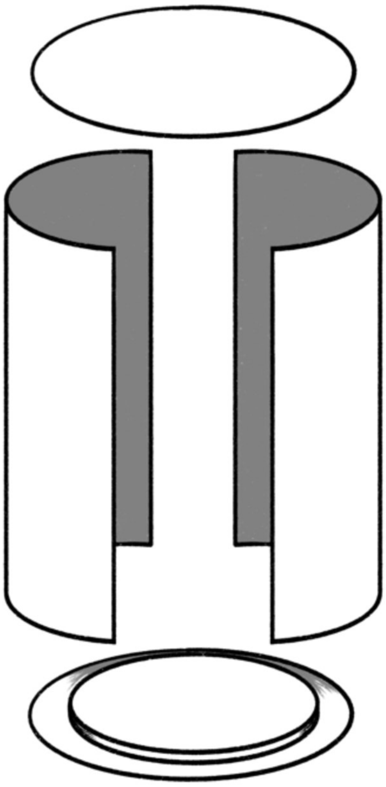

Figure 3.13: Cylindric mold sketch

The sand and filler were weighted then added to an automatic mixer with 100 ml water, after a few minutes mixing the cement and FA were also added. At last, the admixtures and the rest of the water were added, and the mix was mixed until a homogeneous paste was achieved. The flow table test was performed to guarantee the consistency was correct.

The mold was filled with mortar in three layers, after each layer was placed it was compacted by a tamper ten times to ensure it was homogeneously filled. Then it was placed on the machine and the cylindric mold was removed, leaving only the nylon lids, it helped guarantee the load was applied evenly through the surface.

For the compressive strength test, it was used the Instron 4505, an universal tensile testing machine, with a 100 kN load cell, as shown on Figure 3.14. The load was applied at a 30 mm/min rate.

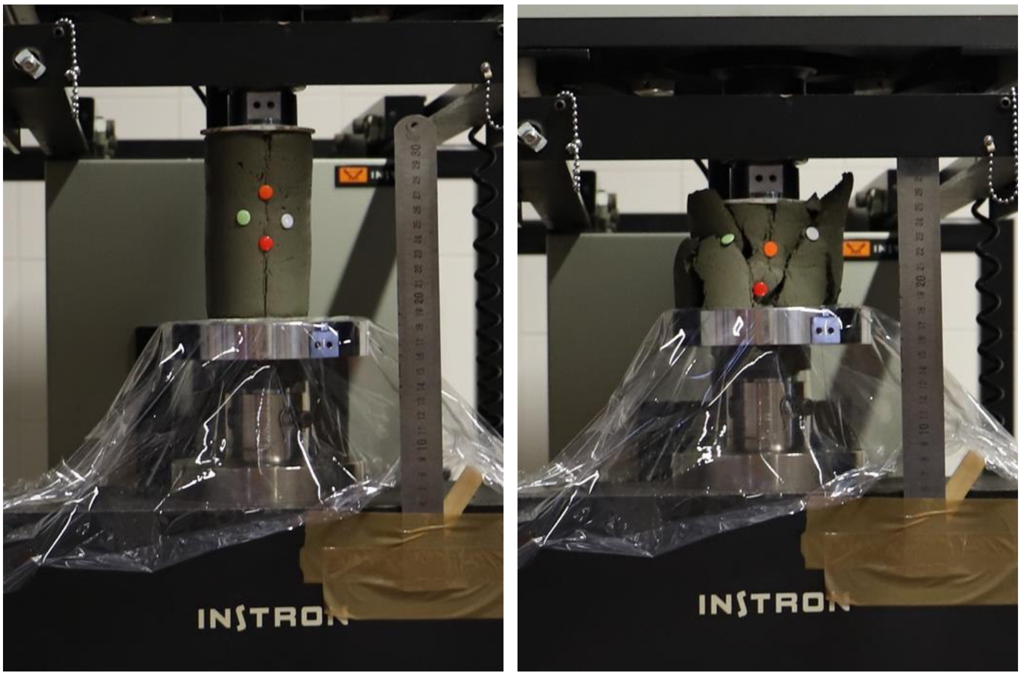

Figure 3.14: Compressive strength test on fresh mortar

The test was recorded using a photographic camera, it was programmed to take a photo each second, then the photos were analyzed using the NI Vision Builder, an application for automated inspection. With the obtained data it was possible to plot graphs for horizontal and vertical displacement versus diameter. The results obtained from the Instron 4505 machine, and from the image analysis were later combined to obtain graphs, including the stress x strain graph for assessment of elastic modulus. The test was repeated five times for each mix.

4. Results

Different test methods were used to study the materials for mechanical and printing properties of the mixes. The obtained results are presented in this section. The results for the material analysis were presented, followed by the results of the mechanical tests, the evaluation of the printable mix for printability and buildability, and the compressive strength test on fresh mortar.

4.1. Grain Size Analysis

To assess the sand grain size and ensure it is suitable for printing the percentage of small size grains, in this case smaller than 1mm, was calculated. The material retained on each of the sieves was weighted and the particle size distribution is shown on Table 4.1.

Table 4.1: Particle size distribution

Sieves	Retained material		Passed through (%)
Nominal sieve opening (mm)	**Mass (g)**	**(m_1/m_2) (%)**	
2,00	0,84	0,21	99,79
1,00	39,12	9,78	90,01
0,500	274,60	68,64	21,37
0,300	83,18	20,79	0,57
0,200	1,40	0,35	0,22
0,100	0,58	0,14	0,08
< 0,100	0,30	0,07	0,00
Total	**400,02**	**100,00**	

According to Eq. 5, the percentage of grains smaller than 1mm is 90,09%, the sand is considered suitable for printing, as less than 10% of the grains did not pass through the 1mm sieve. The granulometric curve is obtained from the data from Table 4.1, and it is shown on Figure 4.1.

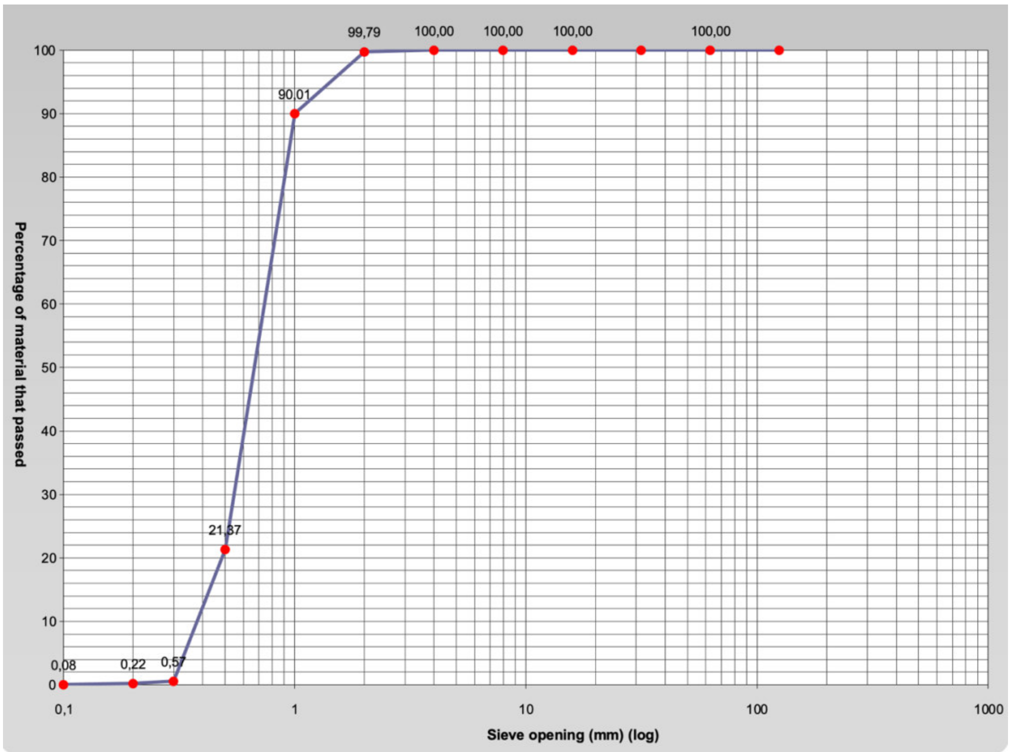

Figure 4.1: Granulometric curve

4.2. Density Analysis

To find the proportion of sand and filler to be used on the experiments, the first step was to determine the bulk density of the aggregates used. For accuracy purposes, this procedure was done twice for each material and the average was taken (Table 4.1).

Although the measurement procedure is not exact, the obtained values are within what was expected, and the results are almost identical for each test. The limestone filler has a slightly lower density that the sand.

Table 4.2: Density analysis result

Material	Sand		Limestone Filler	
Test	**Test 1**	**Test 2**	**Test 1**	**Test 2**
Material (g)	25,12	50,54	13,73	27,14
Water (g)	90,22	80,61	94,68	89,54
Volume total (cm^3)	100	100	100	100
Volume water (cm^3)	90,22	80,61	94,68	89,54
Volume material (cm^3)	9,78	19,39	5,32	10,46
Material density (g/cm^3)	2,57	2,61	2,58	2,59
Average (g/cm^3)	**2,590**		**2,585**	

4.3. Compactness Test

After calculating the density, the compactness test was done using a 69 g metallic cup with an 865 cm^3 volume capacity. The results for the tests with 0% to 30% filler substitution are shown on Table 4.2.

Table 4.3: Compactness test results

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
% filler substitution	0%	10%	15%	20%	25%	30%
Sand (mix) (g)	1 533	1 533	1 508	1 453	1 370	1 277
Filler (mix) (g)	0	170	266	363	457	547
Mix + cup (g)	1 602	1 745	1 778	1 782	1 771	1 752
Mix (g)	**1 533**	**1 676**	**1 709**	**1 713**	**1 702**	**1 683**
Bulk density (g/cm^3)	**1,77**	**1,94**	**1,98**	**1,98**	**1,97**	**1,95**
Sand (g)	1 533	1 508	1 453	1 370	1 277	1 178
Sludge (g)	0	168	256	343	426	505

A graph comparing the density versus percentage filler substitution is shown on Figure 4.2. It was expected that the graph obtained from the test results would create a 2nd degree equation, even though the filler grain size is smaller than the sand, its density also is, resulting in a maximum point According to the graph obtained from the test results, and its equation, the most compact composition is mix 4, with 20% substitution.

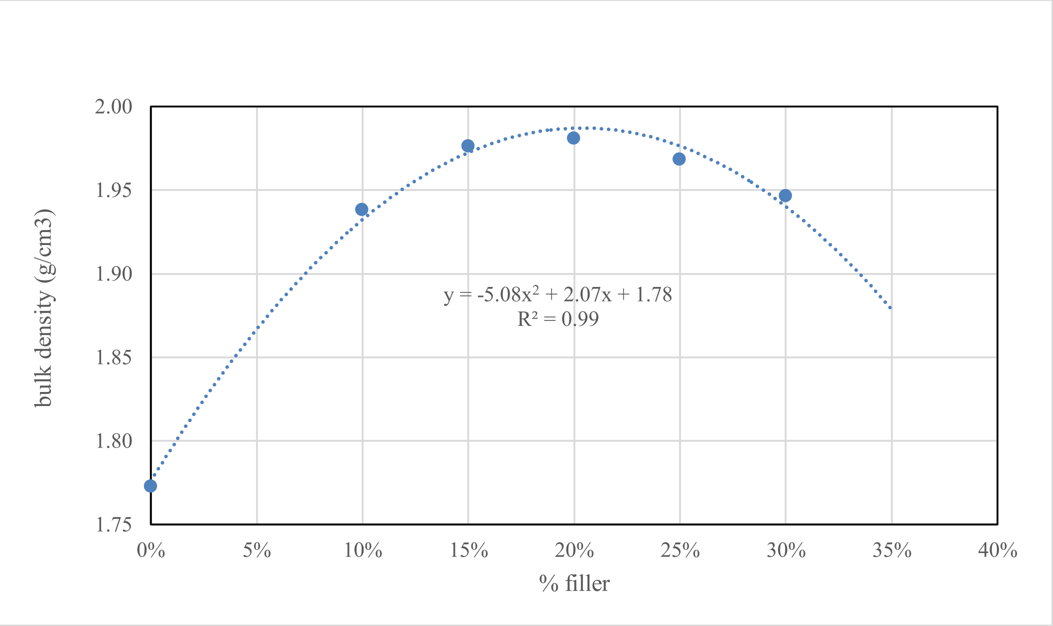

Figure 4.2: Compactness test analysis

4.4. Set Accelerator Analysis

The flow table test was performed to determine the consistency of fresh concrete and to analyse the effect of the different selected admixtures. The goal was to maintain the consistency of the mixes with a good workability for printing, allowing to maintain its shape after extrusion and support the upper layers without deformation. The time for a 30mm reduction on the diameter was calculated.

The mixes which the admixtures were added at last did not perform well, it was difficult to measure the water quantity necessary for the right consistency as more water is needed before the admixtures are added. Because of that, only the results for the mixes with the admixtures added on the beginning were considered.

The tests results are shown on the Table 4.3. The mixes were tested for four different parameters:

- Time for a 30mm reduction on the diameter;
- Initial diameter (d_0);
- Water percentage;
- Woergunit SA 160, percentage used according to the cement.

Table 4.4: Set accelerator analysis

Mix	Input		Results	
	Woergunit SA 160 %	**% water**	**d_0 (mm)**	**t (min)**
M1	0,0%	9,9%	181,5	29,0
M2	4,0%	12,7%	171,5	12,0
M3	6,0%	12,2%	167,5	6,2
M4	8,0%	12,9%	166,0	9,9
M5	10,0%	14,5%	160,0	6,3
M6	2,0%	10,3%	221,5	4,5
M7	6,0%	10,2%	165,5	7,9
M8	8,0%	12,9%	151,0	17,8
M9	6,0%	11,8%	165,3	14,2
M10	0,0%	10,8%	223,5	25,2
M11	2,0%	11,1%	167,0	33,1
M12	8,0%	11,1%	123,3	36,4
M13	8,0%	14,8%	152,5	19,5
M14	10,0%	13,2%	126,0	37,9
M15	4,0%	13,2%	155,0	58,4

The graphs on Figure 4.3 shows the results comparing the Woergunit SA 160 percentage versus time for a 30mm reduction on the diameter, and water percentage. The tests with 4%, 8% and 10% Woergunit SA 160 needed more water to achieve a good consistency when compared to 6%.

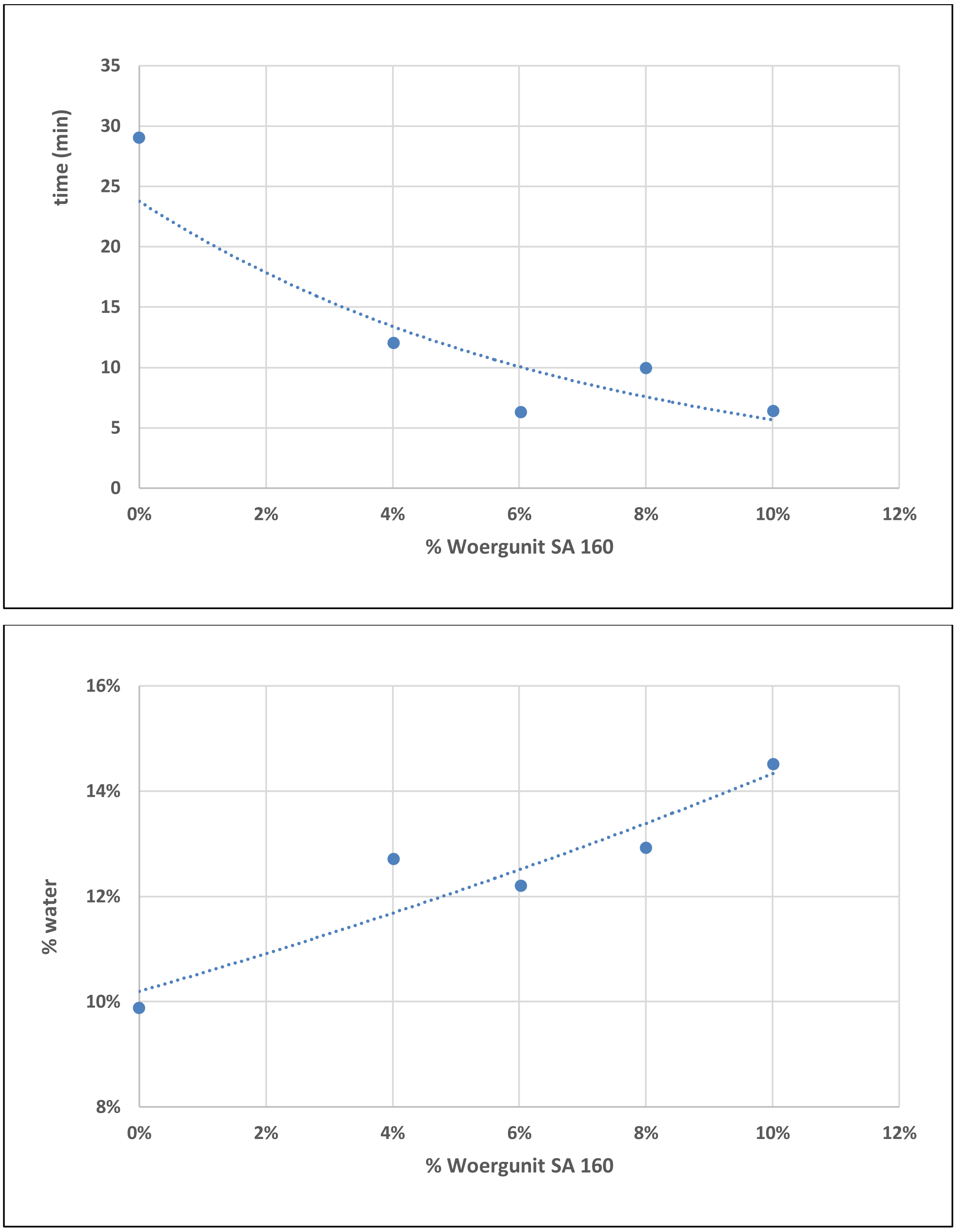

Figure 4.3: Set accelerator analysis

Analysing the graphs is possible to conclude that the mixes with 6% Woergunit SA 160 presented an average shorter time for a 30mm reduction on the diameter, and needed less water than the mixes with 4%, 8% and 10%. As consequence, it was chosen to use 6% of the admixture for the following tests.

4.5. Mechanical Tests

The mechanical tests were performed in 2 separate groups:

- Group 1: evaluate the influence of the filler on mechanical properties
- Group 2: find the best filler and cement percentage substitution according to the mechanical properties

4.5.1. Group 1

Before starting the printing tests, the flexural strength test and compressive strength test were performed to analyze the influence of the filler on mechanical properties. The results are shown on Table 4.4 and Table 4.5.

Table 4.5: Flexural strength test results

Mix	1	2	3
M (g)	608	598	618
	602	615	620
	596	603	614
F (N)	4910	6710	5480
	5160	7090	5680
	4780	5990	4820
l (mm)	100	100	100
	100	100	100
	100	100	100
b (mm)	40	40	41
	41	40,5	41
	39,5	40	40,5
d (mm)	41	40	40
	40	40	40
	40	40	40
f (N/mm)	10,95	15,73	12,53
	11,80	16,41	12,99
	11,34	14,04	11,16
$f_{avg.}$ (N/mm)	11,37	15,39	12,23

Table 4.6: Compressive strength test results

Mix	1	2	3
f (N/mm²)	82,44	99,19	96,81
	87,75	98,25	95,38
	89,94	99,81	93,81
	88,31	93,56	96,94
	58,19	97,38	96,50
	33,25	98,38	97,88
$f_{avg.}$ (N/mm)	73,31	97,76	96,22

Mix 2 presented better results for both flexural strength and compressive strength, mix 3 got similar results. Which means that the mixes with 15% and 20% of filler substitution presented better results than the mixes with no filler at all. This outcome was already expected based on the compactness test result; more compact mixes have higher mechanical resistance.

4.5.2. Group 2

From the mixes analysed for printability and buildability on printing tests, six mixes were tested for flexural and compressive strength as well. Results are shown on Table 4.6 and Table 4.7. All mortars had waste materials added, 20% cement substitution for FA and from 0% to 20% fine sand substitution for filler. Other than different waste percentages, it was studied 5 different admixtures: SP, VMA V70, VMA V90, and Frioplast. Flow table test was also performed, the average diameter was 155 mm for mix 42 and 145 mm for mix 44.

Table 4.7: Flexural strength test results

Mix	10	18	21	31	42	44
M (g)	462	536	498	540	537	526
	460	544	483	537	535	531
	449	525	493	540	527	532
F (N)	2,23	6500	4910	5,17	3,55	3,18
	2,26	5030	3720	4,81	3,45	3,46
	1,87	5270	4360	4,37	3,23	3,78
l (mm)	100	100	100	100	100	100

Mix	10	18	21	31	42	44
l (mm)	100	100	100	100	100	100
	100	100	100	100	100	100
b (mm)	40	40	40	40	40	40
	42	41	40	40	40	40
	40,5	41	40	40	40	40
d (mm)	42	40	40	42	40	40
	40	40,5	39,5	42	40	40
	40	41	40	40	39,5	40
f (N/mm)	4,74	15,23	11,51	10,99	8,32	7,45
	5,04	11,22	8,94	10,23	8,09	8,11
	4,33	11,47	10,22	10,24	7,76	8,86
$f_{avg.}$ (N/mm)	4,70	12,64	10,22	10,49	8,06	8,14

Table 4.8: Compressive strength test results

Mix	10	18	21	31	42	44
f (N/mm²)	22,81	57,63	44,38	61,06	53,56	59,69
	25,75	61,69	46,06	62,13	59,19	60,94
	25,63	62,63	38,63	65,81	55,94	57,38
	22,88	61,44	37,56	65,25	60,69	58,94
	23,38	55,81	44,06	63,81	59,25	61,94
	26,81	56,06	45,13	66,63	56,00	62,38
$f_{avg.}$ (N/mm)	24,54	59,21	42,64	64,11	57,44	60,21

Mix 10 had no waste material, opposed to the other mixes. It got the worst result from both tests. For flexural strength test, mix 18 got the best result. For compressive strength test, mix 31 performed better, followed by mix 44.

From the results, it is possible to conclude that adding FA improves the compressive strength, however it lowers the flexural strength. Compressive strength is one of the most important properties of concrete and mortar. The binder strength has a significant effect on performance. Considering the performance on the compressive strength test and with the purpose of using fewer chemical components, it was chosen to proceed with mix 44.

4.6. Printing Results

The first phase of the printing test was to find the mix suitable for extrusion. The printing parameters used for all tests are shown on Table 4.9.

Table 4.9: Printing parameters

Mixes	1-11	12-39	39-41	42-43	44-54
Layer thickness (mm)	15	10	13	10	12
Between layers (mm)	17	20	25	20	25
Head speed (mm/s)	70	70	70	70	70
Head rotation (Hz)	50	50	40	50	40

The first six mixes were prepared using sand with 2000 µm maximum grains size and presented a few problems. Table 4.10 contains the average results for flow table test on the mixes. Mix 2 was too much fluid, the mortar just overspread around the floor, and mixes 1, 3, 4, 5, and 6 did not even extrude at all, the machine overheated, and nothing came out through the printing head. It was decided to stop the test and clean everything before the mortar dried inside the pipe, which could cause permanent damage to the equipment.

Table 4.10: Flow table test result

Mix	1	2	3	4	5	6	7	8	9
Diameter avg. (mm)	>300				182,0	178,0	255,0	200,0	208,5

It was then decided to change the sand for SACT 0-1, with 1000 µm maximum grain size and add more water for the next tests. For mix 7, and it was finally possible to extrude the mortar, however the consistency was not right yet, but AP could be used to solve that.

To calculate the voltage of the electric motor to add the AP at the nozzle, the extruded material from mix 7 was weighted and the extrusion time was taken. Knowing that in 2,15 minutes 5,52 kg of the mix was extruded, the mix discharge was 5,57 kg/min. The mix was prepared with 33,13 kg of material in total, within 0,302% was cement. This means that the cement discharge was 0,77 kg/min. So the required discharge to add 6% of AP to the mix is

46,5 g/min and the electric motor should operate with 3,94 V. This procedure was later repeated for mixes 10, 11, 12, 18, 21, 22, 26, 31, 32, 38 and 39.

4.6.1. Printability Analysis

Once the new cement: aggregate ratio was defined, one step back was taken. The mixes were tested without waste materials at first to understand how it would behave. Then it was tested adding the filler to the mix at different percentages. At last, the mixes with 20% FA were tested for different filler percentages. It was also tested with different admixtures to choose the best composition.

The mixes 10 to 32 were analyzed for printability. The consistency test was done before printing. Table 4.11 contains the printing test outputs. The extruded mix was weighted to calculate the discharge required to add the AP at the nozzle. For mixes 21, 26, 31, and 32, a cup with known volume was filled and weighted to find the mixes density.

Table 4.11: Printability analysis

Mix	**10**	**12**	**18**	**21**	**26**	**27**	**28**	**31**	**32**
Consistency avg. (mm)	245,00	170,00	172,50	145,00	170,00	157,50	165,00	165,00	157,20
Extrusion time (min.)	2,50	3,15	2,77	1,60	1,17	1,25	0,88	7,90	1,50
Discharge (kg/min)	2,64	2,36	2,76	2,71	3,19	-	-	3,02	2,77
Weight (kg) - cup	-	-	-	1,81	1,94	-	-	1,84	1,85
Volume (dm^3) - cup	-	-	-	0,87	0,87	-	-	0,87	0,87
Materiais used (kg)	22,47	24,54	24,81	22,61	23,18	22,75	20,96	37,84	25,54
%cement	0,45	0,45	0,45	0,44	0,43	-	-	0,44	0,44
Cement (kg/min)	1,17	1,06	1,24	1,20	1,38	-	-	1,33	1,21
AP 6% (g/min)	70,49	63,34	74,21	71,99	82,53	-	-	79,89	72,41
Motor (V)	5,04	4,71	5,21	5,11	5,60	-	-	5,47	5,13

For mix 10 the AP was added at the nozzle, but it was still too fluid, and the layer height used on the program was too high, the extruded piece is shown on Figure 4.4.

Figure 4.4: Printing test – mix 10

The print parameters were modified, and less water was used in mix 12, with no AP added this time. The printing test for mix 12 is presented on Figure 4.5, the overall result is a little better, but the shape retention needs some improvement yet.

Figure 4.5: Printing test - mix 12

Limestone filler was added at different percentages on mixes 18 to 27. Different admixtures were also tested. Mixes 20, 26, and 27 did not achieve satisfactory results when extruded.

For mix 18 the filler substitution was 10%, there was no AP added, the print was homogenous, and the shape retention improved, as shown on Figure 4.6. Mix 21 was similar to mix 18 but with less water, which means a smaller consistency value (Figure 4.7).

Figure 4.6: Printing test - mix 18

Figure 4.7: Printing test - mix 21

The mixes with 10% filler performed better than the mixes with 20% filler or no filler at all.

For mixes 28 to 32, the filler percentage was kept at 10% and 20% FA was added. Three different admixtures combinations were tested. Mix 28 did not achieve a homogeneous extrusion, even though the consistency was low the mortar was too fluid. The same thing happened to mix 32 (Figure 4.8), this may be caused by the admixtures used.

Figure 4.8: Printing test – mix 32

Mix 31 (Figure 4.9) had the same consistency as mix 28 but different admixtures were used, and the extrusion achieved the expectations. For all the mixes analyzed for printability, the best mixes were mix 18 and 31, so they served as base mixes for the next phase: the buildability analysis. Mix 18 were also tested for compressive strength on fresh mortar.

Figure 4.9: Printing test – mix 31

4.6.2. Buildability Analysis

For the buildability analysis the mixes were printed until it reached the maximum number of layers without collapsing. Mixes 33 to 40 used mix 18 as base and mixes 41 to 47 used mix 31 as base but with different admixtures. Table 4.12 contains the consistency test results and layer thickness, it was not performed for mixes 40 and 41.

Table 4.12: Flow table test result

Mix	**36**	**42**	**44**	**46**	**47**
Layer thickness (mm)	10	10	12	12	12
Consistency avg. (mm)	247,50	155,00	145,00	200,00	137,50

For mixe 36 it was tried to add the AP at the nozzle, but the system did not work properly as the conducting pipe did not have enough pressure. So, for mix 40 a new nozzle was tried, and it became possible to extrude the mortar successfully. 3 batches of the mix were needed to achieve 88 cm height, but air bubbles started to come up, and the extrusion was not homogenous anymore (Figure 4.10).

Figure 4.10: Printing test - mix 40

For mix 41, and to avoid the flaws on the extrusion, the mix was prepared with more water than the previous one. 2 batches of the mix were needed to achieve 101 layers, with 122 cm total height. This was the maximum height the robot was programmed to; thus, there is the possibility that more layers could have been achieved. Figure 4.11 shows the extruded piece for mixes 40 and 41. For mix 42, the same composition as used for mix 31 was tried, including the admixtures, but this time the AP was added at the nozzle. The result was not good since the extruded piece fell apart before reaching 50 cm high.

Figure 4.11: Printing test - mixes 40 and 41

Mixes 44, 46, and 47 had the same composition that mix 41 but with different water quantities, resulting in different consistencies. Although the results were good, the consistency was unpredictable, even with the same water quantity for the three mixes and they presented different results for flow table test.

Since the extrusion is done with fresh mortar, the consistency is a key factor. It was decided to use mix 41 as a base, with no AP added, and for five different consistencies: 140 mm, 160 mm, 180 mm, 200 mm, and more than 300 mm. Flow table tests were performed to assess the consistency and guarantee it matched.

Even though mix 51 did not have a higher W/C ratio, the materials were left on buckets overnight and this might have influenced their humidity. The flow table test result was 210 mm, and the extrusion did not come out as expected. The mortar was too fluid and could not maintain its shape, as shown on Figure 4.12. Since the result with 210 mm was not good, it was decided not to perform the printing test for a mix with 300 mm.

Figure 4.12: Printing test - mix 51

For mix 52 (Figure 4.13) the flow table test result was 135 mm. Two batches of the mix were prepared, and the extrusion test reached the maximum layer count without failing. The printed sample had 113 cm high in total, with 114 layers. This mix got the best performance for the printing test.

Figure 4.13: Printing test - mix 52

With 182 mm in the flow table test, mix 53 extrusion test began favorably. The printing was homogenous, and the shape retention was good. But after the third layer the printing thread began to get thinner until it stopped extruding on the fourth layer. The printing head started to overheat, and it was decided to stop the test before it could cause damage to the equipment.

Mix 54 attained 155 mm in the flow table test. Two batches of this mix were prepared for the printing test. The extrusion was homogenous, the equipment worked with no problem, but at some point, the layers started to offset to the side and extrusion began to fail, as shown on Figure 4.14. The printing test for this mix was performed twice, but it did not even reach 30 cm height in both trials.

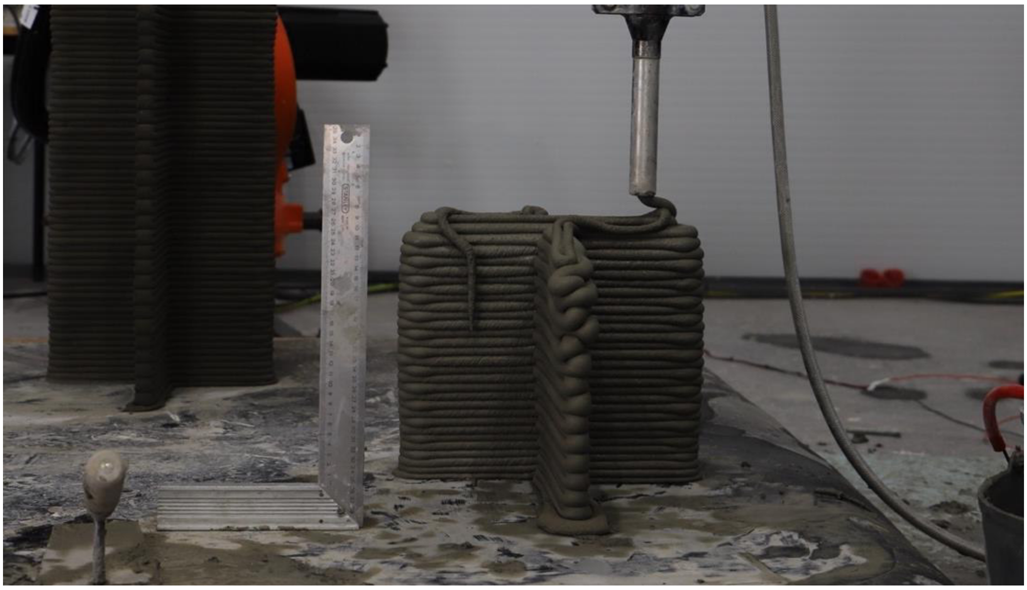

Figure 4.14: Printing test - mix 54

4.7. Compressive Strength on Fresh mortar

For the last phase of the buildability analysis mixes 18, 52 and 54 were also tested for compressive strength on fresh mortar. Five samples of each mix were tested but due to technical issues in the Instron machine, only three mixes could be analyzed for each mix, as the data could not be saved for the other test runs. Considering the COVID situation, there was not enough time to repeat the tests, but it is recommended doing so for future studies.

Using a software for automated inspection, NI Vision Builder, the images from the camera for each test were combined to obtain data for horizontal and vertical displacement versus diameter.

The results obtained from the Instron 4505 machine, and from the image analysis were combined on a spreadsheet to compute the results and plot the graph for stress and strain. The graphs obtained for mixes 54 and 55 did not presented a satisfactory curve, it was not possible to analyze the data. Since the evaluation depends on several steps and different equipment are involved, if one small data or input is off all the result will be affected. For this reason, it was only possible to examine 5 tests: 3 for mix 18 and 2 for mix 52, the graphs are shown on Figures 4.15 – 4.20.

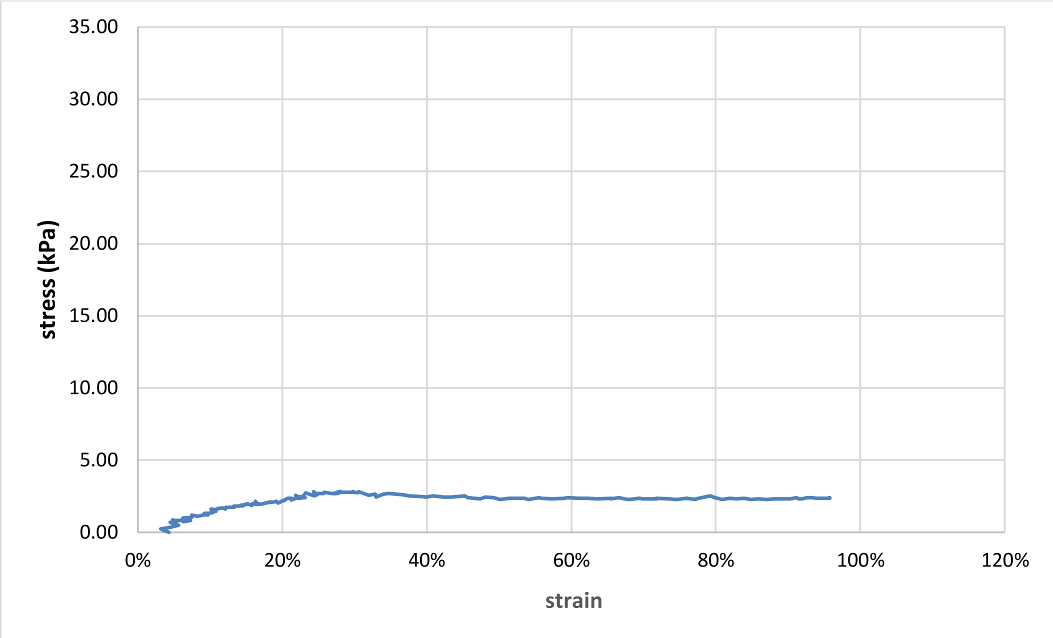

Figure 4.15: Stress x strain - mix 18.1

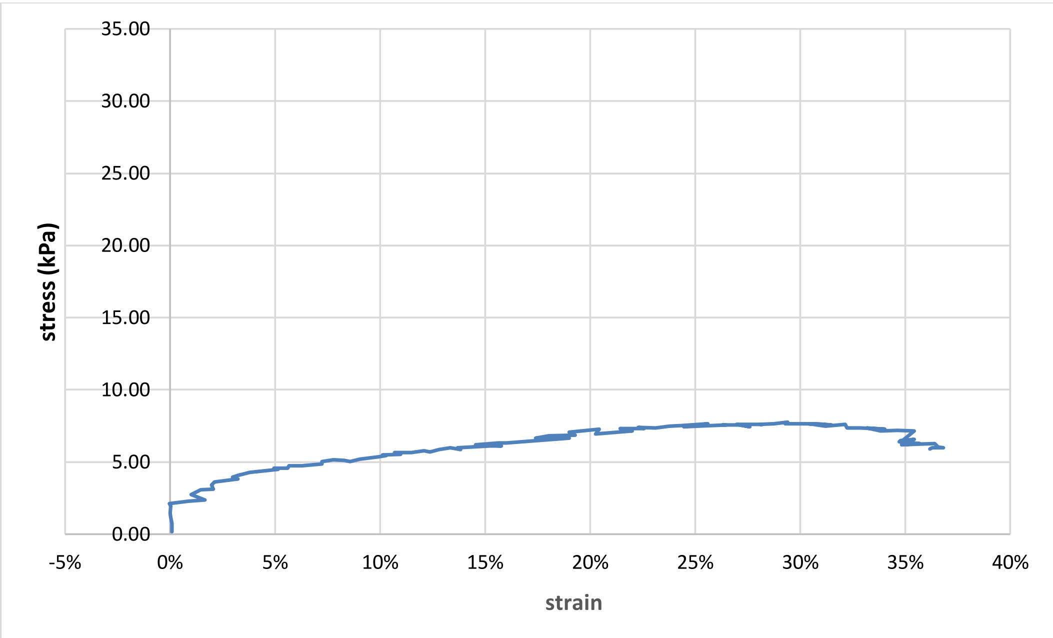

Figure 4.16: Stress x strain - mix 18.2

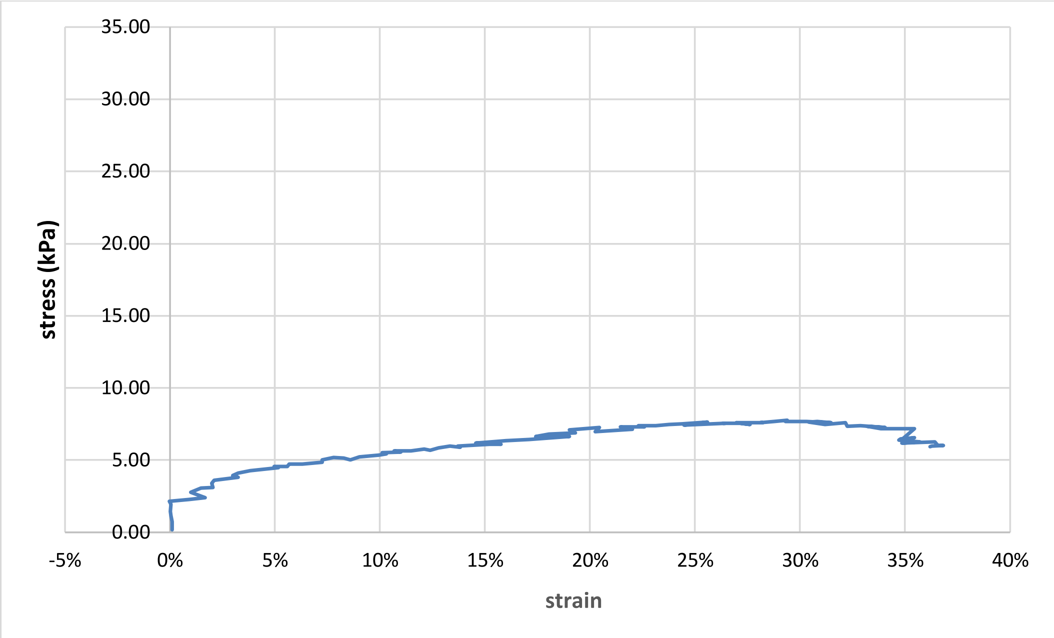

Figure 4.17: Stress x strain - mix 18.3

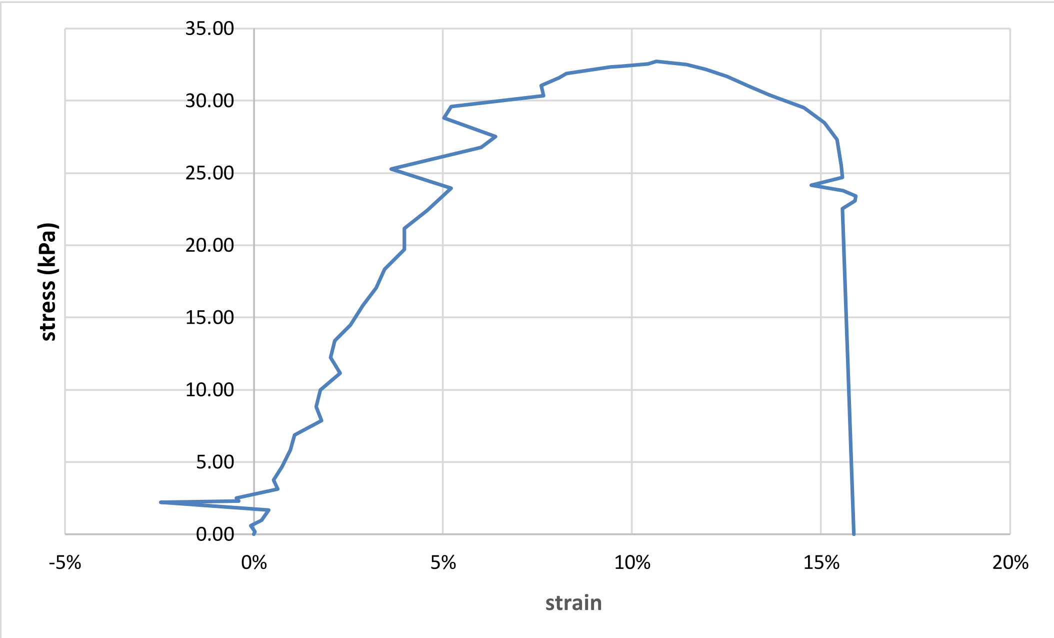

Figure 4.18: Stress x strain - mix 52.1

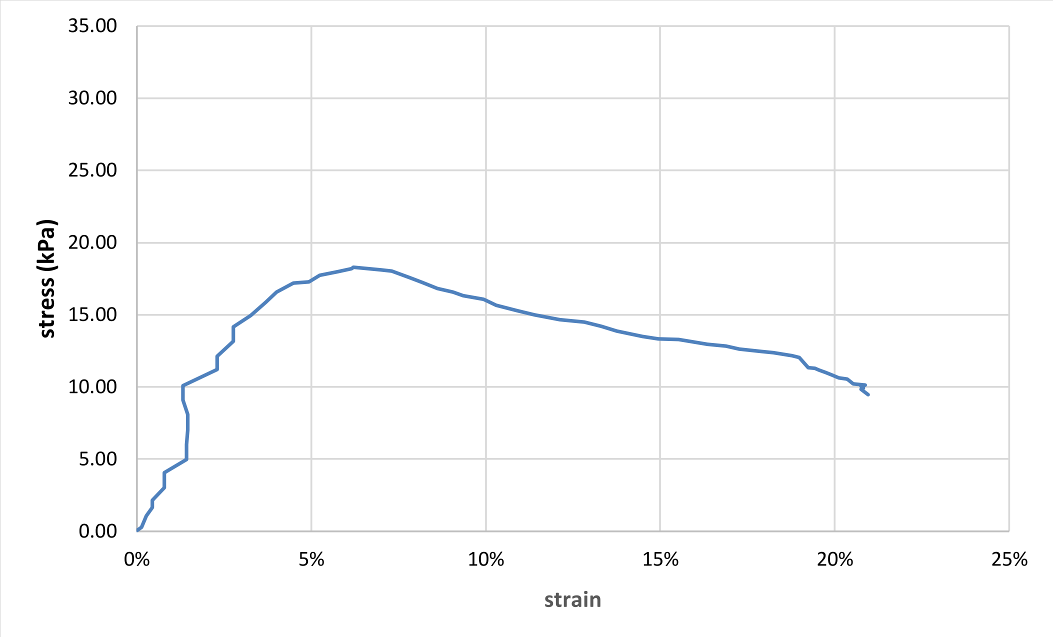

Figure 4.19: Stress x strain - mix 52.2

Elastic modulus describes the relative stiffness or rigidity of a material, while a stiff material will have a high value, a flexible material will present a low value. In terms of the stress and strain curve, the modulus of elasticity is the slope of the linear part of the graph. Table 4.13 contains the value for each mix examined.

Table 4.13: Elastic modulus (E)

Mix	**18.1**	**18.2**	**18.3**	**52.1**	**52.2**
E (kPa)	14,2	40,2	29,4	450,6	202,1

Examining the mixes composition, both mixes had 10% filles substitution but the difference between them was the 20% FA substitution on mix 52. Comparing the elastic modulus, mix 52 presented much higher values, meaning that mix 52 is stiffer than mix 18 and better suited for this project.

Taking a step back to analyze for flow table test, performed before the printing tests, mix 52 had 135 mm and mix 18 had 172,5 mm. For printing test, mix 18 was homogenous and had a good printability. Mix 52 was also homogenous, its buildability was analyzed by printing until it reached the maximum number of layers without collapsing. The printed sample had

114 layers; the maximum height supported by the machine. So, mix 52 got the best performance for printing test, and it was already expected to perform better on the compressive test on fresh mortar as well.

Conclusion

The main objective of this work was to achieve a cementitious mix for 3D printing by incorporating waste material, namely filler and FA. The extrusion process was used. It is simple and can be used for structural and architectural production with good results: it reduces waste production, labour cost, construction time and construction cost, when compared to the traditional method. This technique allows complex designs and utilisation of waste materials for a sustainable construction.

Thirty compositions with different admixtures percentages were tested to study the effect of set accelerator on fresh paste. The flow table test was performed to find the best option, the mix with 6% Woergunit presented an average shorter time, so it was chosen to use this quantity. Compactness test was performed to find the best proportion between fine sand and limestone filler. The mixes were tested for 0% to 30% filler substitution and the mix with 20% substitution was the most compact.

For mechanical tests, ten mixes were tested in 3 groups for compressive strength and flexural strength. For the first group, the mixes were analysed to study the influence of the filler on mechanical properties. The mixes with filler performed better than the mixes with no filler. For the second group, it was tested mixes with waste materials, both FA and filler. The mix with FA and filler performed better than the mix that had only filler added. On the third and last group, both mixes had waste materials, but different admixtures added. The mix with SP and frioplast performed better than the mix with SP, VMA V70 and frioplast.

A robotic arm from KUKA Industrial Robots with a printing head attached was used for printing tests the mixes were examined visually, observing the surface quality, and the presence of deformation, failure, tearing and splitting. 54 mixes were analysed for printability, shape retention and buildability.

Initially the 1:2 ratio for cement and sand was used, but it was not possible to extrude, so a 1:1 ratio was used instead. The best mix had 10% filler, 20% FA, and the admixtures added were SP and frioplast. Two batches of the mix were prepared, and it reached the maximum layer count for the program used, with 113 cm height and 114 layers.

For the last phase, 3 mixes were tested for compressive strength on fresh mortar, but because of technical issues and covid restriction it is recommended repeating the tests for future studies. The evaluation depends on several steps, including image inspection and spreadsheets to plot stress and strain graphs, from which the elastic modulus was obtained. The mix with better results was the same mix with the best performance on the printing test.

The executed research concludes that 3D printing can be used for construction and the incorporation of waste material showed satisfactory results for both mechanical and printing tests.

The following steps are to test this technology for build walls, and later entire houses. A floor plan for a tiny house was already made and the printing tests for the walls has already begun at CDRSP.

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