escola superior de tecnologia e gestão
instituto politécnico de leiria

Internship Report

Master in Civil Engineering - Building Construction

# *Green Cement Based Material Optimization for Additive Manufacturing in Construction*

**Vani Basvagatha Annappa**

Leiria, *September of 2018*

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# *Green Cement Based Material Optimization for Additive Manufacturing in Construction*

**Vani Basvagatha Annappa**

Report developed under the supervision of Florindo José Mendes Gaspar, professor at the School of Technology and Management of the Polytechnic Institute of Leiria and co-supervision of Artur Mateus, Vice- Director at Centre for Rapid and Sustainable Product Development (CDRSP).

Leiria, *September of 2018*

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# Dedication

I would like to dedicate this internship work to my parents; they always supported me in all means to educate and offer a better future. They supported me during my hard days and encouraged me to pursue my dreams and they always believed in me and boosted my confidence and gave me an opportunity to study abroad. They are my backbone and always give the advice to make me a good person and citizen in all possible ways.

My teachers from school days to university, they were always present to help in my studies and education, so I like to dedicate to all my teachers and professors in my life for helping me, directly and indirectly, to be in this position in my life.

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Last but not the least, I would like to thank Sika group for providing all the necessary materials and guidance to use them properly to achieve better results during this work.

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# Resumo

O rápido crescimento da tecnologia de impressão 3D levou ao desenvolvimento de impressoras 3D de grande escala que podem imprimir com betão. O processo de impressão 3D com betão não utiliza cofragem e portanto proporciona maior flexibilidade aos projetistas, economiza mão de obra e materiais e reduz o desperdício. Estas impressoras foram usadas para construir elementos estruturais e edifícios à escala real, que têm sido o foco desta nova era de impressoras 3D na indústria da construção.

Os materiais são uma parte importante do processo de impressão, visando a obtenção de uma mistura específica satisfazendo todos os requisitos de material cimentício. Neste campo existe o interesse para ampliar o foco nos resíduos de indústrias de construção e envolver esses resíduos na impressão 3D promovendo a construção sustentável, e combinando a tecnologia com o processo de construção.

Neste trabalho as lamas de pedra foram usadas como matéria-prima em argamassa, com o objetivo de realizar impressão 3D de forma rentável e acessível. A argamassa foi impressa usando braço robótico com um processo de impressão por extrusão. Seis argamassas com diferentes proporções de lama de pedra e adjuvantes foram testadas de forma sistemática para determinar as propriedades da argamassa adequada à impressão. A resistência à flexão e compressão das amostras impressas ou moldadas foram medidas e comparada.

*Palavras-chave:*

Impressão 3D, Material Cimentício, Lama de Pedra.

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# Abstract

The rapid growth of 3D printing technology has led to the development of large-scale 3D printers that can print concrete. The process of 3D printing in concrete does not use formwork and thus gives increased flexibility to designers, saves the cost of labour and materials and reduces waste. These printers have been used to construct structural elements and full-scale buildings which have been the focus of a new age of 3D printers in the construction industry.

The materials are an important part of the printing process, aiming to obtain a particular mix satisfying all the requirements of cementitious material. There is interest to broaden the focus on waste from construction industries and involving these wastes in 3D printing for sustainable construction, blending technology with the construction process.

In this work, stone sludge was used as raw material in the mortar, having the objective to do 3D printing in a cost-effective and affordable way. The mortar was printed using a robotic arm with an extrusion printing process. Six mortars with different proportions of stone sludge and admixtures were tested in a systematic way to determine the printable properties of mortar. The bending and compressive strength of printed or casted samples were measured and compared.

Keywords:

3D printing, Cementitious material, Stone sludge

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# 1. Introduction

Last few years the construction industry has encountered the influence of modern technology i.e. Additive Manufacturing (AM) also known as 3D printing. It is growing rapidly in the entire sector but in construction lot of work yet to be carried out and it allows chain manufacturing and supply of the 3D products and prototypes.

Additive Manufacturing allows enlarging the range of construction by printing large-scale buildings and structural components. The professor Berokh Khoshnevis [1] developed "counter crafting" to construct house through gantry system by depositing thick layers and smoothening the outer surface using the trowel. Enrico Dini [2] a civil engineer from Italy invented "D Shape" technology in September 2007; it uses huge gantry system for printer movement and method is the combination of powder bed and binder jetting techniques for gigantic printing. In 2014 Chinese construction company Win Sun Decoration Design Engineering Co [3], successfully build the house using 3D printing, the structural components were prefabricated in the factory and assembled at the site and later in a year they managed to construct five storeys building using the same technique. Similarly, Dutch Dus Architects [3] are planning to construct a canal house in Amsterdam using 3D printing; it is the 1st project in Europe. These examples illustrate the perspective and practical nature of 3D printing in realistic construction.

AM is a solution to some of the challenges in construction [4]: safety of workers at the site and from the harsh environment, no special skilled labours, low waste generation, less transportation expense, low cycle, production time and cost. The main challenge of 3D printing in construction is material properties, developing the composition suitable for printing and exhibiting the properties that of conventional material in construction. According to author MA Guo Wei at.al [4], the solution to the above mentioned challenges are aspired by few researchers Gibbons et.al, Maier et .al, Xia and Sanjayan and Khoshnevis et.al, they experimented on few cementitious materials and have their own mix design for 3D printing.

This internship focuses on optimizing the mortar for 3D printing utilizing the waste from various industries. There are several industries generating waste and this should be taken care otherwise it will lead to serious health problems and environmental issues. We tried to utilize such waste in the work to make the new technology more sustainable and economic for our future.

3D technology in the construction industry is growing at greater phase, but yet there is no perfect composition/mixture which satisfies the requirement of the conventional way of construction and performance. So the report illustrates the work on various cementitious materials and their behaviour under various circumstances.

## 1.1 General Background

Till now additive manufacturing was adopted in highly commercial sectors such as aeronautical and biomedical due to expensive raw materials and technology [5]. As per the world's leading information technologic company Gartner, 3D printing has both advantages and disadvantages. They believe that five newly emerging technologies will change the business before 2020. The 3D printers used now a days have the ability to customize the design and cycle development as per the needs of individual in order to communicate and to find the solution for design in engineering [6].

AM is growing at a faster phase from past 25 years in various industrial domains but lagging in building construction sector in terms of technology and innovation. Our current process is labour dependent with a simple and systematic approach requiring formwork to support components. Present design and complexities involved in constructions are exposing the workers to the unhealthy environment [7].

AM had two classical methods powder bed and inkjet head printing (3DP) and fused deposition modelling (FDM), where cement as a binder in between sand layers. Trial and error is practiced by many companies and institutions for large-scale construction using the above mentioned methods that varying in terms of ingredients and applications [5].

At present, there are two major types of concrete printing technologies at large scale: i.e. D shape and counter crafting [7].

As per Labonnote N et.al "3D printing" refers to the various processes used to synthesize a three-dimensional object [6]. AM gives detail idea on how the part is manufactured purely on a digital process. AM provides a new room for complexity free manufacturing by considering design freedoms and parameters [8].

Additive manufacturing is defined as a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, as per ASTM F2792-412a [9].

“Construction” defined as the process of generating high or large structures by linking small structural element; they may be residential houses, bridges and other types buildings.

AS per Labonnote N et.al [6] “Additive construction” is a similar to “additive manufacturing” which can be described as “the process of joining materials to create constructions from 3D model data”. This allows assembly of the processes such as design and production through digital means to a certain extent.

## 1.2 Objectives

The major objective of all institutions, researchers and companies is to find answers to the following questions which are of major interest. The answers to these questions will bring evolution in the construction field.

- what construction-specific material science challenges do we face?
- what structural challenges come into play during scaling up additive manufacturing?
- what building design opportunities emerge when using additive construction?
- what are the requirements for a successful (marketable) concept for use in the building industry [6]?

The objective of the work is to find solutions for the above challenges which involve finding the optimal composition of the materials, for better performance, strength and ease of printing in construction.

This research, “Green Cement-Based Material optimization for additive manufacturing in construction”, aims to enlighten and highlight how 3D printing can benefit the construction industry and to achieve the mix using industrial waste for 3D printing. This research aims to accomplish the above mentioned objectives by preparation of samples, testing and analyzing the results. Some benefits that could arise as a result of this research are:

- Incorporation of industrial waste
- Autonomous construction
- Elimination of formwork in the construction industry
- Reduction in labour and construction cost
- Reduction in construction time
- Reduction in waste

## 1.3 Structure of the Report

This report is divided into 6 main chapters and each title has certain number of sub-titles. The main titles are Introduction, mortars in additive manufacturing or bibliography, mortar and equipment preparation on testing, experimental results, conclusion and future developments:

- Chapter 1: Introduction

It gives a brief idea about the concept of work, definition of the concept, and objective of the internship.

- Chapter 2: Literature Review

This chapter provides an extensive review on history of 3D printing, types, the mortar used in past and present, cost analysis of this technique, advantages and disadvantages and comparison of methods used in Construction sector.

- Chapter 3: Mortar and Equipment Preparation

This chapter explains various raw materials, methodology, procedure of conducting the tests and types of printers and equipment's used.

- Chapter 4: Results and Discussion

The analysis of results obtained after testing and discussing possible results and reasoning of such results.

- Chapter 5: Conclusion and Future Developments

This chapter concludes the internship objective and provides future work recommendation.

# 2. Literature Review

This chapter explains the various work carried out in past and present in civil engineering academics using mortar and concrete in construction using additive manufacturing or 3D printing. The history of the 3D printing from 1986 and how it has evolved over time in the 21st century and how it has been used in civil engineering and construction industry.

## 2.1 History of 3D Printing

Chuck Hull considered as the father of 3D printing, an American engineer and co-founder of 3D systems in 1986. He invented the stereolithography apparatus which enabled objects to be formed by the interaction between lasers and photopolymer resin [10].

The next invention was Fused Deposition Modelling (FDM) by Scott Crump, the co-founder of Stratasys Inc., in 1989. Later in 1992, the Selective Laser Sintering (SLS) was invented.

As time passes, improvisation is default in every technology, so as in 3D printing industry. At present research teams are printing product with various materials such as plastics, metals, ceramics, paper, food and concrete further moving towards large-scale components without formwork [11].

- **Freeform construction**

Buswell et.al [12] defined freeform construction as “processes for integrated building components which demonstrate added value, functionality and capabilities over and above traditional methods of construction”.

Freeform construction is auto - mechanized by robots attached to the crane system for constructing structural components. As this method is free of formwork UHPC[1] (Ultra-

---

[1] UHPC- A cementitious composite material with water/cement ratio lower than 0.25 and higher percentage of discontinuous internal fiber reinforcement having compressive strength between 150 to 250Mpa.

High-Performance Concrete) which used in construction and thus develops significantly higher mechanical properties than Counter crafting project [12].

### 2.1.1 Types of Additive Manufacturing

There are various types of 3D printing techniques being used in various industries for additive manufacturing and these techniques are explained briefly. The main focus is on the techniques that are used in construction industry and 3D printing of cementitious material.

The additive manufacturing is broadly classified into two categories; they are extrusion printing and powder printing.

- **Extrusion printing**

The extrusion printing is equivalent to fused diffusion modeling (FDM) method which extrudes cementitious material from a nozzle mounted on a gantry/robot to print the structure layer by layer. This technique was designed for onsite construction application such as large-scale building components. Counter crafting is an example of extrusion printing developed by Khoshnevis and concrete printing designed by Lim et.al. [13]

- **Powder printing**

It is also known as powder based three-dimensional printing; this technique binds powder by depositing liquid in such a way that it can create complex design and geometries. The designed components are produced away from the site basically; it is used to manufacture precast components. The typical examples are the D shape technique and emerging object [13].

It has thin layers which are closely packed with each other and spread on the platform, each powder layer can be glued by a binder or by using a laser. Each successive layer is glued together until the 3D part is generated. The factors such as size distribution of powder, the density of the part and packing plays a vital role in the efficiency of this method [14].

The advantages of this method are fine resolution and high precession in printing quality, so it can be used for complex design. The part is supported by surrounding powder, which can be removed after completion of printing and can be used again, but it is expensive with the slow process taking a longer time to print [15] [16][17].

Types of 3D printing and their techniques are explained briefly:

- **Fused deposition modelling**

A thermoplastic polymer is used in FDM to 3D print layers by using a continuous filament, this filament should be in semi-liquid state at the nozzle for extrusion of material and filament is heated at the nozzle to glue on previously printed layers. The mechanical parameters of the printed parts depend on the layer thickness, width and orientation of filaments [18]. The main cause of failure of printed parts is mechanical weakness due to interlayer bonding [19]. The other weakness along with mechanical properties is poor surface finish on the other hand it’s fast being low cost and simple process compare to others [20].

The main challenges in FDM are bonding between layers, the formation of voids while printing and orientation of fibers [21, 22]. The latest FDM systems include two nozzles, one for the part material and another one for the support material. It is used widely in printing ceramic components due to its low cost and simple technique [23].

- **Stereolithography (SLA)**

Developed in 1986 and one among the 1st used additive manufacturing process [24]. It is also known as photo-polymerization as it uses UV light to start the process and the component is formed in a liquid polymer in slices from top to bottom which hardens in UV radiation [23]. Monomers can be used to print ceramic-polymers; while printing the solidified part which acts as support and the remaining liquid is removed [25]. Stereolithography is a slow process with limited raw materials to print which makes the process expensive [23, 24].

- **Direct energy deposition (DED)**

This method has different names: Laser Engineered Net Shaping (LENS), Laser solid forming (LSF), Directed Light Fabrication (DLF), electron beam AM and wire +Arc AM. DED is used to produce high-quality superalloys by using source of energy on the substrate and inserting melted material at the top [26]. This method can be used as an alternative to powder bed as it can fill cracks and repair manufactured parts at multiple axes at the same time [27]. It is used for less complex components, so it has low surface quality and it is relatively slow compared to SLS and SLM. It can be used in automotive and aerospace to repair some parts [16, 26].

- **Laminated object manufacturing**

It generates components by slicing and laminating of sheets or materials layer by layer and commercially used additive manufacturing method [28]. It is used widely in industries such as electronics, paper and smart structures due to reduced tool cost and manufacturing cost for large structures, as it gives room to use a variety of materials like polymer, ceramics, paper and metal-filled [28,29].

- **Ink jetting, counter crafting and D Shape**

It is a highly efficient method for additive manufacturing of ceramic at a faster speed, complex design and flexibility of printing [24]. Two main types of ceramic inks are wax based inks and liquid suspensions [25]. Counter crafting is similar to inkjet but used for bigger concrete structures with large nozzles under high pressure [30]. This technique was improvised by using a trowel to smoothen the outer surface during extrusion. The layer at bottom act as support for upcoming layers and it uses a crane for onsite applications. It was developed to overcome the speed in construction and longer duration required by humans and to minimize the material use [24, 30, 31, 32].

The layers of desired geometry can be printed using D shape it is similar to powder deposition and Z-Crop 3D printing process [25]. It can produce components of 1.6m high, once the printing is complete it is dug out and the remaining powder is removed [31].

The techniques in additive manufacturing are also classified into the following categories:

a) Concrete layered overlay: counter crafting and concrete printing, extrusion of concrete and self- stabilization.

b) Sand powder- layered adhesive stack: layers were bonded using selective liquid agent. D shape is an example.

c) Mechanization: This method uses robots for printing and uses various materials (brick, metal and plastics) along with the concept of robotic fabrication [33].

## 2.1.2 Comparison and Discussion

The above section gave a brief description of various types of printing techniques. There are many processes which are similar to each other but they differ from each other depending on the purpose of use.

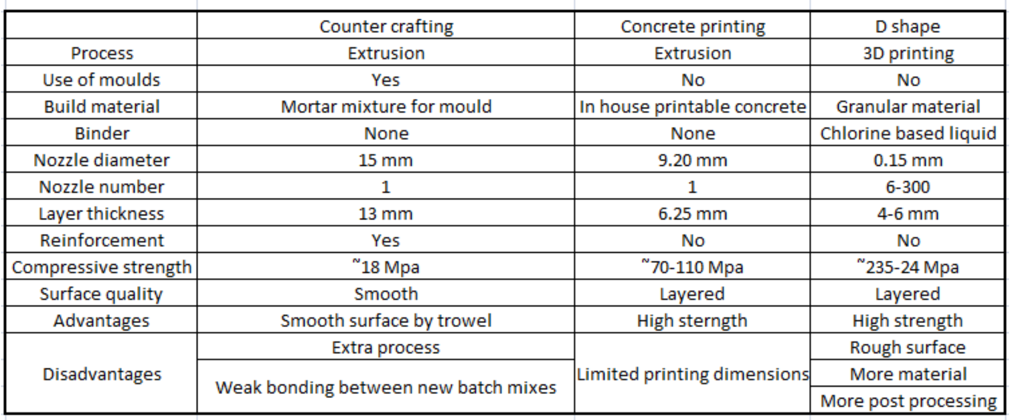
Here the discussion is based on the cementitious processes:

**D shape** has long print speed resulting in a poor finish with material waste but allows freedom to create components. The hybrid system allows integration of specific manufacturing process involved.

**Concrete additive** manufacturing also seems to allow freedom of shape control however; it does not have a smooth or neat surface finishing. This method of manufacturing was to be used in combination with a flexible moulding system; the substantial post-processing would be required to get smooth results.

**Counter crafting** gives very smooth extrusion results by using proper trowels on other hand the use of weaker mortar materials is only disadvantage over 3D concrete printing [26].

While comparing hybrid and flexible mould system, D shape technique has its own support unlike counter crafting and 3D printing which have higher potential.



| | Counter crafting | Concrete printing | D shape |
|---|---|---|---|
| Process | Extrusion | Extrusion | 3D printing |
| Use of moulds | Yes | No | No |
| Build material | Mortar mixture for mould | In house printable concrete | Granular material |
| Binder | None | None | Chlorine based liquid |
| Nozzle diameter | 15 mm | 9.20 mm | 0.15 mm |
| Nozzle number | 1 | 1 | 6-300 |
| Layer thickness | 13 mm | 6.25 mm | 4-6 mm |
| Reinforcement | Yes | No | No |
| Compressive strength | ~18 Mpa | ~70-110 Mpa | ~235-24 Mpa |
| Surface quality | Smooth | Layered | Layered |
| Advantages | Smooth surface by trowel | High sterngth | High strength |
| Disadvantages | Extra process<br>Weak bonding between new batch mixes | Limited printing dimensions | Rough surface<br>More material<br>More post processing |

*Figure 2.1 : Comparison of types of 3D printin [26].*

## 2.2 Mortar

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### 2.2.1 Properties of Mortar

The conventional way of construction is one among the oldest additive construction i.e. using brick and mortar to bond the layers can be considered as an additive manufacturing before 3D printers [6].

The fresh concrete in additive manufacturing plays a vital role during printing. In order to print few parameters of fresh mortar should satisfy the following properties [32] :

I Pumpability - The ease with which material can move through the system at constant pressure.

II Printability - Possibility of printing the material with respective depositing device

III Buildability - Withstanding its own weight in the fresh state without failure and deformation under self-weight.

IV Open time - The amount of time the material is possible to be elastic and possible to achieve the above-mentioned properties.

There is a patent for 3D printing powder composition and methods of use by Ronal RAEL from University of California on 2011-09-20.

A powder composition for 3D printing, comprising as per the patent for concrete and other cementitious material as per claims 15 [34]:

(a) Approximately 0.75 to 2.0 parts (from 10) by weight of an adhesive material.

(b) Approximately zero to 2.0 parts by weight of an absorbent material.

(c) Approximately 4.0 to 6.0 parts by weight of a base material.

Relevant materials for additive construction comprises of the combination of paste and bulk materials. The paste usually consists of cement and superplasticizer but bulk materials as follows:

- Natural aggregates such as soil, sand, natural gravel, crushed stone, clay or mud.
- Recycled aggregates such as those from construction, demolition or excavation waste.
- Manufactured aggregates such as air-cooled blast furnace slag and bottom ash.

- Natural fibers such as cellulose and recycled wood fiber [6].

According to author S Lim et.al [32] for large-scale construction like walls and facades which require high-performance mortar comprising of 54% sand and 36% cement and 10% water by mass, each mortar has selective properties based on mix design. As per Pshtiwan Shakora et.al [35] to build a wall of 10 mm height, the composition used was 28% cement, 60% sand, 7.97% fly ash and 4% silica fume with 232 $Kg/m^3$ water.

In order to print the mortar, it should satisfy certain properties, so that it can be printed continuously, smoothly and to attain the required strength. The mortar should satisfy the following properties:

- Flowability - Smooth transfer of mortar from the storage system to extrusion system without any blockage and at constant air pressure. As per Guowei Ma [36] and other researchers flowability at the site can be measured by slump test.
- Extrudability - It depends on particle size distribution and mixing procedure in the dry state. It is considered one of the important parameter while printing and also referred to as extrusion of material from the nozzle and pipe continuously without the development of cracks and breakage while printing [36].

Biranchi Panda and Ming Jen Tan [37] explained the influence of yield stress[2] on extrusion, higher the yield stress more difficult in extrusion resulting in a discontinuous filament. Guowei Ma [36] et.al discussed if the filament extruded is long for a certain distance without any separation and opening gaps between each filament deposition without any liquid drainage and clogging of the system and which can be referred as better and smooth extrusion.

Yield stress and viscosity of the material is governed by particle size, gradation, surface area; paste/aggregate volume and as per literature review few tests such as flow table test and drop test were performed in the past to determine the flow behaviour which helps in the extrusion of the material [37].

- Shape Retention - is explained by Biranchi Panda and Ming Jen Tan [37] is the ability of the material to retain its shape after extrusion as per the design and an equation to calculate Shape Retention Factor (SRF) which is a dimensionless quantity:

---

[2] Yield Stress- Cement surface get adhered by Superplasticizer, limiting the interaction and strength development which results in lower yield stress in fresh state.

$$\mathrm{SRF} = \frac{Cross\ sectional\ area\ of\ 3D\ sample\ before\ demoulding}{Cross\ sectional\ area\ of\ 3D\ sample\ after\ demoulding}.$$

Material with low slump shows high SRF; mortar should have high yield stress to withstand its own weight while printing but it should be within limits, SRF and stress factor exceeding the limits making an extrusion of the material difficult.

- Buildability - Even though 3D printing advancing in construction but buildability is still an issue which needs special concern, as the freshly deposited material should be able to resist the upcoming layers and their weight without falling or breaking [37]. Still, research is going on to scale up the size and stack the material in the vertical direction. It is a critical parameter to evaluate the printability of the mortar which in turn evaluates the performance of extrusion and deposition of wet material and behaviour under load [36].
- Open Time - is defined as the duration in which the material remains in the fresh state with good workability for printing [36]. Sometimes open time is confused as the setting time of the mix, but it is the time in which the material can be extruded and is smaller than the setting time of mix [37]. It can also be referred to as the time period in which the fresh mix possess good extrudability and it can be measured by Vicat apparatus or flow test.

As printing have certain speed and time, the deposited material should have enough time to initiate the chemical activity necessary to have better bonding with successive printed layers but if the waiting time between each layer is too long which leads to development of cold joints as a result development of weak bonding between filaments and reduction of mechanical strength as the waiting time increases. Open time should be such that it balances between cold joints and crack development in filaments [36].

- Relationship between extrudability, buildability and printability

Guowei Ma et.al [36] derived the relationship between extrudability, buildability and printability. The extrudability is dependent on the flowability and early age stiffness. Extrudability is directly proportional to the flowability and stiffness of the material, flowability was characterized by spreading diameter (Ds) and it is dependent on time (t). The extrudability coefficient can be defined as the ratio of spreading diameter (Ds) and time interval t.

Material with low slump can have better shape retention property and if the penetration resistance is high then it can resist the upcoming loads. Hence, the buildability is directly proportional to penetration resistance (Pr) and slump (Hs). Thus, the buildability is define by the ratio of penetration resistance (Pr) and slump (Hs)

In general optimizing design of printability relies on the balance between the extrudability and buildability [36].

$$Extrudability\ (Pe) = \frac{Flowability(Ds)/Time(t)}{Max(Ds)/Min(t)} X100\%,$$

$$Buildability\ (Pb) = \frac{Stiffness(\mathrm{Pr})/Slump(Hs)}{Max(Pr)/Min(Hs)} X100\%,$$

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

The extrudability is inversely proportional to rest time, whereas the buildablity increases with time. It was observed that the better the extrudability, the worse the buildability and vice versa.

## 2.2.2 Rheology of Cement and Mortar

Mikanvoic and Jolicoeur [38] explained the effect of superplasticizer (SP) on the fresh cement-based material to improve their rheology. Superplasticizers nowadays used in cement in order to improve the workability at given water /cement ratio or on the other hand they allow the same workability to be obtained as that of plain cement with a great reduction in water content.

Jianwei peng [39] measured the effect of superplasticizer on the rheology fresh cement asphalt paste. He used “RheoPlus QC” coaxial cylinder rotary rheometer to measure the rheology of the cement paste. Later he explained the mechanism that the SP absorb the surface of cement grains and disperse the flocculated cement. After being mixed with water, cement grains being hydrated consequently by developing a heterogeneous charge distribution on the surface hydrating cement grains. The observation shows the advantages of SP by decreasing yield stress and viscosity of cement paste with cationic emulsion and an increase of SP show the same results irrespective of the type of cement.

The rheology of fresh cement paste is mainly dominated by the interaction of cement particles which may adsorb SP molecules.

As per R.J.M Wolfs [40], 3D printing material can be low to zero slump and it should maintain its shape during printing and after deposition. The material should be able to carry its own weight soon after printing and this characteristic is known as Green strength, which is dependent on interparticle friction and cohesion between particles.

Yu Zhang [41] used rheometer to study the thixotropy, viscosity and yield stress. Except the thixotropic behaviour, the buildability of the 3D printing concrete materials was significantly related to green strength. There is a relationship between the green strength, structure re-build (thixotropy), yield stress and buildability of the concrete. The deposited material tends to fail by developing cracks, deformations and collapsing of the component when the yield stress coincides with the force equal to crack development. So geotechnical tests were conducted to assess the properties of early age printed concrete.

Jae Hong Kim [42] explained the behaviour of the cement paste under high pressure, the material at the centre experiences maximum velocity and less near the surface of the pipe. Pumping can affect the rheology of the material and the measured yield stress of the paste at a different water/cement ratio and that represented in a graph indicates the thixotropic effect. Increase in the yield stress with a decrease in water/cement ratio and the samples of water/cement ratio 0.35 and 0.40 experienced 15% reduction in the yield stress when the pressure is greater than atmospheric pressure.

The samples with high water/cement ratio did not experience any significant pressure effects. Theoretically, the yield stress of the cementitious material is proportional to interlocking force between solids. The material with lower water/cement ratio has smaller yield stress at high pumping pressure due to the presence of flocs or coagulated solids. If the pressure is steady then the rheology of the material is the same over the investigation period. Thixotropy of the sample is sensitive to both atmospheric pressure and high pressure.

### 2.2.3 Ultra High Performance Concrete

At France University for ultra-high performance concrete, the 3D printing premix prepared was composed of Portland cement CEM I 52.5N (30 − 40%w), crystalline silica (40 − 50%w), silica fume (10%w) and limestone filler (10%w). The water /cement ratio was calculated for entire mix using w/(c + s) = 0.1, the ultra-high performance and self-placing mortar[3] was mixed with polymer-based resin in order have quality adhesion between printed layers. Wall element of 139 layers with dimension of 1360x1500x170 mm printed in 12 hours weighing 450 kg. The component was designed for Acoustic and structural performance [5].

Ingrid Paoletti [43] gives brief, how additive manufacturing has evolved in architecture by providing freedom of design in construction components and room for complex components. In the corresponding work, the mix was made up of two clays such as 58% red earth, chamotte red 20% and the setting time was extended by using 1% sodium carbonate into 21% water. Bricks with architectural designs were printed in 4 hours and backed for 9 hours. Tested for absorption and structural resistance and in turn the absorption was similar to traditional bricks and had better structural resistance.

Weng et.al [44] used Ordinary Portland Cement, silica fume, silica sand, fly ash, natural river sand, water and superplasticizer. To study they prepared five mixes with various sizes of silica sand and sand and the mix design for the mix is listed in Table2.1.

| OPC | Sand | W | FA | SF | SP/(g/l) |
|---|---|---|---|---|---|
| 1 | 0.5 | 0.3 | 1 | 0.1 | 1.3 |

All the ingredients content are expressed as weight proportion of cement content

***Table 2.1: Mix proportion [44].***

The particle size of sand and silica sand are represented in the graph in Figure 2.2, the sand size bigger than 1.2 mm was not used but four different sizes of silica sand were used 0.6-1.2 mm, 0.25-0.6 mm, 0.15-0.25 mm and less than 0.15 mm. A cylinder of 11 cm

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[3] Self placing- property of mortar to get compact and level without influence of external sources.

diameter, 2 cm thickness and height 50 cm with 50 layers was printed. The printed element was deformed at the 30th layer but in the last trial, they were able to print 80 cm height without any deformation [44].

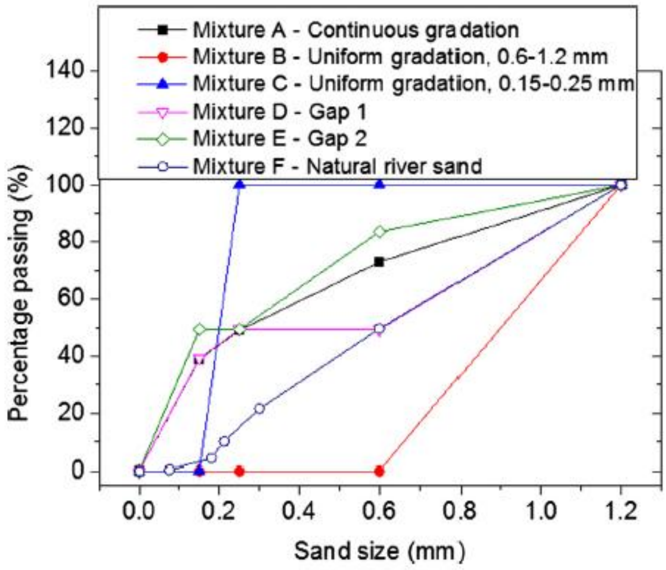
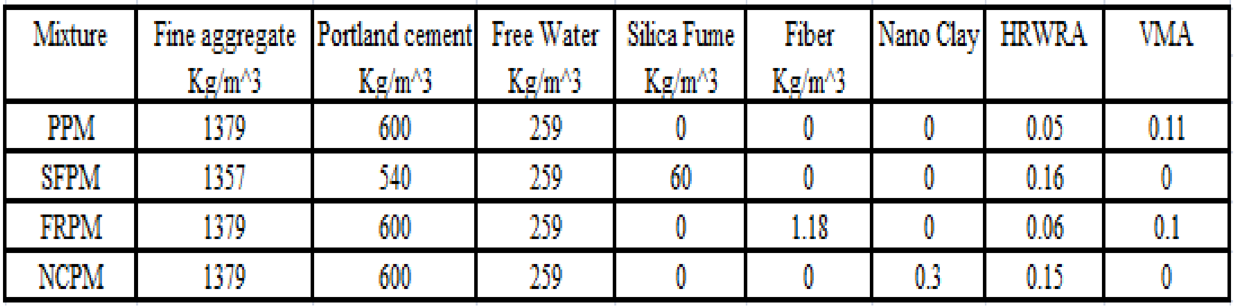


*Figure 2.2: Particle size distribution [9].*

Viscosity modifying admixture (VMA) was used to obtain Ultra-high performance concrete (UHPC) by using nano clay, fibers having a length less than 6mm and densified silica fume as supplementary to cement, in addition it improves cohesion in the fresh state that helps in developing mechanical strength thereby reduces the permeability of hardened concrete. Few laboratory tests were done in order to characterize fresh properties of mortar for 3D printing and evaluation of printing mixture. Print quality, shape and cylinder stability was tested for these compositions listed in Table 2.2 [9].



| Mixture | Fine aggregate Kg/m^3 | Portland cement Kg/m^3 | Free Water Kg/m^3 | Silica Fume Kg/m^3 | Fiber Kg/m^3 | Nano Clay | HRWRA | VMA |
|---|---|---|---|---|---|---|---|---|
| PPM | 1379 | 600 | 259 | 0 | 0 | 0 | 0.05 | 0.11 |
| SFPM | 1357 | 540 | 259 | 60 | 0 | 0 | 0.16 | 0 |
| FRPM | 1379 | 600 | 259 | 0 | 1.18 | 0 | 0.06 | 0.1 |
| NCPM | 1379 | 600 | 259 | 0 | 0 | 0.3 | 0.15 | 0 |

% Percentage are reported by cementitious materials mass

*Table 2.2*: *Compositions of various mixes [9].*

To print a reinforced concrete beam, water/cement ratio was restricted to 0.39, 4 mm of aggregate, 0.5% polypropylene fibers were used to prevent early age shrinkage. Presence of fibers makes concrete more stiff, hence to make it more viscous polycarboxylate superplasticizer was used to attain the balance of the material pumpability. 3 m long beam with rectangular cross section 0.60 m and 0.45 m designed which was divided into 5 segments. Each segment was printed separately and was joined by rebar at the end. The beam was subjected to 3 point bending test and the initial flexure stiffness was comparable to normal reinforced concrete beam [45].

The concrete material designed to overcome certain printing constraints:

- The cementitious material should be viscous enough in fresh state so that it can be extruded from nozzle smoothly and buildable.
- The printed mix should poses high strength for omission of possible weakness due to connection between successive layers.
- The maximum diameter of aggregate should be lower than nozzle and extrusion head.

## 2.2.4 Fibre Reinforced Portland Cement Paste

Scaffolding was done by 3D printing in that two main materials are Ordinary Portland Cement (OPC) and Calcium Aluminate Cement (CAC). The mixed ratio contains 67.8% CAC, 32.2% of OPC and 4.5% of the total mix was replaced with lithium carbonate as an accelerating agent and Zb60 containing humectant and water. Specimens were printed in different sizes and shape to study compressive strength, porosity and surface roughness [46].

In this study infill mortars[4] are used for specimens and the composition of the mix is 61.5% cement, 21% silica fume, 15% water and 2.5% water reducing agent in order to keep low water-cement ratio 0.3 and 0.3% hydration inhibitor. A mix with 40% cement and 60% sand with water cement ratio of 0.4. To distribute fibers uniformly in the mix, they were added at the end and mixed at 50 rpm. Few paths were designed to print above-

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[4] Infill Mortar- used to repair damages, openings and cavities in walls and structural components.

mentioned mixes and tested their bending and compressive strength, density and porosity. According to author steel reinforcement was necessary to achieve higher strength [47].

The reproduction of the plinth[5] by fiber reinforced concrete and the composition was 1:1 sand : cement ratio, 0.3 water-cement ratio and 0.1% micro polypropylene fibers, including 1.25% of water reducer [64]. Department of Functional Materials in Medicine and Dentistry tried to incorporate fibers along with gypsum and the fibers used are Polyacrylonitrile fiber fillers (PAN), polyacrylonitrile shortcut fiber (PAN-sc), polyamide fiber fillers and glass fibers. The fiber content of 1% was used along with self-setting polyurethane resin for a depth half of the sample [48]. Singapore centre of 3D printing used chopped glass fiber in 3D printing with different composition but they restricted the content of fibers up to 1% to avoid clogging to achieve smooth, continuous extrusion during printing process [49]. Fiber alignment is also influenced by the extrusion pressure, fibers parallel to loading direction acts as voids and perpendicular fibers are intact under high pressure by increasing density.

China University tried to use copper tailings as a fine aggregate with partial replacement to sand and keeping few raw materials constant: cement, silica fume, fly ash and fibers. Six mix proportions were tested from 0 to 50% replacement of sand, reducing the water quantity by 30% and a solid content fraction of 37.2% are adopted in order to achieve the flowability for the mix. They studied wet and hardened properties of the mix such as flowability, extrudability, buildability and open time by printing, but hardened properties were tested on prisms of the above mix [36].

### 2.2.5 Geo Polymer Concrete

The primary raw material of geopolymer is fly ash, silica fume and ground granulated blast furnace with geopolymer binder. Singapore University used five different mix proportions, but the proportions were random in order to check the extrusion of the material and later the most suitable mix proportion was improved by adding fibers. Later the same author performed an experiment in order to achieve the proper mix proportion of geopolymer paste for 3D printing. The composition is listed the Table 2.3 [49].

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[5] Plinth - the portion of wall between ground level and ground floor.

| Materials | Weight by percentage |
|---|---|
| Fly ash | 27.85 |
| Slag(GGBS) | 1.68 |
| Silica Fume | 3.36 |
| Sand | 49.55 |
| Potassium Silicate | 12.5 |
| Water | 4.16 |

***Table 2.3: Mix design of 3D printable geo polymer mortar [49].***

Maryam Hojati [50] and team participated in a competition organized by NASA to produce an indigenous material for construction on Mars. Materials used for the work follows the rules and regulation for the competition and restricted to use uneconomical materials. The material used was geopolymer and few chemicals to reduce the amount of water. They used both cement and cement free mortars of different mixtures but they presented the mixture design which satisfied the NASA requirements and was successfully extruded. They used basalt and river sand as fine aggregate passing sieve number of 16 (1.19mm). Firstly, they used OPC and water but they didn’t use this mixture as it fails to satisfy the NASA requirements which motivated them to use geopolymer concrete. Martian soil, sorel cement or magnesium oxychloride cement and Polypropylene fibers were used in the second trial as they are alternative to ordinary Portland cement mortar. In the third trial, they incorporated metakaolin or fly ash in geopolymer concrete and calcium to accelerate the setting time at room temperature [50].

### 2.2.6 Shotcrete 3D Printing

Digital Building Fabrication Laboratory of TU Braunschweig in february 2018 printed using shotcrete method with robots, called shotcrete 3D printing [51]. The Institute of Building Materials, Concrete Construction and Fire protection (IBMB), is trying to develop a mixture suitable for digital fabrication by shotcrete method. This technology allows the frameless construction of the complex structure, thereby producing high-quality products with minimum resources as per the designs. This method uses robotic arms that perform shotcrete and stabilization of formwork.

Ibrahim O. Huthman in his master thesis explained the possibilities of using shotcrete in additive manufacturing, as they have few similarities. Both adopt ultra-high performance concrete in their application with similar machine that has pumps to push/print concrete at the nozzle. Observing these similarities he deduced that 3D printing of concrete can have innovation with shotcrete methods [52]. Stellenbosch University produced concrete materials for shotcreting, where they used calcium alumina cement replacing of standard cement types for printing by robots [53].

## 2.3 Cost Benefit Analysis

The cost plays a vital role in every field and the same with 3D printing and its components. This section explains how the cost is considered in the circular economy and the details of cost by a 3D printing company.

### 2.3.1 Circular Economy

3D printing is compatible for the circular economy by reducing the material wastage and utilization of minimum material rather than subtractive method of production and has significant contribution in different ways to the circular economy system such as reuse, remanufacturing and recycling of materials and products.

The additive manufacturing evaluation for the circular economy can be classified into two types: 1st is to evaluate the additive manufacturing with the conventional method and analyzing the various situations in which this method is effective in terms of cost, 2nd is to determine possible resource used in respective steps while producing components. This helps to keep track of each process and to identify the consumption of resources and to control the waste where ever it is possible. In cost analysis there are two types they are: “well-structured” and “ill-structured” and the inventory comes under each kind are labour, material and machine for the well-structured failure of the components and cost of machine system under ill-structured [54].

In additive manufacturing, labour work is to refill the material and operate the machine and software and in this method, the amount of ill-structured cost is least and most of the time hidden there by a reduction in the list of inventory usually the main reason of cost in production and manufacturing. In 2011 the amount of money spend on inventories was 10% of the revenue in that year and it was around $537 billion, so additive manufacturing has the ability to reduce this expenses, as components can be produced or generated as per demand and can be customized.

Nazi et.al. [55] explained how in business cost estimation plays vital importance if the price is overestimated then it affects the sales of the product and similarly if it is underpriced leading to financial losses in the business.

In additive manufacturing, the integral part is the machine and it’s about 74% of the entire construction cost followed by materials and time is an important factor which impacts the results [56]. As the method is still new in the market and in construction, the printers used for printing are expensive than traditional construction. This can be sorted out if the new technology is used in a proper way with strategies; planning and execution like control on the deposition rate which in turn reduces the cycle time, human resources and machine cost thereby reducing construction cost as per Roland Berger [57] the cost will drop in future.

1st Russian 3D printing company “Apis Cor” [58] gives their construction economics as per the work carried out in the past. They compare the traditional construction with 3D printing, and they are:

1. The quality of the construction is much better as it eliminates human error and overcoming the limitations of human inadequacy.

2. Cost reduction in the construction of buildings with more complex and unique design- as volume plays an important role during construction.

3. Less human dependency hence resulting in less expenditure on servicing personnel, insurances, taxes, hospital and so on.

4. Faster and reliable than humans and working continuously without break.

5. Restriction on material utilization, logistic and no labour for formwork installation.

6. In the course of construction, there is no waste or debris, which would require removal form construction sites and recycling.

## 2.3.2 Cost of printing

The major factors on which cost depends are the configuration and thickness of the wall, grade of mixture and location of the construction to determine the price to print 1 $m^3$. The exact value can be calculated only on the basis of a building project.

The main type of building structure is done in the form of two rectilinear layers connected with a sinusoidal bridge. In this embodiment of 1 $m^2$wall thickness is 300 mm requires 0.093 $m^3$ of printing mixture. To date the cost of construction calculated to be 6000 (82.6€) to 9000(123.39€) rubbles per $m^3$ [58].

At present additive manufacturing and 3D printing is expensive due to the high cost of equipment, materials and time. The printer available in the market is designed for particular material as per the producer and these materials are usually expensive due to certain properties they possess such as adherence to harden and give better finishing. We know in business time equals money, if the process is slow then the cost of products and components is high (number of machines, availability of materials and availability of time) [59].

## 2.4 Advantage and Disadvantages

As we know every coin has two faces, so do additive manufacturing. It has merits and demerits and they are discussed as follows:

**Advantages of AM:**

Apart from the enormous time and cost savings, AM has several advantages they are:

- It gives freedom of design to designers and it can be delivered quickly from CAD documents.
- Errors are reduced from incorrect designs; designs to prototype iterations are faster.
- It works without a skilled machinist to prototype from the CAD model.
- With appropriate materials, the model can be utilized as a part of consequent assembling operations to create the final parts. This also serves as a manufacturing technology.
- By AM technology, tooling can be produced in a shorter time. This helps in bringing the products to the market at a lesser time.

**Drawbacks of AM:**

AM technology still cannot fully complete with conventional manufacturing, especially in the mass production field because of the following drawbacks:

- **Size limitations**: The materials used in AM lack mechanical strength which does not allow producing large size object. Large sized objects also often are impractical due to the extended amount of time needed to complete the build process.
- **Imperfections**: Produced parts possess rough and ribbed surface and appearance of the final product is unpleasant and unfinished look.
- **Cost**: The equipment is expensive and involves high investments at the beginning and the materials required to print are another operational cost, so basically it is an expensive process with huge investment.

## 2.5 Comparing Conventional Manufacturing Process and AM Process

This section gives a brief comparison between conventional and additive manufacturing process in general to get a clear vision for choosing better one.

**Material efficiency**: Additive construction unlike subtractive manufacturing resulting in the lower waste generation and if the waste is generated can be reused.

**Resource efficiency**: AM does not require these additional resources. As a result, parts can be made by small manufacturers that are close to customers. This presents an opportunity for improved supply chain dynamics. Conventional processes require high resources such as machine tool, cutting tools and coolants.

**Part flexibility**: No compromise in detailing of part for the ease of manufacturing, and possible to build a component with variation in mechanical properties along the various sections, thereby an opportunity for design and innovation.

**Production flexibility**: The quality of component is based on process, not on operator skills and it won’t need additional expensive machine so it is economical. As such, production can be easily synchronized with customer demand [60].

# 3. Mortars and Equipment Preparation

This chapter describes the raw materials used, mix preparation, mixes composition, the procedure of tests on hardened samples, preparation of the equipment and mixes prepared for printing.

## 3.1 Materials

Selections of the materials were done referring to various bibliographies on 3D printing in construction and works that have been carried out in past few years. The main component of the composition is portland cement, as cement is one of the major materials used in construction for ages, due to its properties. The detailed mix proportion will be discussed later in this section

We tried to use various materials in order to optimize the mix for 3D printing. The ordinary Portland cement (CIMPOR CEM II/B-L) act as a binder, fine sand passing 500µm-250µm was selected, as the nozzle of the printer could not print the particle of bigger size than 500 µm.

Keeping sustainability into mind we tried to incorporate wastes from varies industries such as stone sludge from a nearby quarry, cork, eucalyptus ash and aluminium polishing waste. In order to reduce the amount of water and make the mix pumpable, buildable and plastic during printing; few admixtures were used, as follows Viscocrete 20HE, Frioplast P, Sika Control 40, Plastiment VZ, Viscocrete650DUO and Sigunit TM and in order to reduce the shrinkage of the mixture during its early stage the fibers were used.

### 3.1.1 Stone Sludge

Stone sludge is one of the wastes generated in huge quantity at quarries. The powder obtained during the cutting and polishing of dimensional stones is called stone sludge shown in Figure 3.1. Usually, the waste from the quarry comes in two forms i.e. powder and sludge. Powder-dust is generated while blasting and grinding but sludge is obtained while cutting and polishing as this procedure involves a huge amount of water. This waste is being dumped into a landfill which causes environmental issues and health problems in the neighbourhood. So, many of the researchers and engineers are trying to utilize/incorporate this waste to make the useful product so, we incorporated it into the mix as a replacement to sand.

***Figure 3.1: Stone sludge sieving.***

### 3.1.2 Cork

Usually, cork in construction is used as insulation material shown in Figure 3.2, in facades, roofs and flooring. As we know cork is organic, renewable in nature and it’s a green material, so we decided to study the behaviour of the mix with cork and pure cork of size 0.1mm was used. The main idea of using cork is to produce concrete with insulating properties which prevent additional thermal insulation in facades and other parts of the structure.

*Figure 3.2: Cork.*

### 3.1.3 Eucalyptus Ash

The utilization of eucalyptus twigs for generating heat/burning in various industries are the main reason for the generation of ash. Even the eucalyptus oil refineries produce wastes which can be used. In this work ash from the industry was used which possesses little bit of pozzolanic properties and allow the replacement of cement up to a certain percentage. Many researches and works have been carried out using this particular waste in concrete, but not yet used for 3D printing.

### 3.1.4 Aluminium Polishing Waste

Aluminium is the 3rd most abundantly available resource on the earth and it goes through various processes till it reaches the final product. Every process produces a certain amount of waste but the amount of waste generated during polishing is high and it is fine in texture and nature, which is a bonus and easy to incorporate with cement. The waste was obtained from the nearby machine polishing industry which was hazardous in nature and difficult to dispose of, so we decided to use this waste as it posses' strength properties which are necessary to bear the load.

### 3.1.5 Admixtures

The admixtures from the SIKA Portugal company were used and they as follows:

a) Viscocrete 20HE

Superplasticiser specifically designed for the production of soft plastic concrete with very high early strength characteristics. It is used in precast concrete, concrete with high water reduction, high strength concrete, in situ concrete requiring fast stripping time and self-compacting concrete. It improves workability and finishability, improves shrinkage and creep behaviour, higher ultimate strength and increases the durability of concrete. Dosages: 200-1000 ml per 100 kg cementitious material.

b) Frioplast P

Admixture helps viscosity action which facilitates the placement of the concrete by extrusion machine. It is used mainly for manufacturing of prestressed beams with following properties; good mechanical resistance, high resistance to freeze thaw cycles, reduces segregation and increase concrete homogeneity and act as lubricator which facilitates extrusion. Dosages: 435 ml per 100 kg of cement.

c) Sika control 40

It is used in the production of high-quality concrete when a large reduction of the drying retraction is required. It exhibits following properties: increases cohesion in pore volume, reducing contraction when a loss at the water, improves waterproofing, reduces retraction by about 40% depending on concrete and won’t influence the remaining properties of the concrete. Dosages: 0.5-2% of cement

d) Plastiment VZ

It is a water reducer and retarder for concrete, used in high-quality concrete under the following circumstances: at high temperature, areas under high loads at a time, long haul in hot weather and high mechanical resistance. They possess the following properties: reduction of kneading water increases mechanical properties reduces cracking by decreasing the permeability of the concrete and reduction in segregation of concrete. Dosages: 0.15-0.60% of cement

e) Viscocrete 650 DUO

It’s a strong water reducer and suitable in the following cases: Concrete with high reduction of kneading water, very plastic or fluid concrete with improved initial and final strengths by providing medium and high strength class concrete with any consistency, in which if you want to achieve a great cement economy and acts of cement particles for two main mechanism surface adsorption and spatial effect that has following properties: a high level of water reduction resulting in concretes with strong increase in mechanical strength, high compactness and very low permeability, an intense plasticizing effect allowing to obtain even with a water, favourable consistencies for easy placement and more favourable behaviour regarding shrinkage and creep. Dosages: 180-430 ml per 100kg of cement.

f) Sigunit TM

It is a preservative accelerator admixture for projected concrete and high performance concrete. Accelerator for the dry process and for the wet process under following situation: support for excavation fronts in tunnels and mines, stabilization and consolidation of rocks, slopes and high performance cast concrete with following characteristics: high initial resistance, alkali-free, losses by rebound are clearly reduced, improves the adhesion of concrete to the base, promotes projection on ceilings and significant reduction of dust. Dosages: 2-10% of the cement

g) Sikafiber ProMacro 25

These are Synthetic microfiber made up of polypropylene for structural reinforcement of concrete. It promotes resistance to bending and energy absorption. These fibers are utilized in the following cases: resistance to cracking, impact resistance, resistance to flexo-traction, abrasion resistance, resistance to chemical attacks and increases energy absorption capacity.

Used in flooring in concrete, prefabrication, partial repairs on concrete and in general, for situations in which traction, impact and energy absorption capacity.

There are following advantages of using sika fibers and they as follows:

- Increased energy absorption and tensile strength
- They are not affected by corrosion or oxidation processes.
- They improve impact and abrasion resistance.
- Increase waterproofing.
- Reduce the risk of concrete disintegration.
- Improve tensile strength.

- Perfect dispersion in concrete.
- They considerably improve passive fire resistance by reducing the delimitation of concrete.
- Reduce wear on fabrication and casting equipment

The diameter of the fibers is 0.51 mm approximately and its 25 mm in length. The dosage of the fibers 1-10$Kg/m^3$.

h) Polypropylene Glass Fibres

These fibers are polypropylene homopolymer glass fiber reinforced 30% chemical coupled to improve flow and good mechanical properties. These are white in colour with the dimensions 0.60 mm diameter and 10.28 mm in length. The technical data sheet is available in appendices.

## 3.2 Mortars

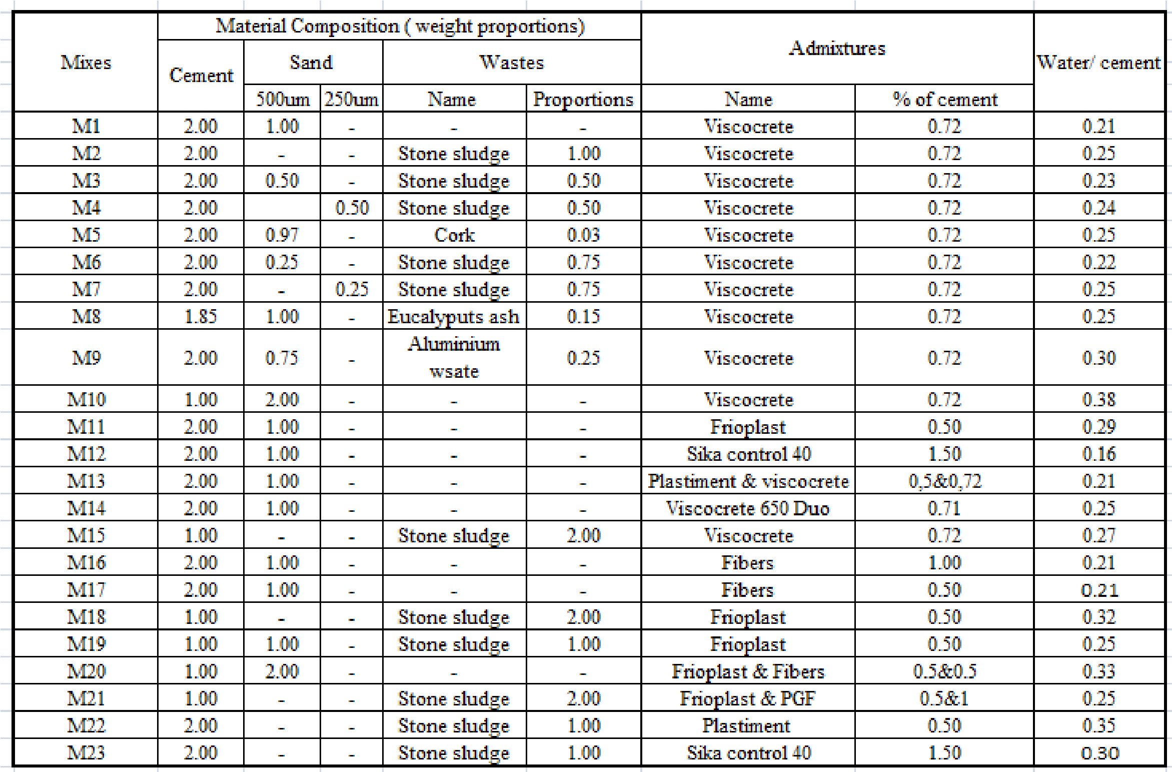
This sub-title describes the step by step procedure of preparing mixes and testing methods.

### 3.2.1 Mixes for Testing

Several mixes were obtained from the past bibliographies and work done by others on this method and finally few mixes with wastes and admixtures were planned to incorporate in this work.

The reference [9] enlightens that 1:2 of cement : sand was used in 3D printing by companies, universities and individuals, but initially twin extruder was not able to extrude the mix, so we tried mix of 2:1 of cement : sand and it was possible to extrude, hence this mix was taken as reference mix. In order to obtain various compositions the reference mix was varied. Stone sludge was included as waste and in certain mixes sand was replaced by stone sludge by 50% and 100% along with the addition of superplasticizer. Eucalyptus ash was used as replacer for cement up to 15%, the cork was used as a replacer to the sand up to 3% and aluminium polishing waste was used as replacer for 25% in the mix.

Some mixes were prepared with a different size of sand such as 500µm and 250µm in order to find the better one for the nozzle. Various admixtures were used to increase the performance of the mixes and the addition of fibers to reduce early shrinkage problem. One mix was prepared where the composition was totally changed to 1:2 of cement : stone sludge. Viscocrete650DUO was used in order to compare the performance with Viscocrete HE 20. The percentage of superplasticizer used as per the technical data sheets from the company and the amount used is that of the weight of the adhesive material of the mix, the mixes listed below in Table 3.1.



| Mixes | Material Composition ( weight proportions) | | | | | Admixtures | | Water/ cement |
|---|---|---|---|---|---|---|---|---|
| | Cement | Sand | | Wastes | | | | |
| | | 500um | 250um | Name | Proportions | Name | % of cement | |
| M1 | 2.00 | 1.00 | - | - | - | Viscocrete | 0.72 | 0.21 |
| M2 | 2.00 | - | - | Stone sludge | 1.00 | Viscocrete | 0.72 | 0.25 |
| M3 | 2.00 | 0.50 | - | Stone sludge | 0.50 | Viscocrete | 0.72 | 0.23 |
| M4 | 2.00 | | 0.50 | Stone sludge | 0.50 | Viscocrete | 0.72 | 0.24 |
| M5 | 2.00 | 0.97 | - | Cork | 0.03 | Viscocrete | 0.72 | 0.25 |
| M6 | 2.00 | 0.25 | - | Stone sludge | 0.75 | Viscocrete | 0.72 | 0.22 |
| M7 | 2.00 | - | 0.25 | Stone sludge | 0.75 | Viscocrete | 0.72 | 0.25 |
| M8 | 1.85 | 1.00 | - | Eucalyputs ash | 0.15 | Viscocrete | 0.72 | 0.25 |
| M9 | 2.00 | 0.75 | - | Aluminium wsate | 0.25 | Viscocrete | 0.72 | 0.30 |
| M10 | 1.00 | 2.00 | - | - | - | Viscocrete | 0.72 | 0.38 |
| M11 | 2.00 | 1.00 | - | - | - | Frioplast | 0.50 | 0.29 |
| M12 | 2.00 | 1.00 | - | - | - | Sika control 40 | 1.50 | 0.16 |
| M13 | 2.00 | 1.00 | - | - | - | Plastiment & viscocrete | 0,5&0,72 | 0.21 |
| M14 | 2.00 | 1.00 | - | - | - | Viscocrete 650 Duo | 0.71 | 0.25 |
| M15 | 1.00 | - | - | Stone sludge | 2.00 | Viscocrete | 0.72 | 0.27 |
| M16 | 2.00 | 1.00 | - | - | - | Fibers | 1.00 | 0.21 |
| M17 | 2.00 | 1.00 | - | - | - | Fibers | 0.50 | 0.21 |
| M18 | 1.00 | - | - | Stone sludge | 2.00 | Frioplast | 0.50 | 0.32 |
| M19 | 1.00 | 1.00 | - | Stone sludge | 1.00 | Frioplast | 0.50 | 0.25 |
| M20 | 1.00 | 2.00 | - | - | - | Frioplast & Fibers | 0.5&0.5 | 0.33 |
| M21 | 1.00 | - | - | Stone sludge | 2.00 | Frioplast & PGF | 0.5&1 | 0.25 |
| M22 | 2.00 | - | - | Stone sludge | 1.00 | Plastiment | 0.50 | 0.35 |
| M23 | 2.00 | - | - | Stone sludge | 1.00 | Sika control 40 | 1.50 | 0.30 |

PGF- polypropylene glass fibers

***Table 3.1*: *Mixes Composition.***

The mixes mentioned in Table 3.1 were cast to test the mechanical performance and to decide the best mixes for printing trials. As per the obtained results, we decide to print mixes M18, M19, M20, M21, M22 and M23.

### 3.2.2 Mixing Procedure and Methods

Firstly various size of the sand and various mixes were tried to extrude from the nozzle of the printer. Later it was observed that the sand grains higher than 500 µm are unable to extrude, so the sand of size lower than 500 µm was preferred.

To obtain a sand fraction of 500µm-250µm, coarse sand was sieved using an automatic sieve shaker is shown in Figure 3.3.

***Figure 3.3:Mechanical sieving of sand.***

- **Mix Preparation Procedure**

The preparation of mix was done according to EN 1015-2 [65]. The reference mix 2:1 cement : sand was first prepared. The quantity of the mix was calculated as per the volume of the mould, the dimensions of mould are 160x40x40 mm. The quantity was 2100g of total to fill the mould (1400g of cement and 700g of sand). The quantity of the cement and sand were weighed on the balance as shown in Figure 3.4(a) with accuracy of 0.01g and 10g superplasticizer (viscocrete 20HE) was measured, added to 100ml water and then materials were added in the automatic mixer shown in Figure 3.4(b) and the water is added in the small interval in order to obtain the required consistency and plasticity. The amount of water added was recorded and later the consistency was tested by flow table method according to EN 1015-3:1999 shown in Figure 3.4(c).

***(a) Weigh of cement*** ***(b) Mixing of mortar*** ***(c) Flow table test***

***Figure 3.4: Mix preparation procedure.***

After the consistency test, the mortar was transferred to the mould and it was vibrated by automatic vibrator for 5min until it was properly compacted and all the air bubbles were removed. It is left for air drying up to final as shown in Figure 3.5 setting of the mortar i.e. 24 hours and after setting it is demoulded and placed in curing tank for 28 days with stagnant and stable water and at a temperature of 20°C. A similar procedure was followed to prepare the rest of the mixes.

***Figure 3.5: Casting of mortar.***

### 3.2.3 Tests on Wet Mortar- Consistency Test

The consistency of the mortar was determined by flow table test and the procedure was followed according to EN 1015-3 [66].

Before conducting the test all the equipment’s were cleaned with a damp cloth and then dried. The mould was placed centrally on the flow table and the mortar was filled in two layers, each layer was compacted ten times by tamper, to ensure the mould was uniformly filled. The outer surface of the mould was cleaned by trowel to smoothen the top surface and it was removed carefully. The flow table was jolted 15 times at a constant frequency of approximately one per second and the diameter of the mortar was measured in both direction perpendicular to each other. The mean value of consistency was calculated in mm.

### 3.2.4 Tests on Hardened Mortar

Four types of tests were performed on the hardened mortar and they were: bending test, compression test, absorption and density test. They are explained in detail below.

#### 3.2.4(a) Bending Test

Bending tests were done according to EN 1015-11 [67]. The cured samples were taken out of curing tank and the surface was dried with a cloth. The Vernier calliper was used to check the dimensions of the samples. The test was performed in the Compression Testing Machine (CTM) machine and it was setup for the bending test. It had two steel bars at the bottom to support the prisms and they were placed at 100 mm and another bar on the upside at centre between supporting bars.

The prism was placed intact as shown in Figure 3.6 such that load was applied to one of the faces (which have been cast against the steel of the mould). It was aligned carefully so that the load was applied to the whole width of the face in contact with platens and the load was applied at 10 N/s velocity as per standards.

During the test, the prisms broke at a certain load and that load and strength was recorded. Similarly, the tests on all the prisms were performed. The compression test was performed on the pieces of the broken prism.

*Figure 3.6: Flexure test.*

The bending test result ($N/mm^2$ ) was calculated from the following equation:

$$1.5\frac{FxL}{bd^2} \ ,$$

where:

Fx- Force in KN
L- Length of support (From outer span)
b- Width of prism in mm
d- Depth of prism in mm

### 3.2.4(b) Compression Test

---

Compression test was done according to EN 1015-11 [67]. The five half prisms obtained from the bending test was used to determine the compressive strength of the mix and one half was used to study density and absorption.

The compression test machine was “form-test brand” test machine which was capable of applying the load at a velocity of 200N/s. The up and down surface of the compression area was 40mmx40mm as shown in Figure 3.7.

The compressive strength ($N/mm^2$ ) was obtained from the equation:

$$\frac{F}{bxd} ,$$

where:

F- Force in KN

b-width of prism in mm

d- Depth of prism in mm

***Figure 3.7: Compression test .***

## 3.2.4(c) Water Absorption and Density

A half prism was used to study water absorption and density, which was placed in a curing tank. After a few hours it was taken out and dry patted with a cloth to remove water from the surface. The prism was placed in the tumbler as shown in the Figure 3.8 and the saturated weight was noted down and then water was added into the tumbler up to certain point and this weight of the saturated sample with water was noted down.

The prism was taken out of the tumbler and now the water was added gradually until it reaches the same level as that of with prism and this weight of water was noted. The prism was kept in an oven at 110°c for 24 hours to evaporate the water, after 24 hours the sample was taken out and weighed to obtain the dry weight of the prism.

*Figure 3.8: Absorption test.*

The formulation for saturated density is

$$\frac{Weight\ of\ surface\ dreied\ sample}{Weight\ of\ surface\ dreid\ sample-(Weight\ of\ water\ and\ sample-Weight\ of\ water)},$$

and the formulation for dry density is

$$\frac{Weight\ of\ completely\ surface\ dried\ sample}{Weight\ of\ surface\ dried\ sample-(Weight\ of\ water\ and\ sample-Weight\ of\ water)}.$$

**Absorption Test**

To determine water absorption of the mortar, rate of the saturated and dried samples has to be calculated. The formula for absorption is

$$\frac{W_{Saturated}-W_{Dried}}{W_{Dried}}X100\,.$$

## 3.3 Equipment to Print

### 3.3.1 At Initial Stage

Twin screw extruder was tested at very initial stage to check the possibility of the material extrusion and to determine the perfect consistency for smooth extrusion. The extruder was placed horizontal on the platform and it runs on mortar. It has a small opening to introduce the cementitious material as shown in the Figure 3.9. The major problem was size of sand greater than 250 µm could not be used and in order to extrude, the mix should be lean as soup which was not the required consistency for printing.

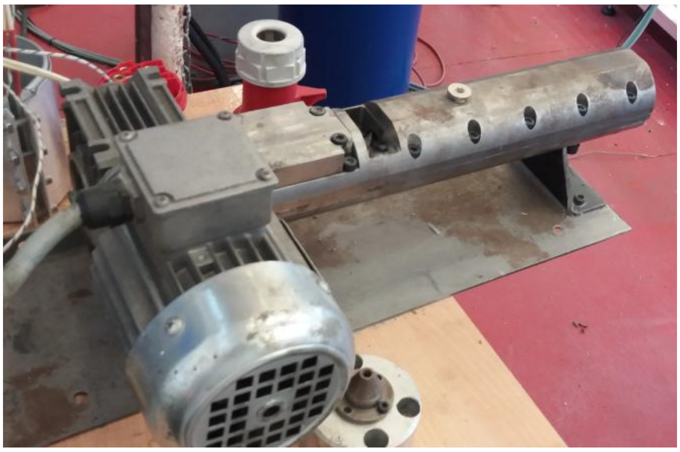


*Figure 3.9: Twin screw extruder with an opening to introduce the material.*

At first small printer was used to print and to test the plasticity, buildability, extrusion and adhesion between the layers. Fused Diffusion Modelling (FDM) printer was used; there are four types of FDM printer Cartesian, Delta, Polar and Robotic Arm. FDM printers extrude a continuous filament of thermoplastic material, which is a slow process when compared to other types of 3D printing, it is also called Fused Filament Fabrication.

The Printer used was Cartesian FDM 3D printer; but usually FDM is used for printing plastics but this printer was altered for ceramics by incorporating a tank for ceramic paste, the paste tank act as an integral part of the system; hence it was a DIY printer made at working place show below in the Figure 3.10.

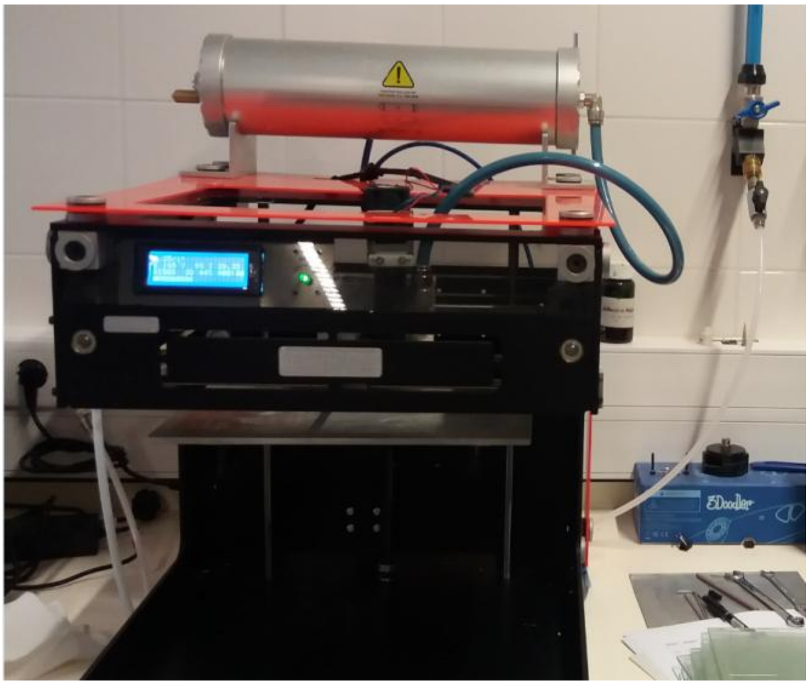


*Figure 3.10: FDM printer.*

The 3D printer working on FDM consists of the printer platform, a nozzle (also called as printer head), the paste tank and raw material in the form of a paste.

The paste extrusion was controlled by blowing a stream of air in between 4-6 bars to achieve smooth and continuous extrusion but the maximum pressure of the system was 8 bars. The component was designed and drawn in AutoCAD 3D model and converted into STL. File. In order to test initially simple component was decided to print (cube) of size 150*150 mm. The mix was prepared using cement and water with the mix consistency of dough.

The problem associated with FDM printer was using cement, as the printer was being used for ceramics and according to company advice it was not appropriate to use cement due to its setting time, the printer didn’t have a pressure system to extrude cement paste. Cleaning of the printer was a big issue and any clogging of printer will lead to overhead expense.

## 3.3.2 Final Stage

The equipments motioned in the above section were not able to print cement mortar, so we decided to use the robotic arm by adapting it for cementitious material. This section will provide information about the equipment used in 3D printing i.e. robotic arm by Yaskawa Motoman- HP20F [69]. Robotic arms are mechanical devices that resemble the human arm. These are used to perform tasks that are either harmful to humans, unsafe, unpleasant or highly repetitive. These tasks are often programmed using a teach and repeat technique where the operator /programmer uses a portable device to teach the robot its task. This is done by going through the motions that the robot needs to make. There is a wide range of shapes, sizes and configurations available. The most significant difference between robotic arms is the number of joints, the reach and the maximum load that the robot can handle. The most robotic arm is driven by electric motors The Motoman HP 20F is a high-speed robot with a 20 kg payload, it has six individual axes: sweep, lower arm, upper arm, rotate, bend and twist as shown in the Figure 3.11.

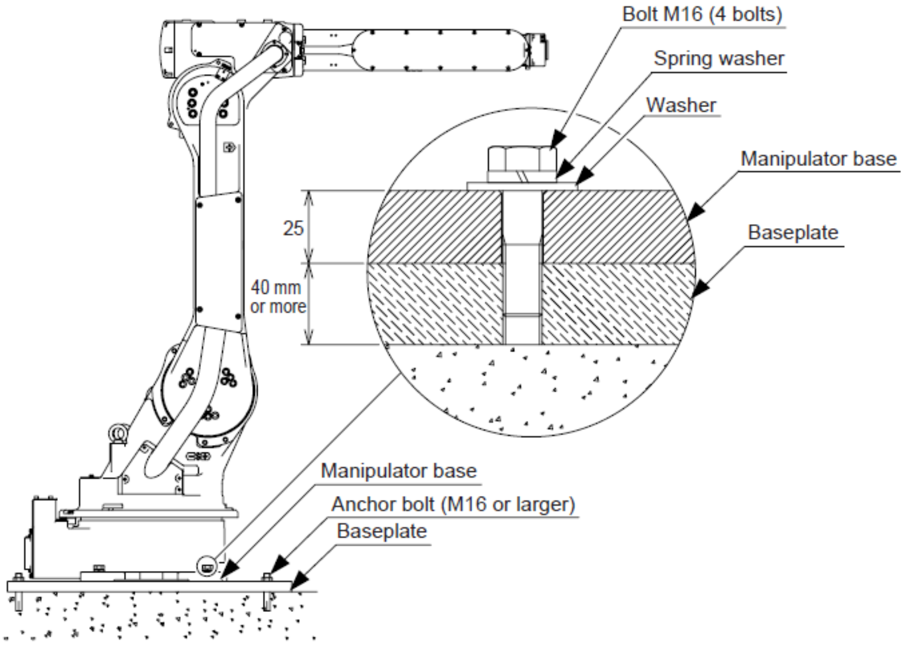


*Figure 3.11: Part names and working axes of the robotic arm [69].*

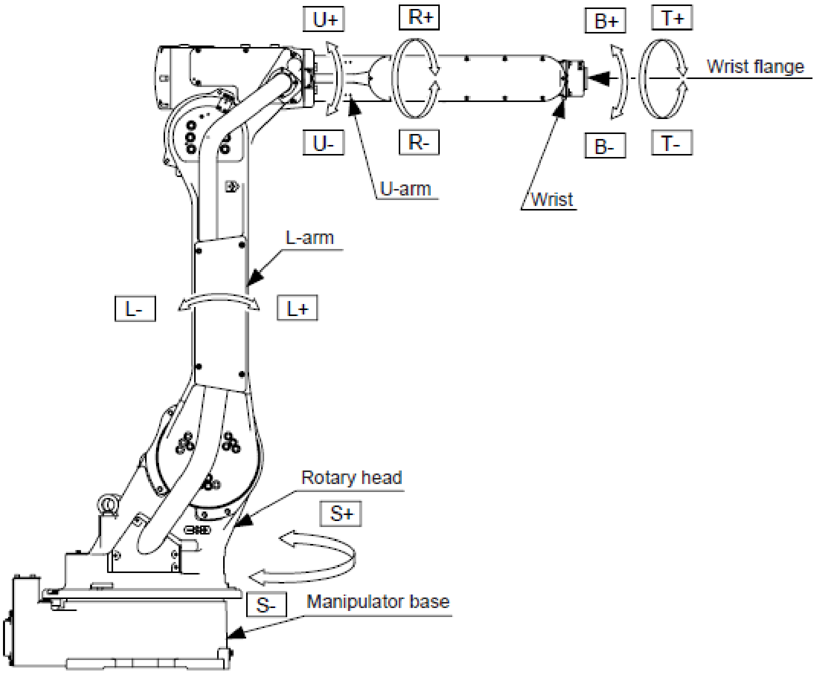


*Figure 3.12: Base parts of robotic arm [69].*

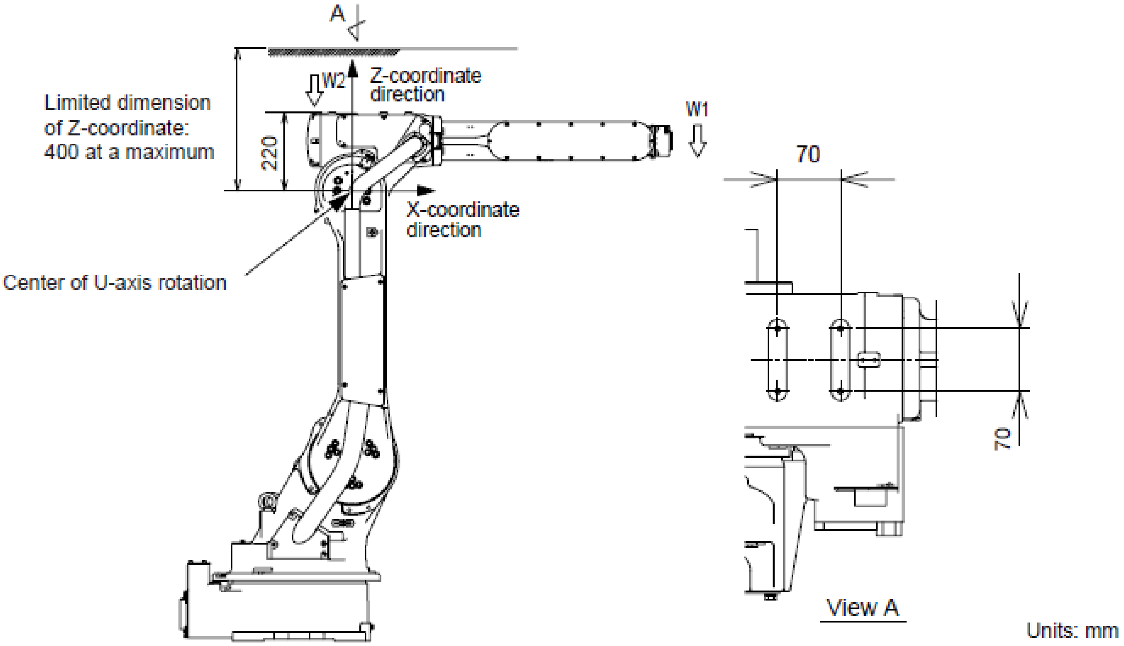


*Figure 3.13: Peripheral equipment mounts [69].*

The HP 20F has various parts which are shown as in the Figure 3.12. The base plate attached to the floor firmly, anchor plate which is to which manipulator base is installed followed by the rotary head, L arm, U arm and wrist at the top. There is a limitation on the installation position of the peripheral equipment on HP 20F is shown in the Figure 3.13. For further detail of the robotic arm can be found in the technical data sheet in the appendices. The robotic arm HP 20F was prepared as per the requirements for printing cementitious material, an additional system with the desired type of nozzle suitable for cementitious material was mounted on the wrist portion of the robotic arm. A tank was designed by us and it was mounted on the L arm of the robot for cementitious material pumping which was connected to a pipe for supplying air pressure for extrusion of the material.

The tank had a capacity of 5 litres with a piston which moved throughout the tank under the influence of the air pressure. The parts of the tank as follows: cylinder made up of aluminium, piston, closing head top and bottom, aluminium braces and kemlock components for ease and secure locking system as shown in the Figure 3.14(a) and 3.14(b), further technical details of the tank is available in the appendices. The pipe connected to the tank for air supply had a separate air pressure control system to control the pressure in the pipe shown in the Figure 3.14(c) and to ensure smooth extrusion without an explosion of the material due to direct connection to the main air supply valve of the building. The pipe extruding the cementitious material was placed adjacent to FDM extruder as shown in the Figure 3.14(d) to use the robotic mechanism for better precision and accuracy. The diameter of the extruding pipe was 20 mm and 3 m long, as we planned to print filament of 10 mm, hence an additional attachment component was attached to reduce the diameter from 20 mm to 10 mm gradually. The movement of the robotic arm was controlled with special software called an Integrated Development Environment (IDE). The platform was made up of aluminium and consists of heating sensors to supply heat from the base.

Recently we designed a single fuse extruder to control the flow rate and to ensure the material was being mixed during extrusion, thereby removing air bubbles which provide a homogenous mix during printing. The above mentioned extruding pipe was shortened to reduce material waste. The Figure 3.14(e) shows the new arrangement of the printer with single fuse extruder with a nozzle arrangement and Figure 3.15 shows entire equipment assembly with robotic arm during printing.

*a) Components of tank* *b) Piston in the cylinder*

*c) Separate pressure system for printing* *d) Attachment of pipe adjacent to FDM extrude*

*e) Single fuse extruder with nozzle*

*Figure 3.14: Components and systems of robotic arm.*

*Figure 3.15: Entire equipment assembly with robotic arm.*

## 3.4 Micro CT- Microcomputed Tomography

Micro CT is a technique which uses X-Ray to scan an object and gives 3D internal imaging of the object without destroying the object and its properties. It's used widely in medical and material characterisation, but recently in construction filed to study the behaviour of the concrete, its interaction between fine and coarse aggregates to determine the porosity, cracks and corrosion of the reinforcement. It was used to understand the porosity, non-interacted particles of waste and alignment of particles during printing.

To study the internal structure of printed mix M15, a Bunker Sky Scan (1174v2) was used as shown in the Figure 3.16 had following parameters: software version 1.1, voltage 50 Kv, Current 800 uA, Image pixel size 11.67 um, exposure 9000 ms, Scan duration 0.1: 35:08 hours and rotation 0.900 deg with filter 0.25Al. Software's used to calculate, measure and 3D images were CTAn, Data viewer and CTVox.

*Figure 3.16: Micro CT Equipment- Sky Scan(1174v2)*

# 4 Results

In this section, different test methods used to characterize the material for mechanical and printed properties of mixes with obtained results are presented. Initially, result of conventional methods was presented, followed by results of the printable mixture evaluated in terms of flowability, extrudability, shape retention, buildability and open time. Mechanical properties of printed and casted sample were tested and compared.

## 4.1 Wet Properties of the Mixes

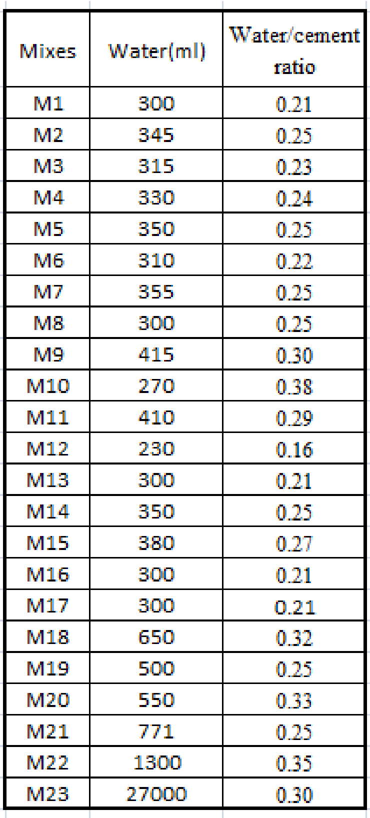
These are the results obtained when the mixes were in wet condition or test performed after mixing water.

### 4.1(a) Mixing Time

The mixing time observed was 1min to attain homogeneous mix at fixed water content as the water was added in small parts in order to control the amount of water. Mixing time played a vital role given that it can affect compressive strength. Hence mixing time is inversely proportional to compressive strength. Mixing was carried out to obtain homogenous material throughout the mix and to reduce the formation of the lumps and air pockets. So 1min of mixing time was enough to obtain the homogenous mix as per the specified water-cement ratio.

## 4.1(b) Water/ Cement ratio

The ratio of the amount of water to the amount of cement is called water to the cement ratio (W/C). The amount of water and w/c ratio of all the mixes is shown in the Table 4.1.



| Mixes | Water(ml) | Water/cement ratio |
|---|---|---|
| M1 | 300 | 0.21 |
| M2 | 345 | 0.25 |
| M3 | 315 | 0.23 |
| M4 | 330 | 0.24 |
| M5 | 350 | 0.25 |
| M6 | 310 | 0.22 |
| M7 | 355 | 0.25 |
| M8 | 300 | 0.25 |
| M9 | 415 | 0.30 |
| M10 | 270 | 0.38 |
| M11 | 410 | 0.29 |
| M12 | 230 | 0.16 |
| M13 | 300 | 0.21 |
| M14 | 350 | 0.25 |
| M15 | 380 | 0.27 |
| M16 | 300 | 0.21 |
| M17 | 300 | 0.21 |
| M18 | 650 | 0.32 |
| M19 | 500 | 0.25 |
| M20 | 550 | 0.33 |
| M21 | 771 | 0.25 |
| M22 | 1300 | 0.35 |
| M23 | 27000 | 0.30 |

***Table 4.1**: Water/ Cement ratio.*

M5 absorbed water due to the presence of cork. Cork is porous in nature and it had an affinity for water resulted in higher water-cement ratio. M7 had higher water-cement ratio than M6 with the same proportion of materials, but with different grain size of sand. M7 had finer sand; resulted in the higher surface area which resulted in higher water-cement ratio.

M9 had water absorption because of aluminium polishing waste; the amount of water absorbed was higher compared to all other mixes. It was due to fineness of the material which required more water to reach a homogenous mix.

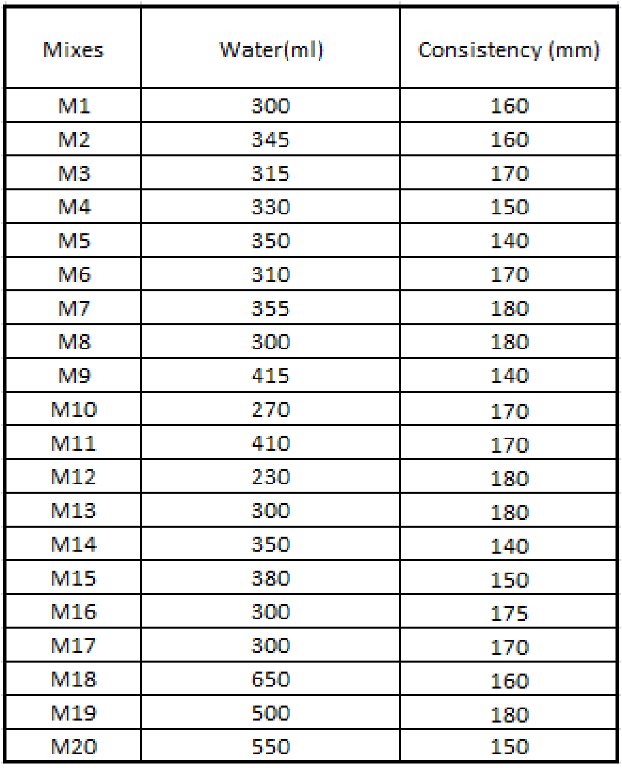
The water quantity depended on the amount of superplasticizer used. It was observed that M12 with sika control 40 gave lower water-cement ratio than others. M11 gave higher water-cement ratio because it was used in smaller percentage compared to other superplasticizers.

It was observed that the amount of water increased as the amount of stone sludge proportion increased in the mixes. M15 consumed the highest quantity of water, as it contained a higher proportion of stone sludge compare to other mixes. M15 had 1.3 times more water-cement ratio than M1.

For mixes M18, M19, M20, M21, M22 & M23 the amount of water was not limited to achieve good printability but the water cement ratio was within desired limits.

## 4.1(c) Consistency

Consistency is a measure of the fluidity and/or wetness of the fresh mortar and gives a measure of the deformability of the fresh mortar when subjected to a certain type of stress [66]. It is the thickness or the viscosity of the paste and was measured by the spread diameter of the mix. The consistencies of all the mixes are listed below in the Table 4.2.



| Mixes | Water(ml) | Consistency (mm) |
|---|---|---|
| M1 | 300 | 160 |
| M2 | 345 | 160 |
| M3 | 315 | 170 |
| M4 | 330 | 150 |
| M5 | 350 | 140 |
| M6 | 310 | 170 |
| M7 | 355 | 180 |
| M8 | 300 | 180 |
| M9 | 415 | 140 |
| M10 | 270 | 170 |
| M11 | 410 | 170 |
| M12 | 230 | 180 |
| M13 | 300 | 180 |
| M14 | 350 | 140 |
| M15 | 380 | 150 |
| M16 | 300 | 175 |
| M17 | 300 | 170 |
| M18 | 650 | 160 |
| M19 | 500 | 180 |
| M20 | 550 | 150 |

***Table 4.2**: Consistency of mixes.*

The consistency of all the mixes was within the limit as per standards EN 1015-6 [68] i.e.140 to 210 mm for plastic consistency. It was observed from the Table 4.2 that M3 and M6 with a coarse gradation of sand consumed less amount of water, but they produced good consistency than M4 and M7 with fine sand. Sand of size 500µm had better consistency than 250µm irrespective of variation in the amount of stone sludge in the mixes.

M5 contains cork which consumed more quantity of water compared to other mixes and consistency was within the limits but at the edge, since cork absorbs more amount of water as it had an affinity for water. Whereas M8 contained eucalyptus ash which gave similar consistency at lower amount of water than M5 and M9.

To reach minimal consistency the M9 consumed highest water quantity compared to other mixes and the percentage of aluminium waste in the mix was 0.25. Aluminium with a low proportion seeks a higher quantity of water to reach minimum consistency.

The use of Viscocrete in M10 allowed to consume lower amount of water but produced similar consistency that of other mixes and was within limits. Frioplast (M11) gave consistency within limits at a lower percentage than other superplasticizers, besides facilitating the extrusion process. Frioplast is best suitable as water reducer gaving good consistency.

Sika control 40 (M12) produced better consistency at a lower amount of water compared to viscocret 650 DUO (M14) and plastiment+viscocrete HE 20 (M13). Fibers (M16 and M17) gave appropriate consistency with an acceptable amount of water quantity. M18 consumed more water due to larger proportion of stone sludge in the mix but M19 consumed less water than M18 as it had lower proportions of stone sludge. M20 consumed more water due to presence of fibers.

Figure 4.1 shows the consistencies of all the mixes at the respective water-cement ratio. From the graph, it was observed that M5, M9 & M14 produced the same consistency with same water-cement ratio but M1, M13, M16 and M17 showed different consistency with same water-cement ratio. M19 gave better consistency than M18 and M20 at lower water cement ratio.

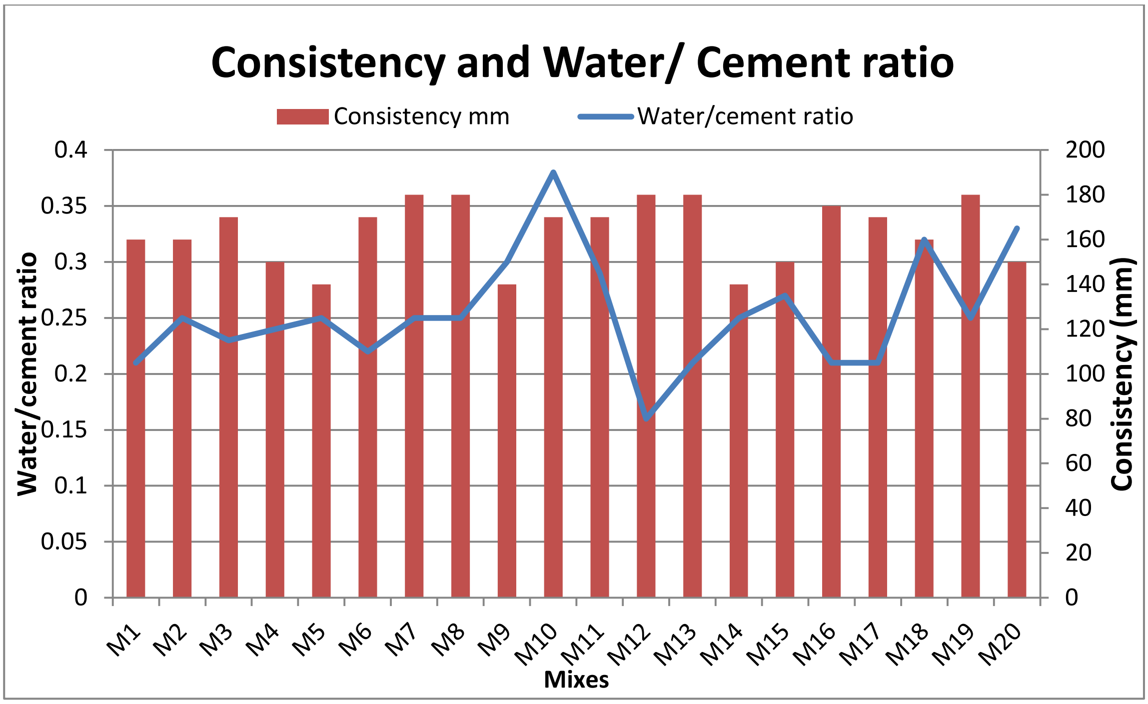


*Figure 4.1: Consistency and Water/ Cement ratio.*

## 4.1.2 Hardened Properties of the Mortar

The behaviour of the mortar was totally different in wet condition and hardened situation. This section explains the hardened properties.

### 4.1.2(a) Bending Test

The mean value of bending test of all mixes was $10.03 N/mm^2$, but few mixes made up of waste showed lower bending resistance than the mean value.

From Figure 4.2 it was observed that M3 and M4 showed the same result irrespective of sand size and M6 and M7 had larger proportions of stone sludge which reduced the bending strength.

M8 & M5 showcased higher resistance than M9, so aluminium polished waste decreased the strength, probably due to some amount of polymer contained in this type of waste. M12, M13 & M14 showed resistance higher than M1 because of the presence of sikacontrol 40, plastiment & viscocrete and viscocrete650DUO superplasticizer respectively. M13 showed higher resistance than M17, hence the mix contained with two admixtures gave a better result than mix with fibers.

M16 has higher resistance compared to other mixes. Presence of fibers in the mix M16 up to 1% resulted in higher resistance to bending, whereas M17 with fibers up to 0.5% did not show the same performance but higher than reference mix M1.

M18, M19 & M20 were prepared to test printability and these mixes did not perform so well when compare to remaining mixes because of lower cement content. Presence of fibers in M20 resulted in better resistance compared to M15, M18 and M19. Figure 4.2 shows the flexure strength of all the mixes at 28days.

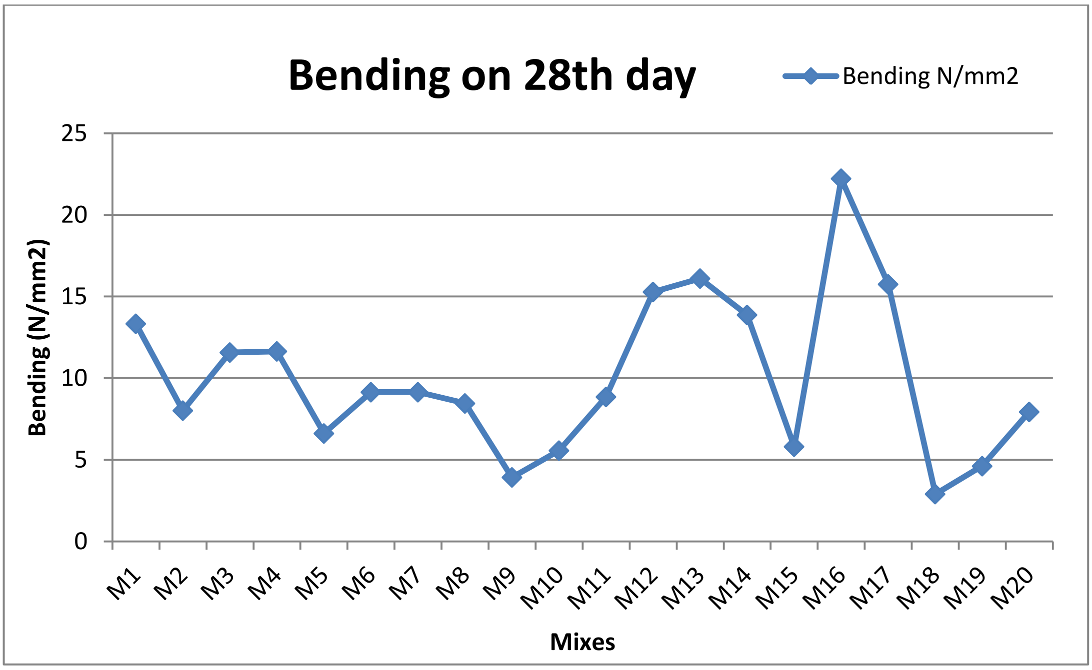


*Figure 4.2: Bending test result at 28days.*

## 4.1.2(b) Compressive Strength

Compressive strength at 28 days of all the samples are shown in Figure 4.3 and it was clear that M1 had good performance under compression but mix containing a small amount of stone sludge i.e. M3 and M4 had similar resistance under compression, which showed stone sludge did not have an effect on compressive strength but M6 and M7 had higher proportion of stone sludge which resulted in lower strength compared to M3 and M4.

M3 had sand of bigger grain size than M4, which helped it to develop compressive strength greater than M4. M5, M8 and M9 had lower compressive strength similar to that of M15, like cork, eucalyptus ash and aluminium wastes did not allow such high mechanical characteristics.

The mix M15 had a higher amount of stone sludge that of cement which didn't withstand the compressive load compare to M3 and M4 , it was because of lower cement content and stone sludge lacks in mechanical strength and the mix made of higher stone sludge consumes more water content which produced least strength when compare to other mixes . M16 and M17 were not able to resist higher compressive load compared to reference mix M1.

The mixes M18, M19 & M20 did not withstand the compressive load, as they were designed to print and they failed in compression at a faster rate compared to M5, M9 and M15.

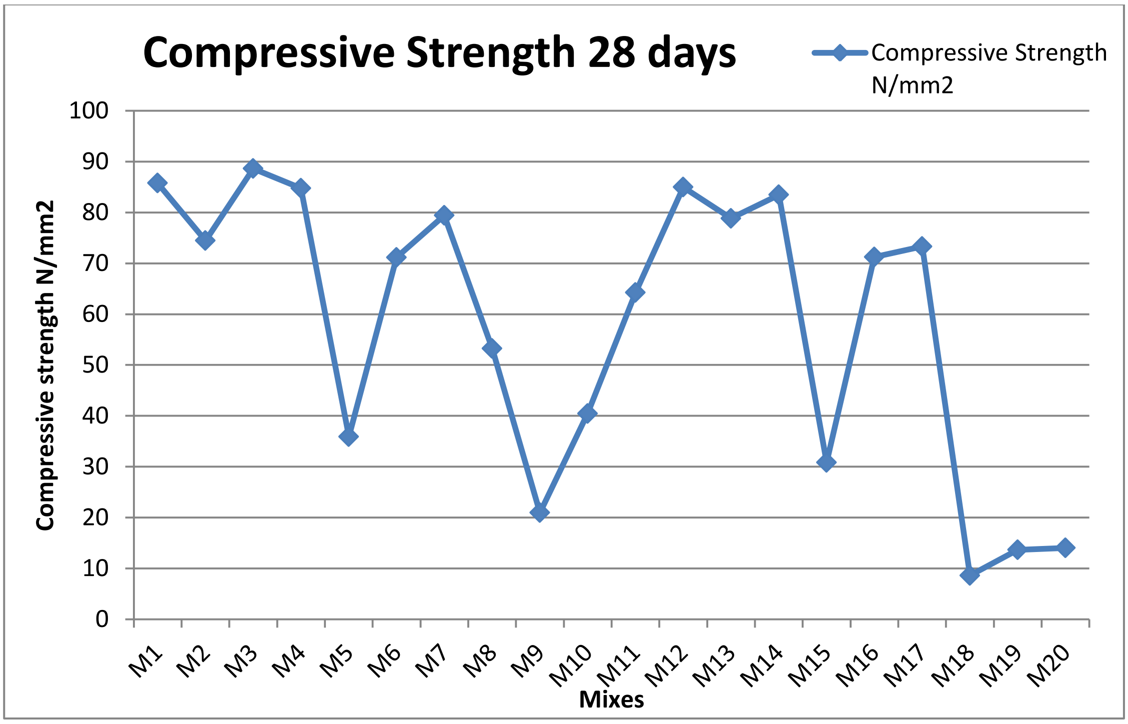


*Figure 4.3: Compressive strength at 28days.*

M1 showed a better result than M11, M13, M14, M16 and M17; hence the addition of admixtures (Frioplast, plastiment & viscocrete and viscocrete650DUO) did not make significant increase in the strength.

Figure 4.4 compared water quantity and compressive strength development and it was observed that M9, M10, M18 and M20 had higher water/ cement ratio resulted in lower compressive strength than other mixes. But M18, M19 and M20 had higher water-cement ratio which enabled good printability with lower compressive strength.

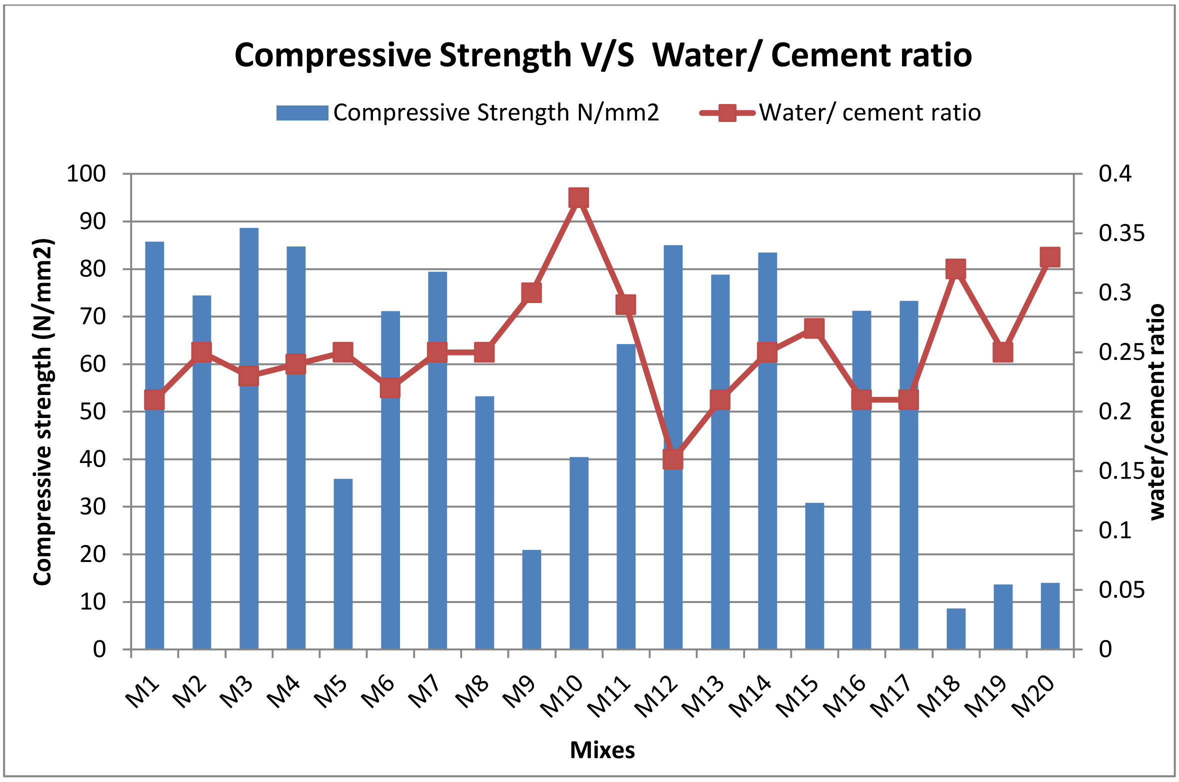
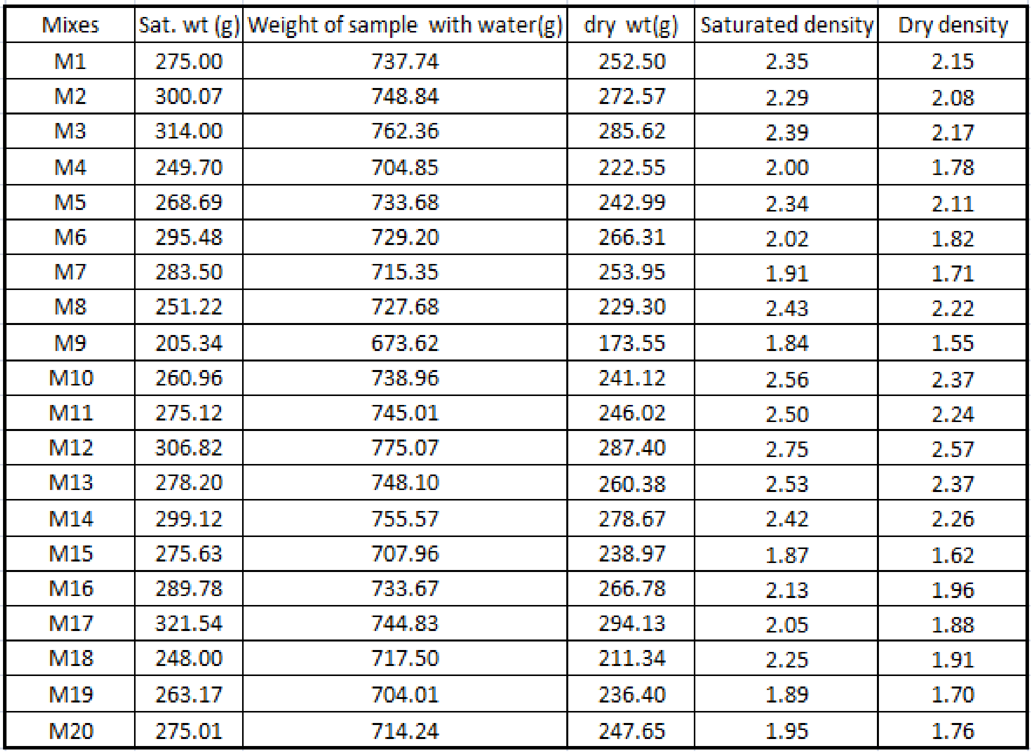


*Figure 4.4: Compressive strength v/s Water/ Cement ratio.*

## 4.1.2(c) Density and Absorption

From the Table 4.3, it was observed that saturated density increased with increase in the amount of sand; Mixes M5 and M8 had medium saturated and dry density. M9 showed lower saturated and dry density due to presence of aluminium waste in the mix, probably because of its polymer content.

M10 had doubled the amount of sand that of M1 resulting higher saturated and density than M1. M12 had highest saturated and dry density compare to samples with other superplasticizers. It was observed that mixes (M11, M12, M13, M14, M16 and M17) with admixtures Frioplast, Sika control 40, Plastiment & Viscocrete, Viscocrete650DUO and fibers showed higher saturated and dry density compared to mixes with Viscocrete.

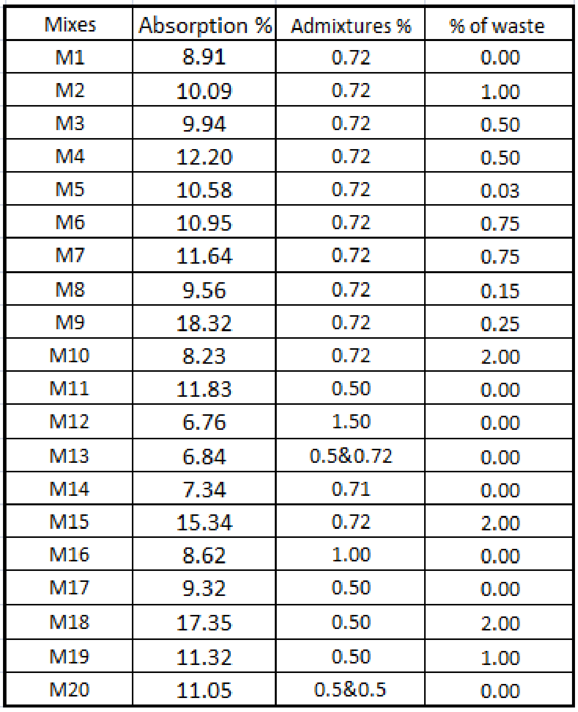


| Mixes | Sat. wt (g) | Weight of sample with water(g) | dry wt(g) | Saturated density | Dry density |
|---|---|---|---|---|---|
| M1 | 275.00 | 737.74 | 252.50 | 2.35 | 2.15 |
| M2 | 300.07 | 748.84 | 272.57 | 2.29 | 2.08 |
| M3 | 314.00 | 762.36 | 285.62 | 2.39 | 2.17 |
| M4 | 249.70 | 704.85 | 222.55 | 2.00 | 1.78 |
| M5 | 268.69 | 733.68 | 242.99 | 2.34 | 2.11 |
| M6 | 295.48 | 729.20 | 266.31 | 2.02 | 1.82 |
| M7 | 283.50 | 715.35 | 253.95 | 1.91 | 1.71 |
| M8 | 251.22 | 727.68 | 229.30 | 2.43 | 2.22 |
| M9 | 205.34 | 673.62 | 173.55 | 1.84 | 1.55 |
| M10 | 260.96 | 738.96 | 241.12 | 2.56 | 2.37 |
| M11 | 275.12 | 745.01 | 246.02 | 2.50 | 2.24 |
| M12 | 306.82 | 775.07 | 287.40 | 2.75 | 2.57 |
| M13 | 278.20 | 748.10 | 260.38 | 2.53 | 2.37 |
| M14 | 299.12 | 755.57 | 278.67 | 2.42 | 2.26 |
| M15 | 275.63 | 707.96 | 238.97 | 1.87 | 1.62 |
| M16 | 289.78 | 733.67 | 266.78 | 2.13 | 1.96 |
| M17 | 321.54 | 744.83 | 294.13 | 2.05 | 1.88 |
| M18 | 248.00 | 717.50 | 211.34 | 2.25 | 1.91 |
| M19 | 263.17 | 704.01 | 236.40 | 1.89 | 1.70 |
| M20 | 275.01 | 714.24 | 247.65 | 1.95 | 1.76 |

***Table 4.3*: *Density test results.***

The absorption of the samples are listed in Table 4.4, the maximum absorption was observed in the sample M9 had aluminium waste followed by M18, M15, M4, M7, M19 and M20 as they contained stone sludge in the mix. M4 and M7 had fine sand which resulted higher absorption when compared to M3 and M6 with bigger size of sand.

M9 had 34.44% of higher absorption than M1 since it was very fine and had greater surface area resulted in higher absorption of water. M4, M11&M15 had 15.58%, 14.07% and 26.51% respectively higher absorption than M1. Whereas M1 had higher absorption than M10, M12, M13 and M16, this absorption was influenced by the amount and type of admixture used in the mixes. M18 & M19 showed higher absorption due to stone sludge presence in the mix and M20 had Frioplast which influenced the absorption of the mix, similar to M11.



| Mixes | Absorption % | Admixtures % | % of waste |
|---|---|---|---|
| M1 | 8.91 | 0.72 | 0.00 |
| M2 | 10.09 | 0.72 | 1.00 |
| M3 | 9.94 | 0.72 | 0.50 |
| M4 | 12.20 | 0.72 | 0.50 |
| M5 | 10.58 | 0.72 | 0.03 |
| M6 | 10.95 | 0.72 | 0.75 |
| M7 | 11.64 | 0.72 | 0.75 |
| M8 | 9.56 | 0.72 | 0.15 |
| M9 | 18.32 | 0.72 | 0.25 |
| M10 | 8.23 | 0.72 | 2.00 |
| M11 | 11.83 | 0.50 | 0.00 |
| M12 | 6.76 | 1.50 | 0.00 |
| M13 | 6.84 | 0.5&0.72 | 0.00 |
| M14 | 7.34 | 0.71 | 0.00 |
| M15 | 15.34 | 0.72 | 2.00 |
| M16 | 8.62 | 1.00 | 0.00 |
| M17 | 9.32 | 0.50 | 0.00 |
| M18 | 17.35 | 0.50 | 2.00 |
| M19 | 11.32 | 0.50 | 1.00 |
| M20 | 11.05 | 0.5&0.5 | 0.00 |

***Table 4.4*: *Absorption result.***

### 4.1.2(d) Comparison of Conventional and 3D Printed Mortar

The strength parameter of the 3D printed mix was compared to the conventional mortar. We decided to cut the printed components into regular prisms of dimension 40*40*160 mm. The M19 printed mortar was cut into 3 prisms and tested for mechanical properties on the 50th day. Table 4.5 shows the comparison of conventional and 3D printed mortars.

| Type (M19) | Bending ( MPa) | Compressive strength( MPa) |
|---|---|---|
| Conventional | 4.61 | 13.66 |
| 3D printed | 3.55 | 12.69 |

***Table 4.5: Comparison of conventional & 3D printed mortars.***

From the Table 4.5, it was observed that mortar prepared by conventional way developed strength faster than that of 3D printed mortar. The mortar prepared by conventional way gained strength at 28 days, whereas 3D printed mortar on the 50th day could not attain the same strength. But the difference between them was minute.

The time taken to develop the strength was important and should be taken into consideration. The 3D printed mortar was not vibrated, not compacted and not cured, hence resulted in slow strength development.

## 4.2 Printing Results

This section explains the results of printed materials in wet conditions.

### 4.2.1 Preliminary Testing

The objective of the preliminary testing was to find the mix suitable for extrusion. During the 1st trial, the material was not extruded because of low open time of mix M1. The time taken to prepare mortar and mounting of the tank was prolonged and in the meantime, mortar started to gain strength which made the extrusion tough.

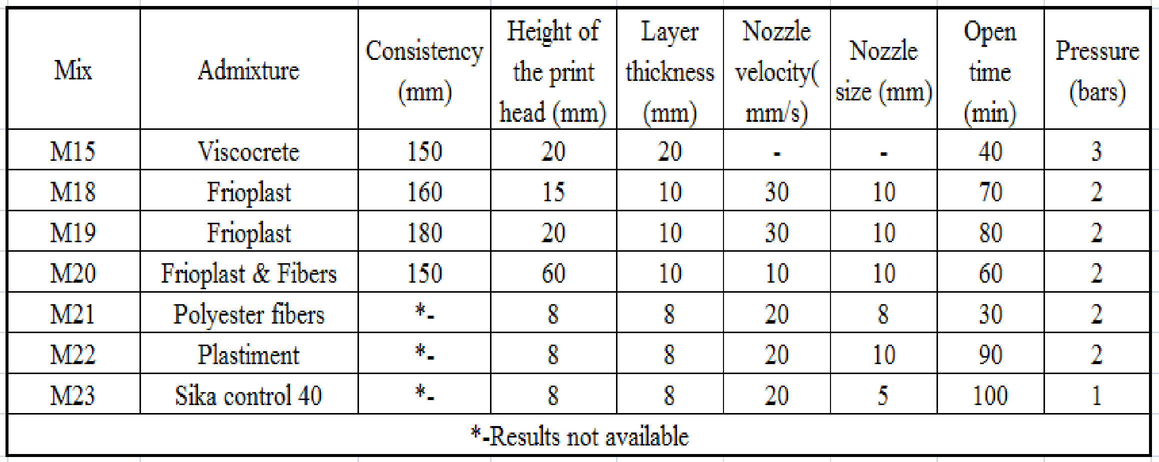
In order to overcome the problem resulted in the 1st trial; we decided to print M15 for 2nd trial. Stone sludge with retardant was used, which increased the open time of the mix and allowed to extrude. The observed result was acceptable but not satisfactory. It was understood that the opening of the nozzle was a key parameter that directly related to the geometry of the extruded filament and the size of the extrusion pipe was 20 mm. Figure 4.5 shows the initial extrusion of M15 at 2bars.

*Figure 4.5: Extruded mortar.*

From the Figure 4.5, it was that the printed material had few cracks on the surface and it was not extruded continuously due to entrapped air and lower water-cement ratio.

### 4.2.2 Final Testing

Table 4.6 shows the parameters which influenced the printability of mixes and to evaluate the wet properties of the mortar.



| Mix | Admixture | Consistency (mm) | Height of the print head (mm) | Layer thickness (mm) | Nozzle velocity( mm/s) | Nozzle size (mm) | Open time (min) | Pressure (bars) |
|---|---|---|---|---|---|---|---|---|
| M15 | Viscocrete | 150 | 20 | 20 | - | - | 40 | 3 |
| M18 | Frioplast | 160 | 15 | 10 | 30 | 10 | 70 | 2 |
| M19 | Frioplast | 180 | 20 | 10 | 30 | 10 | 80 | 2 |
| M20 | Frioplast & Fibers | 150 | 60 | 10 | 10 | 10 | 60 | 2 |
| M21 | Polyester fibers | *- | 8 | 8 | 20 | 8 | 30 | 2 |
| M22 | Plastiment | *- | 8 | 8 | 20 | 10 | 90 | 2 |
| M23 | Sika control 40 | *- | 8 | 8 | 20 | 5 | 100 | 1 |
| *-Results not available | | | | | | | | |

*Table 4.6: Parameters for printability.*

### 4.2.2(a) Flowability

The mixes M18, M19, M21 and M22 satisfied the definition of flowability because they were transported to the extruder smoothly under the constant pressure of 2 bars but M23 was transported at a pressure of 1bar so it had better flowability compared to other mixes.

M20 had different consistency due to fibers, they increased friction while printing which needed more pressure. M23 was plastic but not viscous due to presence of Sika control 40 in the mix. The most important parameter which influenced flowability was the water-cement ratio, the percentage and type of admixture used.

Frioplast was used in M18, M19, M20 and M21, which gave flowability within limits; whereas Plastiment was used in M22 which gave better flowability compare to mixes contained Frioplast but M23 with Sika control 40 gave best flowability than 5 mixes.

No air gaps were encountered while printing as the mixes were mixed homogeneously and the trapped air was removed by adjusting the piston to the exact position.

### 4.2.2(b) Extruadbility

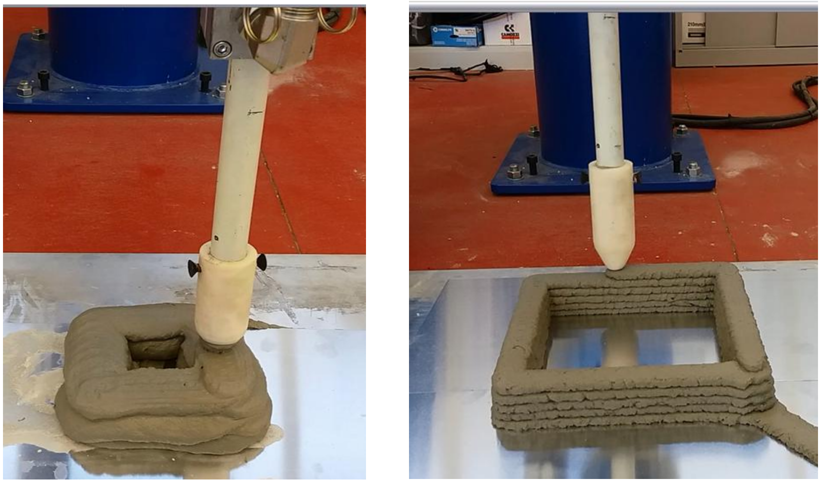
The extrudability obtained was satisfactory as the mixes were extruded without any cracks and air bubbles. The balanced and interrelated relationship of the extrudability in mixes depends on extrusion rate and printing speed [36].

The extruder was used to control the flow rate and flow rate regulator was used to obtain a constant flow rate and helped to obtain a homogenous mix and to remove trapped air. Flow regulator was used to obtain a constant flow rate of 45Hz at 2 bars of constant pressure was maintained for M18, M19, M20, M21 and M22, but 1 bar of pressure was used for M23.

Additionally, the height of the print head above the print surface also played a critical factor related to printing and quality of extrusion. The Figure 4.6 shows the extrusion of the mixes.

*a) Mix M18* *b) Mix M19*

*c) Mix M20* *d) Mix M21*



*e) Mix M22* *f) Mix M23*

*Figure 4.6: Extrusion of mixes.*

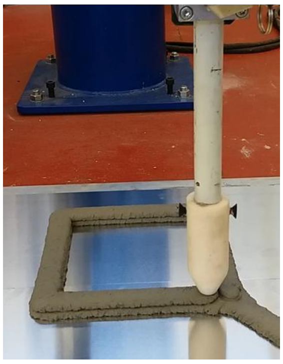
### 4.2.2(c) Shape Retention

From the Figure 4.7 it was observed that the mixes M19, M21, M22 and M23 retained their shape after printing successive layers above them. The same thickness was maintained after printing successive layers above, the bottom layers M19 and M21 had better shape retention when compared to M22 due to lower water/cement ratio.

M23 showed the best shape retention in fresh state compared to other five mixes and the thickness of the printed filament was maintained throughout the printing.

*a) Mix M19* *b) Mix M21*

*c) Mix M22*



*d) Mix M23*

*Figure 4.7: Shape Retention of mixes.*

It was noted that yield stress of fresh concrete was the main parameter which determined the shape stability before setting. Yield stress increased over time in absence of agitation and shear stress [61, 63].

### 4.2.2(d) Buildabilty

The liquid and viscous properties of fresh pastes were crucial to ensure the bonding performance between layers, which greatly depended on the rest time. The shorter the rest time, the higher the bonding strength between layers. The bond strength between layers gradually improved when the printer speed up. However, once the printer reached a certain speed, the required strength of layers may not yet have enough time to develop. Thus, the load carrying capacity decreases at higher speeds [36].

In our test, all mixes were liquid and viscous enough to had better bonding between layers. The buildability for M15, M19, M21 and M23 were accepted, as the layers did not collapse while printing layers on each other. These mixes were printed up to 4, 3, 5 and 21 layers respectively, without break down of lower layers.

But the buildability of M22 was affected by the self-weight of the overlying layers as the height increased during printing. The Figure 4.8(d) shows the bottom compressed layers of M22 mix resulted in settled and merged with lower layers. M23 showed excellent buildability as shown in the Figure 4.8(e) compared to five mixes and the lower layers supported the upcoming layers. The time gap between one layer to another layer was 40seconds.

The M15 printed without extruder didn’t showed good buildability as shown in the Figure 4.89(a).

*a)Mix M15 printed with pipe* *b) Mix M19*

*c) Mix M21* *d) Mix M22*

*e) Mix M23*

***Figure 4.8: Buildability of mixes.***

### 4.2.2(e) Open Time

Open time was determined from the moment when water was added to the mix until the printed filament developed cracks and discontinues during the extrusion process. The open time of each mix was noted down and all mixes had different open time.

An average open time for mixes M18, M19, M20, M22 and M23 was considered 50 min at which the mixes showed satisfactory flowability and extrudability. Presence of fibers lowered the open time for M21 as they absorb the water, so the mortar dried sooner than the expected time. M23 had greater open time due to the presence of Sika control 40.

The width and extrudability of the mortar were different after the respective open time for mixes. In the Figure 4.9, the M18 showed the variation in the width, shape, printability and extrudability after open time. It’s visible that initially printed layers were thicker and had better bonding, but as the time increased the change in the width, a gap between layers and discontinuous filament were observed which was considered as the end of open time for the mix. From the Figure 4.9 it was observed as the time progress the mix lost its consistency, buildability and extrudability which indicated the end of printable properties of the mix was referred as open time.

*Figure 4.9: Open time of mix M18.*

# 4.3 Micro- CT Scan

The major material in the mix M15 was stone sludge and cement was minor material. Initially 470 layers were scanned to determine the object volume and they were 108.67$mm^3$ of cement and 3.75 $mm^3$ of stone sludge. To determine the porosity region of interest was narrowed to 210 layers. The total volume of mix scanned was 3.16 $mm^3$ and the object volume was 3.08 $mm^3$ in 210 layers. The amount of stone sludge observed in the region of interest was 2.73% of cement in M15.

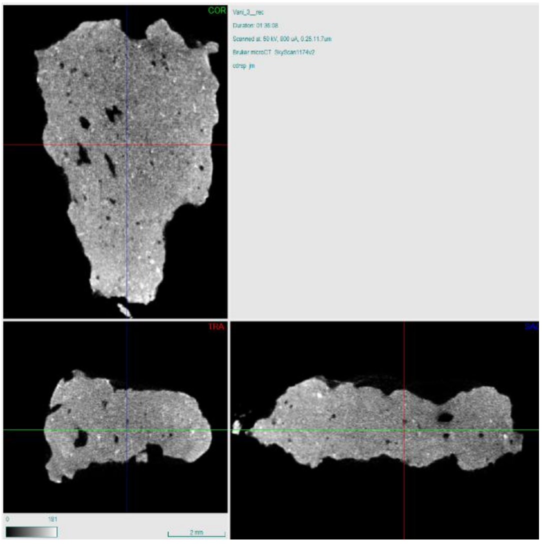


*Figure 4.10: Micro CT image of initial mix with pipe.*

In the Figure 4.10, the porosity was observed in the internal structure of the printed parts, the total porosity was 2.5% of scanned object among 201 layers. The pores were dispersed unevenly and of variable sizes. There were three types of pores: huge, medium and small, the largest dimensions were 1.83 micrometer, 0.40 micrometer and 0.14 micrometer respectively. The pores were present in a considerable amount which is due to the presence of air bubbles in the tank and they appear black in the photo as they don’t absorb any X-rays.

The white portions probably indicate the stone sludge which did not react with the cement. As a result they formed clogs separately because stone sludge had an affinity towards air than water, so resulted in the clog and all the clogs were almost of same size 0.142 micrometer.

The grey portion was the combination of cement and stone sludge; which formed a homogenous mix because of uniform distribution of cement particles in stone sludge,

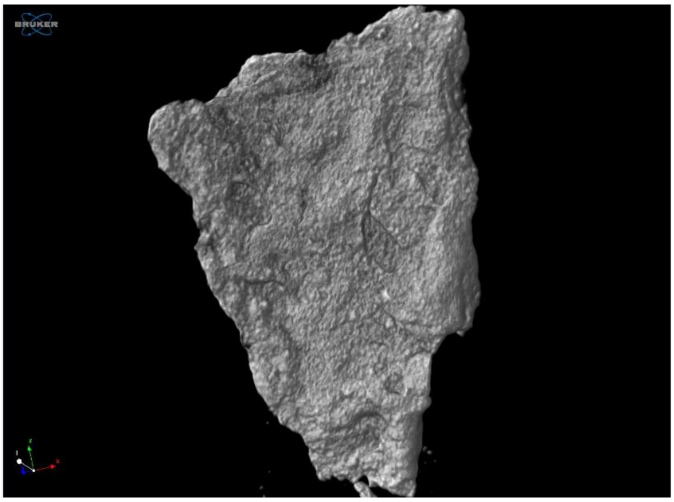


*Figure 4.11: Surface imaging of the same mix.*

The surface was not smooth as the mix was not homogeneous in nature and a crack was observed at the middle top of the sample, it was developed as sample was broken irregularly to perform Micro CT. Pores are visible on zooming the image but the alignment of the particles was not determined by using optical microscopic images of the mix.

These Micro CT results showed that this technique was useful to verify the homogeneity and porosity of the printed material. The future effort will be to achieve homogeneous material for printing of the mortar.

# 5 Conclusion and Future Developments

## 5.1 Conclusion

The main objective of this internship was to achieve a cementitious mix for 3D printing by incorporating stone sludge which will influence the construction industry, cost, environment and labours. 3D printing by extrusion process is simple and can be used for structural and architectural production with good results and economic. This technique allows complex design, prefabrication of houses, offices, structural components and utilisation of waste materials for sustainable construction.

Six mixes with different proportions of stone sludge and admixtures were used to identify the cementitious composition for extrusion based printing. A hollow cube of 21 layers of dimension 200 x 200 mm was printed successfully. The mix composition with 2:1 cement : stone sludge with Sika control 40 admixture showed excellent flowability, extrudability, shape retention, buildability and open time compared to other mixes. Sika control 40 allowed the mix to be plastic to improve the bonding with layers, less viscous to be stable and to retain the shape with acceptable water cement ratio. Hence Sika control 40 gave best performance compared to Frioplast and Plastiment mixes. Percentage of waste and their grain size in the mix influenced the water-cement ratio, strength development and printability. Extrudability was directly proportional to the flowability of the mix and buildability depends on the stiffness and early age strength development, but extrudability was inversely proportional to buildability. Printability was the balance between extrudability and buildability.

Conventional mortar showed the faster development of early age strength properties than printed mortar. But printed mortar had satisfactory strength properties at prolonged age. 3D printing is a new way to solve few problems of conventional construction, cost, waste and time but it can’t replace conventional construction as it is facing several challenges yet. Challenges such as scaling of the components in vertical directions, material properties, strength and trust factor play a vital role.

The internship concludes that stone waste from industries can be incorporated while printing and the mix achieved showed a satisfactory result in both strength and possess printing properties.

## 5.2 Future Developments

The plan for future study is to develop the cube and cylinder of a standard size to test and compare to casted ones. The main idea is to scale up the components vertically to study the behaviour under stress, load, and temperatures and to find a suitable method to carry out the curing of samples. Some improvement on the equipment is needed so that large scale printing can be with ease. Incorporating more wastes such as cork, eucalyptus ash and aluminium polish waste is also a future development to test the printable properties of these materials and improving the performance of the mix by adding fibers. Another future development is conducting a calorimetric study to understand the heat of hydration in the fresh state and its influence on the printing properties.

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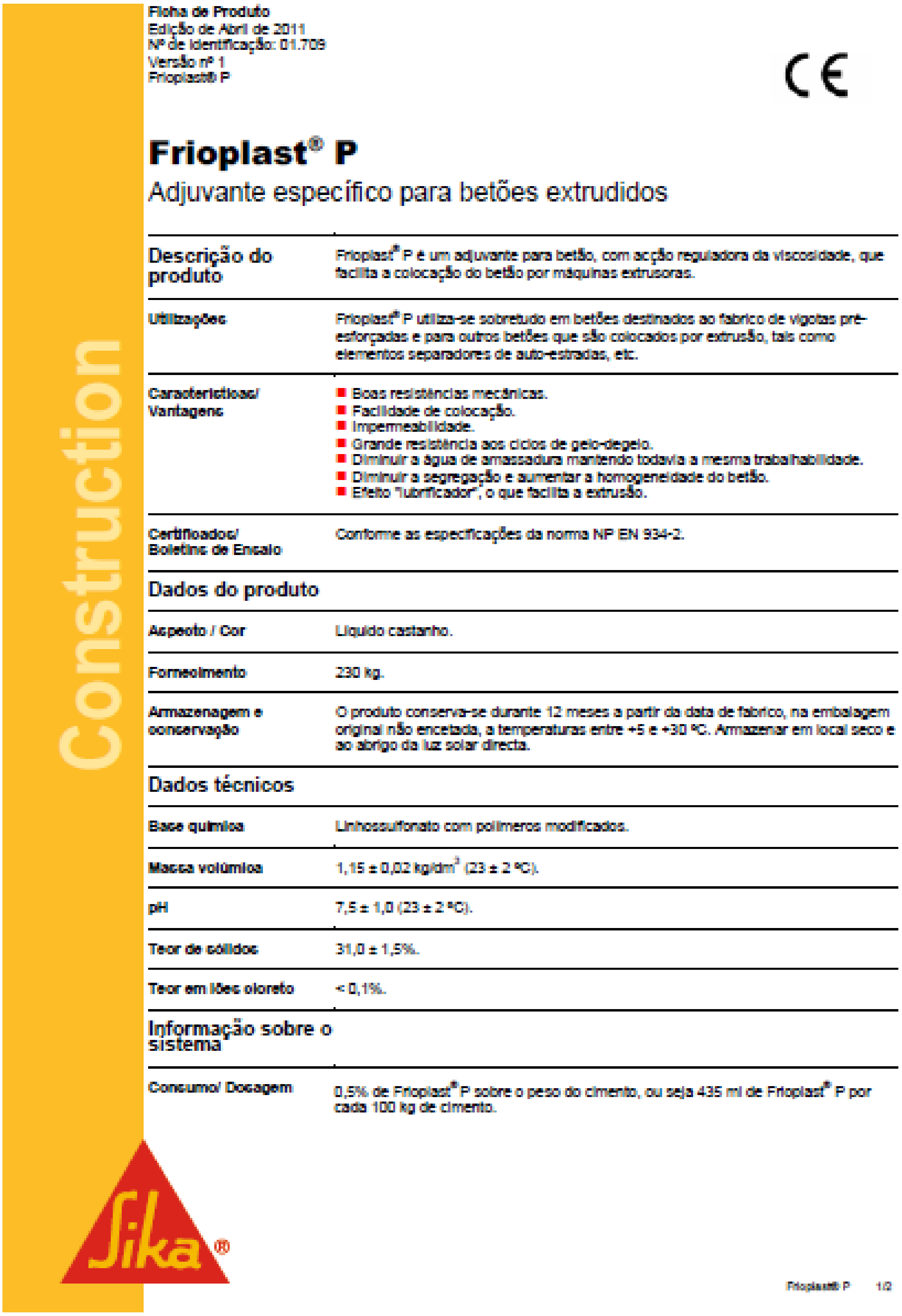
# Appendices



Ficha de Produto
Edição de Abril de 2011
Nº de identificação: 01.709
Versão nº 1
Frioplast® P

## Frioplast® P

Adjuvante específico para betões extrudidos

| | |
|---|---|
| **Descrição do produto** | Frioplast® P é um adjuvante para betão, com acção reguladora da viscosidade, que facilita a colocação do betão por máquinas extrusoras. |
| **Utilizações** | Frioplast® P utiliza-se sobretudo em betões destinados ao fabrico de vigotas pré-esforçadas e para outros betões que são colocados por extrusão, tais como elementos separadores de auto-estradas, etc. |
| **Características/ Vantagens** | ■ Boas resistências mecânicas.<br>■ Facilidade de colocação.<br>■ Impermeabilidade.<br>■ Grande resistência aos ciclos de gelo-degelo.<br>■ Diminuir a água de amassadura mantendo todavia a mesma trabalhabilidade.<br>■ Diminuir a segregação e aumentar a homogeneidade do betão.<br>■ Efeito "lubrificador", o que facilita a extrusão. |
| **Certificados/ Boletins de Ensaio** | Conforme as especificações da norma NP EN 934-2. |

### Dados do produto

| | |
|---|---|
| **Aspecto / Cor** | Líquido castanho. |
| **Fornecimento** | 230 kg. |
| **Armazenagem e conservação** | O produto conserva-se durante 12 meses a partir da data de fabrico, na embalagem original não encetada, a temperaturas entre +5 e +30 ºC. Armazenar em local seco e ao abrigo da luz solar directa. |

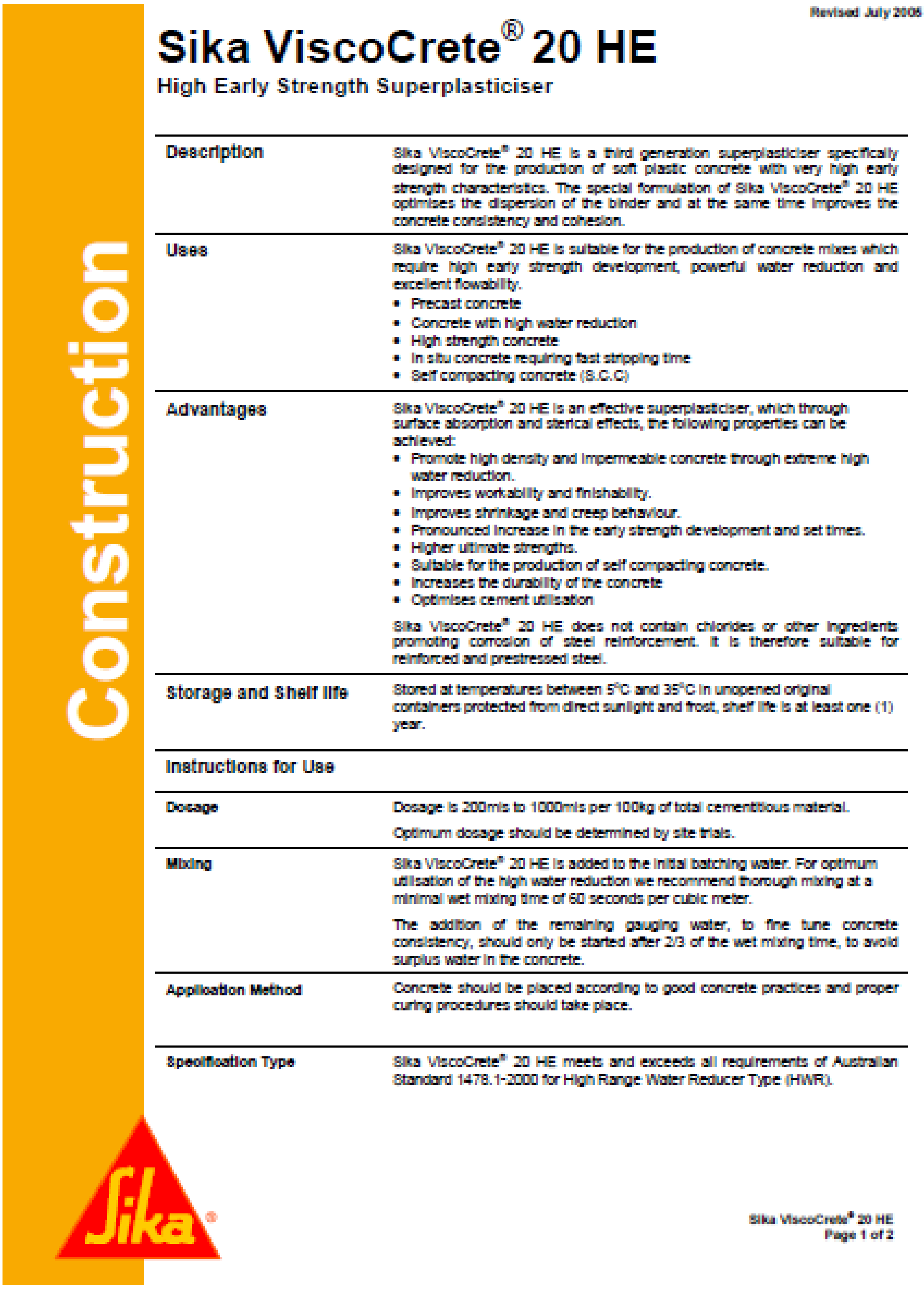
### Dados técnicos

| | |
|---|---|
| **Base química** | Linhossulfonato com polímeros modificados. |
| **Massa volúmica** | 1,15 ± 0,02 kg/dm$^3$ (23 ± 2 ºC). |
| **pH** | 7,5 ± 1,0 (23 ± 2 ºC). |
| **Teor de sólidos** | 31,0 ± 1,5%. |
| **Teor em iões cloreto** | < 0,1%. |

### Informação sobre o sistema

| | |
|---|---|
| **Consumo/ Dosagem** | 0,5% de Frioplast® P sobre o peso do cimento, ou seja 435 ml de Frioplast® P por cada 100 kg de cimento. |

Frioplast® P 1/2



Revised July 2008

Construction

# Sika ViscoCrete® 20 HE

High Early Strength Superplasticiser

## Description

Sika ViscoCrete® 20 HE is a third generation superplasticiser specifically designed for the production of soft plastic concrete with very high early strength characteristics. The special formulation of Sika ViscoCrete® 20 HE optimises the dispersion of the binder and at the same time improves the concrete consistency and cohesion.

## Uses

Sika ViscoCrete® 20 HE is suitable for the production of concrete mixes which require high early strength development, powerful water reduction and excellent flowability.

- Precast concrete
- Concrete with high water reduction
- High strength concrete
- In situ concrete requiring fast stripping time
- Self compacting concrete (S.C.C)

## Advantages

Sika ViscoCrete® 20 HE is an effective superplasticiser, which through surface absorption and sterical effects, the following properties can be achieved:

- Promote high density and impermeable concrete through extreme high water reduction.
- Improves workability and finishability.
- Improves shrinkage and creep behaviour.
- Pronounced increase in the early strength development and set times.
- Higher ultimate strengths.
- Suitable for the production of self compacting concrete.
- Increases the durability of the concrete
- Optimises cement utilisation

Sika ViscoCrete® 20 HE does not contain chlorides or other ingredients promoting corrosion of steel reinforcement. It is therefore suitable for reinforced and prestressed steel.

## Storage and Shelf life

Stored at temperatures between $5^{\circ}C$ and $35^{\circ}C$ in unopened original containers protected from direct sunlight and frost, shelf life is at least one (1) year.

## Instructions for Use

### Dosage

Dosage is 200mls to 1000mls per 100kg of total cementitious material.

Optimum dosage should be determined by site trials.

### Mixing

Sika ViscoCrete® 20 HE is added to the initial batching water. For optimum utilisation of the high water reduction we recommend thorough mixing at a minimal wet mixing time of 60 seconds per cubic meter.

The addition of the remaining gauging water, to fine tune concrete consistency, should only be started after 2/3 of the wet mixing time, to avoid surplus water in the concrete.

### Application Method

Concrete should be placed according to good concrete practices and proper curing procedures should take place.

### Specification Type

Sika ViscoCrete® 20 HE meets and exceeds all requirements of Australian Standard 1478.1-2000 for High Range Water Reducer Type (HWR).

Sika ViscoCrete® 20 HE
Page 1 of 2

**Ficha de Produto**
Edição de novembro de 2017
Nº de identificação: xx.xxx
Versão nº 1
Sikafiber® ProMacro 25

# Sikafiber® ProMacro 25

## Macrofibras sintéticas para o reforço estrutural de betões

### Descrição do produto

Macrofibras sintéticas para o reforço estrutural de betões. Promove o aumento das resistências à flexão e absorção de energia.

**Utilizações**

As fibras são adicionadas ao betão para melhorar as seguintes características:
- Resistência à fissuração.
- Resistência ao impacto.
- Resistência à flexo-tracção.
- Resistência à abrasão.
- Resistência a ataques químicos.
- Aumenta a capacidade de absorção de energia.

Utilização em:
- Pavimentos em betão.
- Prefabricação.
- Reparações parciais em betão.
- Em geral, para situações nas quais se pretendam aumentar as resistências à tracção, ao impacto e a capacidade de absorção de energia.

**Características/ Vantagens**

A adição destas fibras ao betão ou argamassa origina as seguintes vantagens:
- Aumento da absorção de energia e a resistência à tracção
- Não são afectadas por processos de corrosão ou oxidação.
- Melhoram a resistência ao impacto e à abrasão.
- Aumentam a impermeabilidade.
- Reduzem o risco de desagregação do betão.
- Melhoram a resistência à tracção.
- Perfeita dispersão no betão.
- Melhoram consideravelmente a resistência passiva ao fogo, reduzindo a delaminação do betão.
- Reduzem o desgaste nos equipamentos de fabrico e betonagem.

### Dados do produto

**Fornecimento**

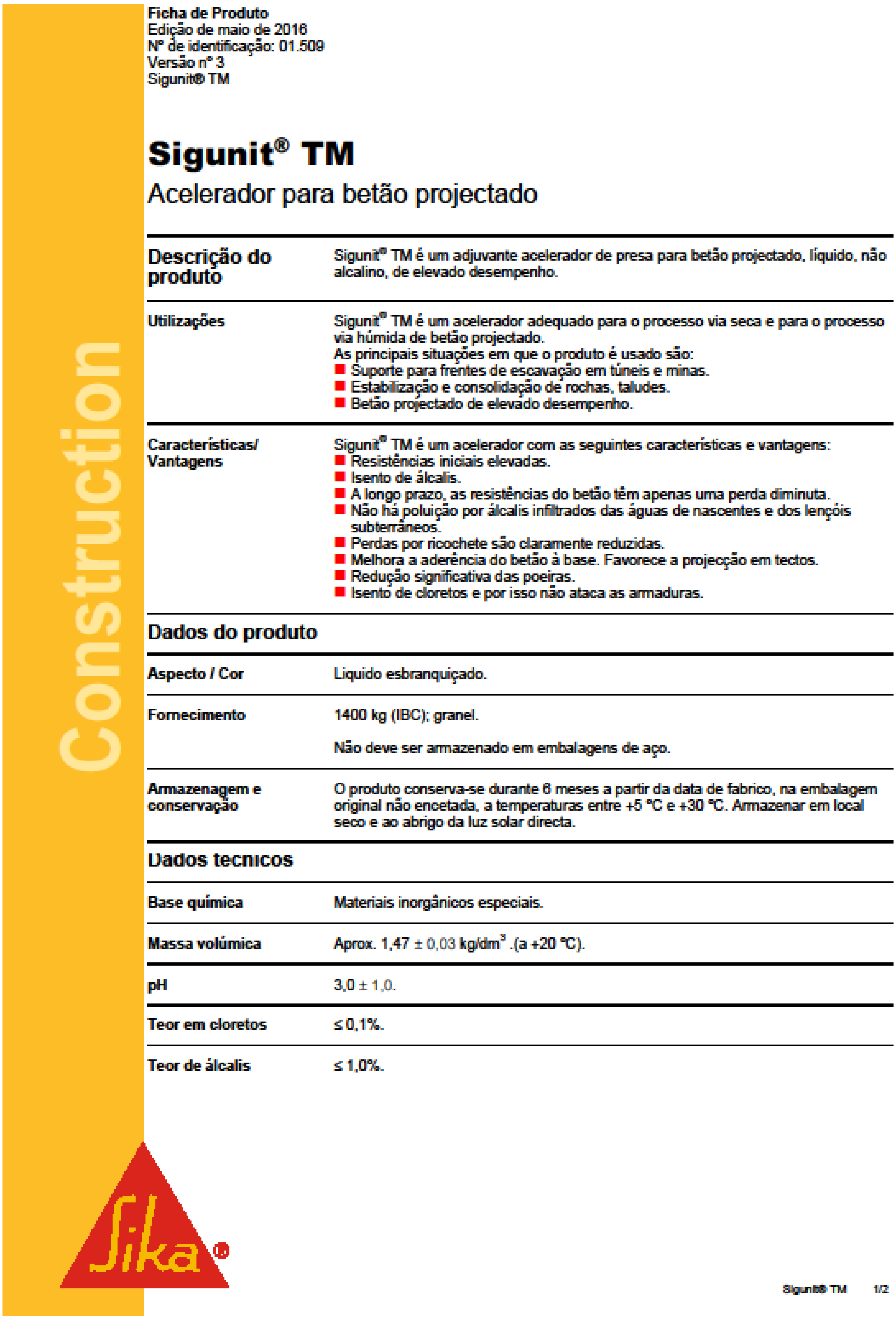
- A verificar.

**Armazenagem e conservação**

Armazenar em local seco e ao abrigo da luz solar directa. Conserva-se por tempo ilimitado.

### Dados técnicos

| | |
|---|---|
| **Base química** | Poliolefinas. |
| **Massa volúmica** | 0,91 kg/dm$^3$ (a +20 ºC). |
| **Cor** | Branco. |
| **Diâmetro equivalente** | 0,51 mm aprox. |



**Ficha de Produto**
Edição de maio de 2016
Nº de identificação: 01.509
Versão nº 3
Sigunit® TM

# Sigunit® TM

## Acelerador para betão projectado

| | |
|---|---|
| **Descrição do produto** | Sigunit® TM é um adjuvante acelerador de presa para betão projectado, líquido, não alcalino, de elevado desempenho. |
| **Utilizações** | Sigunit® TM é um acelerador adequado para o processo via seca e para o processo via húmida de betão projectado.<br>As principais situações em que o produto é usado são:<br>■ Suporte para frentes de escavação em túneis e minas.<br>■ Estabilização e consolidação de rochas, taludes.<br>■ Betão projectado de elevado desempenho. |
| **Características/ Vantagens** | Sigunit® TM é um acelerador com as seguintes características e vantagens:<br>■ Resistências iniciais elevadas.<br>■ Isento de álcalis.<br>■ A longo prazo, as resistências do betão têm apenas uma perda diminuta.<br>■ Não há poluição por álcalis infiltrados das águas de nascentes e dos lençóis subterrâneos.<br>■ Perdas por ricochete são claramente reduzidas.<br>■ Melhora a aderência do betão à base. Favorece a projecção em tectos.<br>■ Redução significativa das poeiras.<br>■ Isento de cloretos e por isso não ataca as armaduras. |

## Dados do produto

| | |
|---|---|
| **Aspecto / Cor** | Liquido esbranquiçado. |
| **Fornecimento** | 1400 kg (IBC); granel.<br>Não deve ser armazenado em embalagens de aço. |
| **Armazenagem e conservação** | O produto conserva-se durante 6 meses a partir da data de fabrico, na embalagem original não encetada, a temperaturas entre +5 °C e +30 °C. Armazenar em local seco e ao abrigo da luz solar directa. |

## Dados tecnicos

| | |
|---|---|
| **Base química** | Materiais inorgânicos especiais. |
| **Massa volúmica** | Aprox. 1,47 ± 0,03 kg/dm$^3$ .(a +20 °C). |
| **pH** | 3,0 ± 1,0. |
| **Teor em cloretos** | ≤ 0,1%. |
| **Teor de álcalis** | ≤ 1,0%. |

Construction

**Ficha de Produto**
Edição de março de 2014
Nº de identificação: 01.714
Versão nº 3
Sika® Control®-40

# Sika® Control®-40

## Adjuvante redutor da retracção

| | |
|---|---|
| **Descrição do produto** | Sika® Control®-40 é um adjuvante para betão redutor da retracção de secagem. Não apresenta efeitos secundários indesejáveis. |
| **Utilizações** | Sika® Control®-40 é utilizado especialmente na produção de betão de alta qualidade, quando se requer uma grande redução da retracção de secagem, aumentando desta forma a durabilidade. Sika® Control®-40 é utilizado nas obras que devem satisfazer exigências rigorosas quanto à limitação da abertura máxima das fissuras. |
| **Características/ Vantagens** | 🟥 Aumenta a coesão no volume dos poros, reduzindo a contracção quando ocorre a perda de água.<br>🟥 Reduz a retracção em cerca de 40%, dependendo do betão.<br>🟥 Não influencia as restantes propriedades do betão.<br>🟥 Melhora a impermeabilidade à água.<br>🟥 Não contém cloretos, nem outras substâncias agressivas para o betão e para as armaduras. |

## Dados do produto

| | |
|---|---|
| **Aspecto / Cor** | Líquido avermelhado, sendo possível uma ligeira descoloração ao longo do tempo, sem influência no desempenho do produto. |
| **Fornecimento** | 200 kg (200 l) e 1000 kg (1 m$^3$). |
| **Armazenagem e conservação** | O produto conserva-se durante 24 meses a partir da data de fabrico, na embalagem original não encetada, a temperaturas entre +5 °C e +30 °C. Armazenar em local seco e ao abrigo da luz solar directa. |

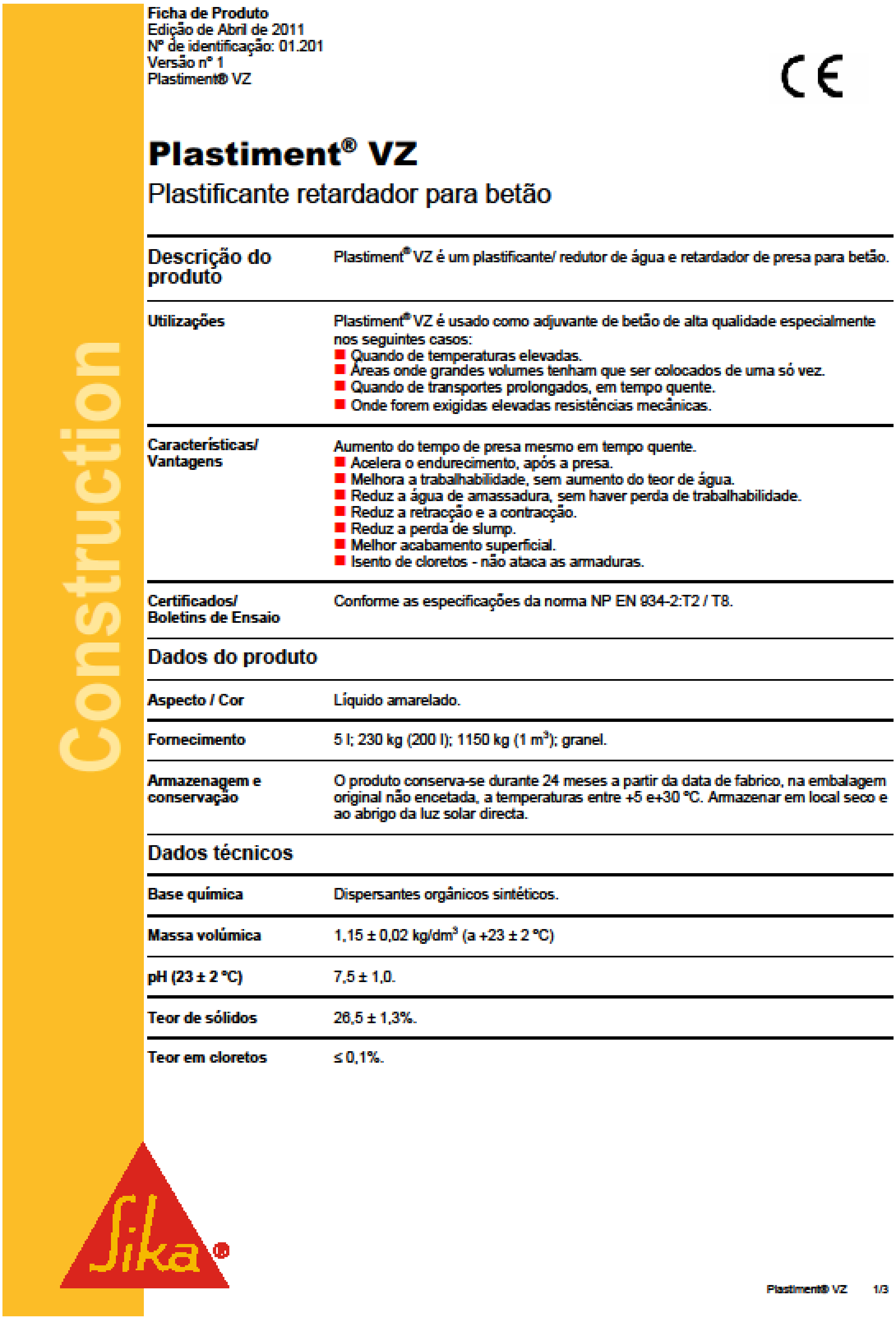
## Dados técnicos

| | |
|---|---|
| **Base química** | Alquil-éteres. |
| **Massa volúmica** | 1,00 ± 0,02 kg/dm$^3$ . |
| **pH (23 ± 2 °C)** | 11,5 ± 1,0. |
| **Teor em cloretos** | ≤ 0,1%. |

## Informação sobre o sistema

### Pormenores de aplicação

| | |
|---|---|
| **Consumo/ Dosagem** | Entre 0,5% e 2% sobre o peso do cimento. |



Construction

**Ficha de Produto**
Edição de Abril de 2011
Nº de identificação: 01.201
Versão nº 1
Plastiment® VZ

CE

# Plastiment® VZ

## Plastificante retardador para betão

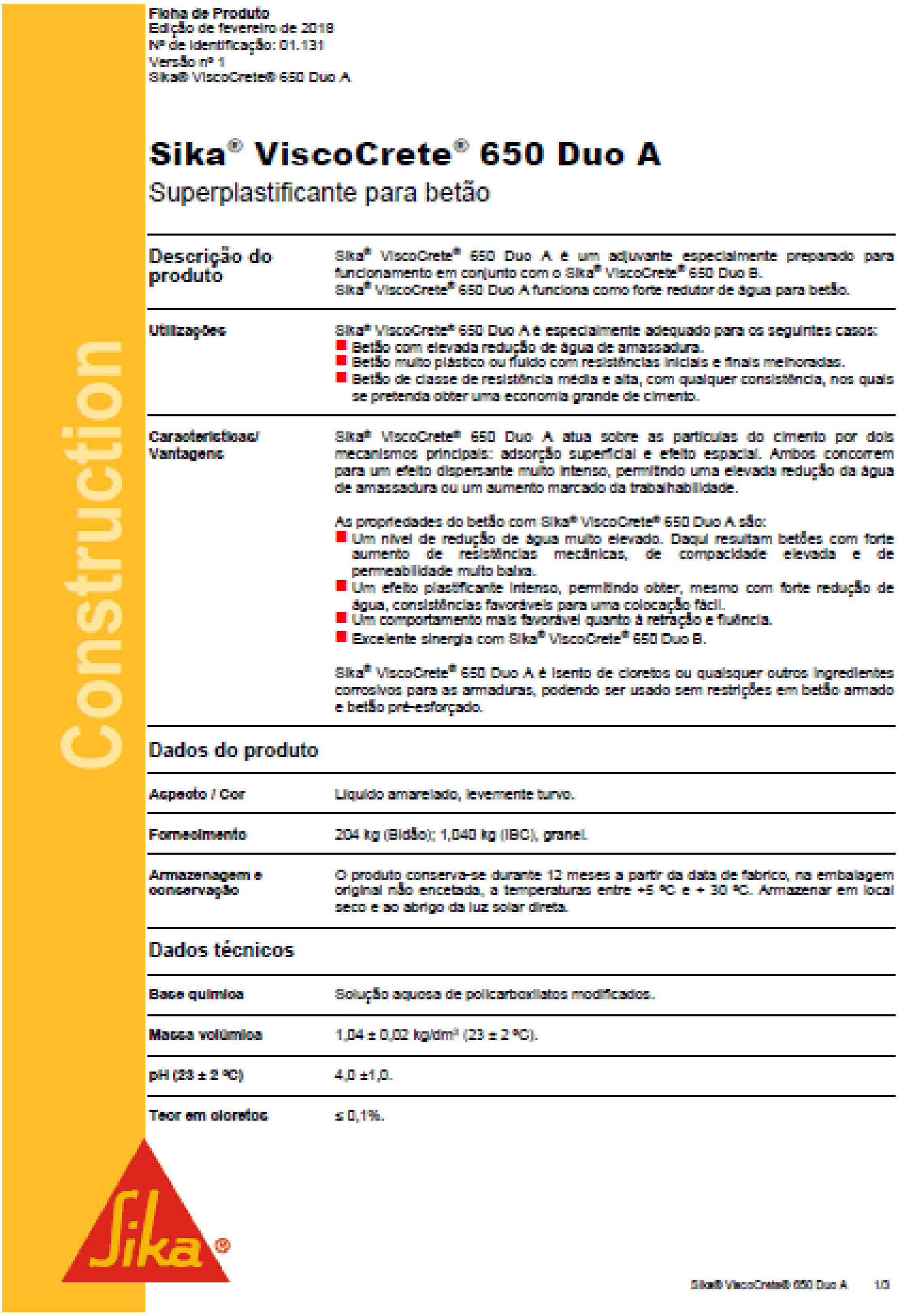
| | |
|---|---|
| **Descrição do produto** | Plastiment® VZ é um plastificante/ redutor de água e retardador de presa para betão. |
| **Utilizações** | Plastiment® VZ é usado como adjuvante de betão de alta qualidade especialmente nos seguintes casos:<br>■ Quando de temperaturas elevadas.<br>■ Áreas onde grandes volumes tenham que ser colocados de uma só vez.<br>■ Quando de transportes prolongados, em tempo quente.<br>■ Onde forem exigidas elevadas resistências mecânicas. |
| **Características/ Vantagens** | Aumento do tempo de presa mesmo em tempo quente.<br>■ Acelera o endurecimento, após a presa.<br>■ Melhora a trabalhabilidade, sem aumento do teor de água.<br>■ Reduz a água de amassadura, sem haver perda de trabalhabilidade.<br>■ Reduz a retracção e a contracção.<br>■ Reduz a perda de slump.<br>■ Melhor acabamento superficial.<br>■ Isento de cloretos - não ataca as armaduras. |
| **Certificados/ Boletins de Ensaio** | Conforme as especificações da norma NP EN 934-2:T2 / T8. |

## Dados do produto

| | |
|---|---|
| **Aspecto / Cor** | Líquido amarelado. |
| **Fornecimento** | 5 l; 230 kg (200 l); 1150 kg (1 m$^3$); granel. |
| **Armazenagem e conservação** | O produto conserva-se durante 24 meses a partir da data de fabrico, na embalagem original não encetada, a temperaturas entre +5 e+30 °C. Armazenar em local seco e ao abrigo da luz solar directa. |

## Dados técnicos

| | |
|---|---|
| **Base química** | Dispersantes orgânicos sintéticos. |
| **Massa volúmica** | 1,15 ± 0,02 kg/dm$^3$ (a +23 ± 2 °C) |
| **pH (23 ± 2 °C)** | 7,5 ± 1,0. |
| **Teor de sólidos** | 26,5 ± 1,3%. |
| **Teor em cloretos** | ≤ 0,1%. |



**Ficha de Produto**
Edição de fevereiro de 2018
Nº de Identificação: 01.131
Versão nº 1
Sika® ViscoCrete® 650 Duo A

Construction

# Sika® ViscoCrete® 650 Duo A

Superplastificante para betão

| | |
|---|---|
| **Descrição do produto** | Sika® ViscoCrete® 650 Duo A é um adjuvante especialmente preparado para funcionamento em conjunto com o Sika® ViscoCrete® 650 Duo B.<br>Sika® ViscoCrete® 650 Duo A funciona como forte redutor de água para betão. |
| **Utilizações** | Sika® ViscoCrete® 650 Duo A é especialmente adequado para os seguintes casos:<br>🟥 Betão com elevada redução de água de amassadura.<br>🟥 Betão muito plástico ou fluido com resistências iniciais e finais melhoradas.<br>🟥 Betão de classe de resistência média e alta, com qualquer consistência, nos quais se pretenda obter uma economia grande de cimento. |
| **Características/ Vantagens** | Sika® ViscoCrete® 650 Duo A atua sobre as partículas do cimento por dois mecanismos principais: adsorção superficial e efeito espacial. Ambos concorrem para um efeito dispersante muito intenso, permitindo uma elevada redução da água de amassadura ou um aumento marcado da trabalhabilidade.<br>As propriedades do betão com Sika® ViscoCrete® 650 Duo A são:<br>🟥 Um nível de redução de água muito elevado. Daqui resultam betões com forte aumento de resistências mecânicas, de compacidade elevada e de permeabilidade muito baixa.<br>🟥 Um efeito plastificante intenso, permitindo obter, mesmo com forte redução de água, consistências favoráveis para uma colocação fácil.<br>🟥 Um comportamento mais favorável quanto à retração e fluência.<br>🟥 Excelente sinergia com Sika® ViscoCrete® 650 Duo B.<br>Sika® ViscoCrete® 650 Duo A é isento de cloretos ou quaisquer outros ingredientes corrosivos para as armaduras, podendo ser usado sem restrições em betão armado e betão pré-esforçado. |

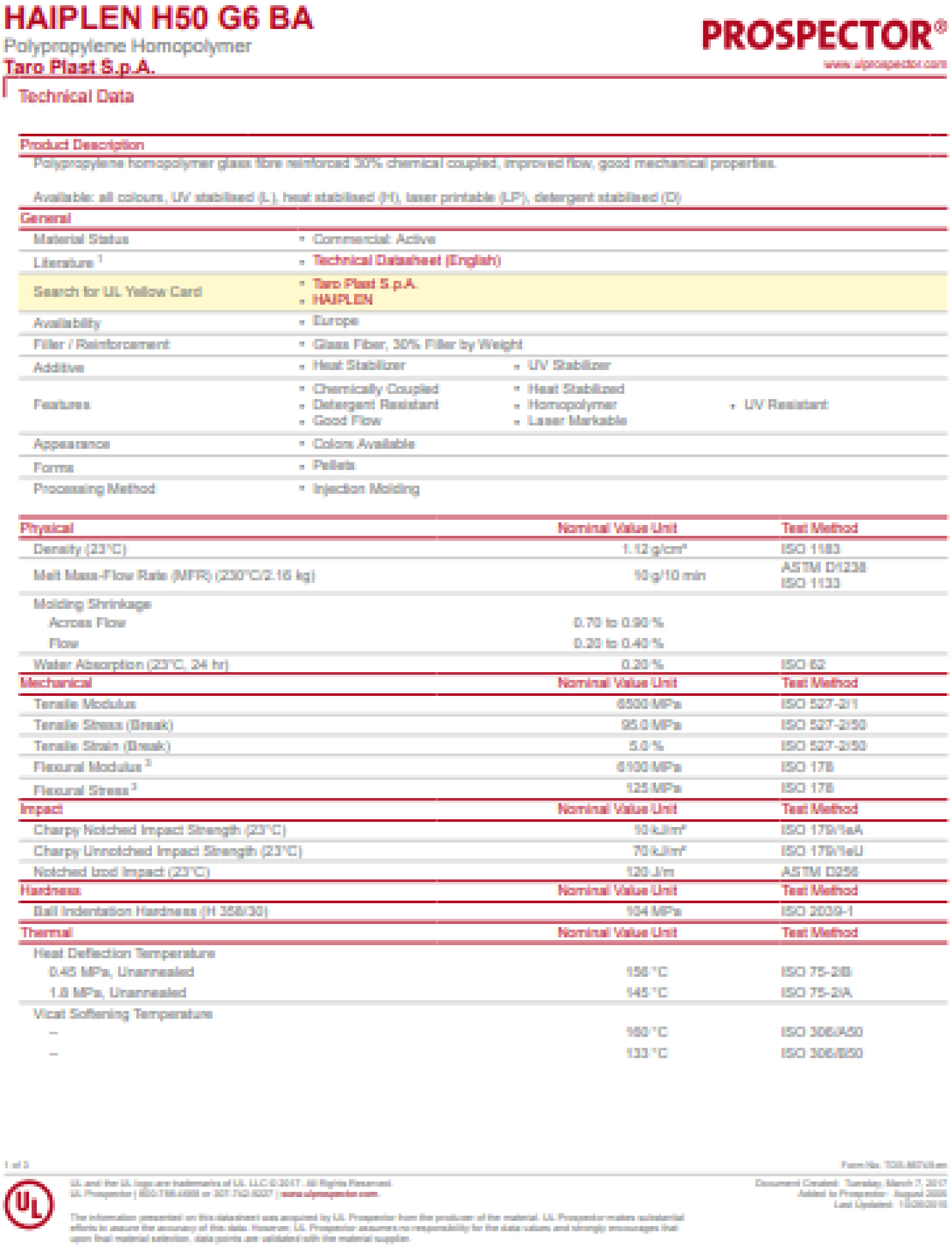
## Dados do produto

| | |
|---|---|
| **Aspecto / Cor** | Líquido amarelado, levemente turvo. |
| **Fornecimento** | 204 kg (Bidão); 1,040 kg (IBC), granel. |
| **Armazenagem e conservação** | O produto conserva-se durante 12 meses a partir da data de fabrico, na embalagem original não encetada, a temperaturas entre +5 °C e + 30 °C. Armazenar em local seco e ao abrigo da luz solar direta. |

## Dados técnicos

| | |
|---|---|
| **Base química** | Solução aquosa de policarboxilatos modificados. |
| **Massa volúmica** | 1,04 ± 0,02 kg/dm³ (23 ± 2 °C). |
| **pH (23 ± 2 °C)** | 4,0 ±1,0. |
| **Teor em cloretos** | ≤ 0,1%. |

Sika® ViscoCrete® 650 Duo A 1/3



# HAIPLEN H50 G6 BA

Polypropylene Homopolymer

**Taro Plast S.p.A.**

## Technical Data

**Product Description**

Polypropylene homopolymer glass fibre reinforced 30% chemical coupled, improved flow, good mechanical properties.

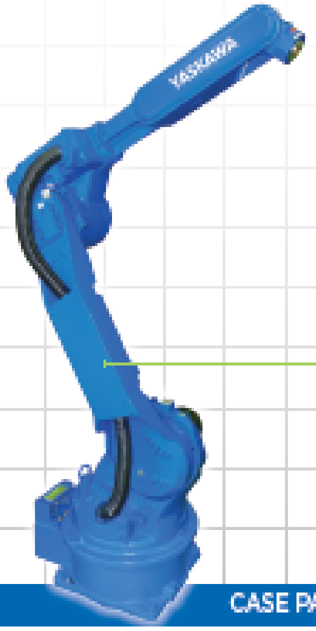
Available: all colours, UV stabilised (L), heat stabilised (H), laser printable (LP), detergent stabilised (D)

| General | | | |
|---|---|---|---|
| Material Status | • Commercial: Active | | |
| Literature [1] | • Technical Datasheet (English) | | |
| Search for UL Yellow Card | • Taro Plast S.p.A.<br>• HAIPLEN | | |
| Availability | • Europe | | |
| Filler / Reinforcement | • Glass Fiber, 30% Filler by Weight | | |
| Additive | • Heat Stabilizer | • UV Stabilizer | |
| Features | • Chemically Coupled<br>• Detergent Resistant<br>• Good Flow | • Heat Stabilized<br>• Homopolymer<br>• Laser Markable | • UV Resistant |
| Appearance | • Colors Available | | |
| Forms | • Pellets | | |
| Processing Method | • Injection Molding | | |

| Physical | Nominal Value Unit | Test Method |
|---|---|---|
| Density (23°C) | 1.12 g/cm³ | ISO 1183 |
| Melt Mass-Flow Rate (MFR) (230°C/2.16 kg) | 10 g/10 min | ASTM D1238<br>ISO 1133 |
| Molding Shrinkage | | |
| Across Flow | 0.70 to 0.90 % | |
| Flow | 0.20 to 0.40 % | |
| Water Absorption (23°C, 24 hr) | 0.20 % | ISO 62 |
| **Mechanical** | **Nominal Value Unit** | **Test Method** |
| Tensile Modulus | 6500 MPa | ISO 527-2/1 |
| Tensile Stress (Break) | 95.0 MPa | ISO 527-2/50 |
| Tensile Strain (Break) | 5.0 % | ISO 527-2/50 |
| Flexural Modulus [2] | 6100 MPa | ISO 178 |
| Flexural Stress [2] | 125 MPa | ISO 178 |
| **Impact** | **Nominal Value Unit** | **Test Method** |
| Charpy Notched Impact Strength (23°C) | 10 kJ/m² | ISO 179/1eA |
| Charpy Unnotched Impact Strength (23°C) | 70 kJ/m² | ISO 179/1eU |
| Notched Izod Impact (23°C) | 120 J/m | ASTM D256 |
| **Hardness** | **Nominal Value Unit** | **Test Method** |
| Ball Indentation Hardness (H 358/30) | 104 MPa | ISO 2039-1 |
| **Thermal** | **Nominal Value Unit** | **Test Method** |
| Heat Deflection Temperature | | |
| 0.45 MPa, Unannealed | 156 °C | ISO 75-2/B |
| 1.8 MPa, Unannealed | 145 °C | ISO 75-2/A |
| Vicat Softening Temperature | | |
| -- | 160 °C | ISO 306/A50 |
| -- | 133 °C | ISO 306/B50 |

**YASKAWA**

**FAST, POWERFUL AND VERSATILE**



# HP20F

**CASE PACKING | DISPENSING | KITTING | MACHINE TENDING**

## KEY BENEFITS

Applicable for use in a variety of applications

Performance-driven, compact design

Reliable operation with internal cables

## SPECIFICATIONS

20 kg maximum payload

3,063 mm vertical reach

1,717 mm horizontal reach

±0.06 mm repeatability

## CONTROLLERS

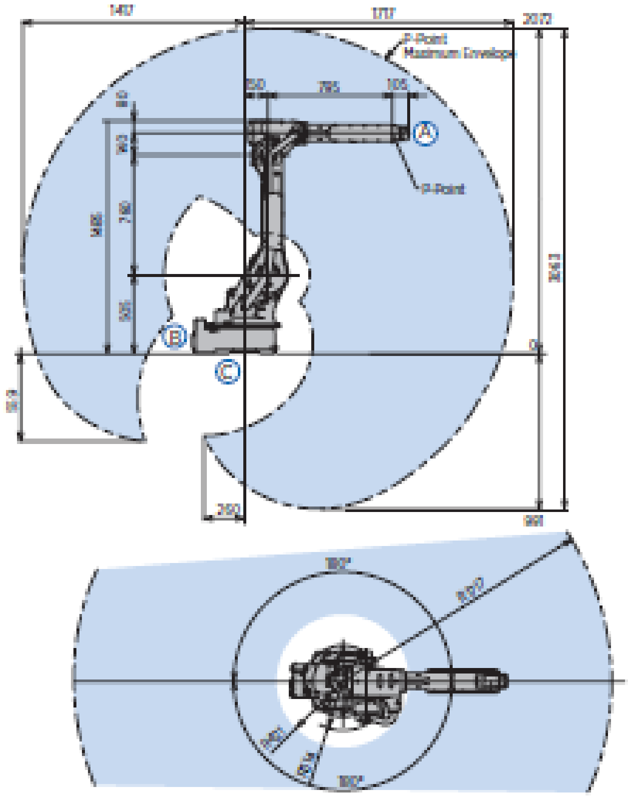
☐ DX200 ☑ FS100 ☐ MLX200

- Versatile robot with 20 kg payload capacity is ideal for many applications, such as picking, sorting, case packing, machine tending and dispensing.
- Extensive 3,063 mm vertical and 1,717 mm horizontal reach. The large work envelope extends behind the robot, allowing space for robot tool storage or maintenance.
- Fast motion profiles and high moment of inertia wrist design enables the HP20F robot to maintain throughput with heavy, unbalanced loads.
- Auxiliary equipment (up to 11 kg) can be mounted on the upper arm to simplify end-of-arm tool design.
- Internally routed airlines and cables from base to the end-of-arm tool maximizes reliability of operation.
- The HP20F can be floor-, wall- or ceiling-mounted.
- Ideally suited for use in high-density work cells with multiple robots working in close proximity.

## FS100 CONTROLLER

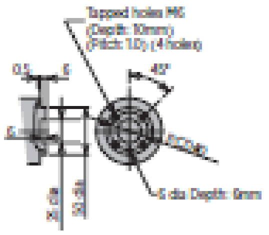
- Small, compact controller.
- 470 mm wide, 200 mm high, 420 mm deep.
- Designed for packaging and small parts handling robots with payloads of 20 kg and under.
- Compatible with integrated MotoSight 2D vision (optional).
- Improved communication speeds and functionality.
- High-speed I/O response and high-resolution timers.
- Open architecture enables software customization in widely accepted environments such as C, C++, C# and .NET.
- Uses similar programming pendant hardware as DX200 controller, providing a consistent programming interface.
- Built-in collision avoidance with multiple robots.

## HP20F ROBOT



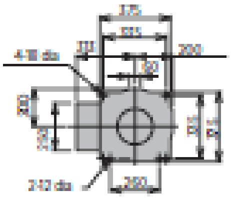
All dimensions are metric (mm) and for reference only.
Request detailed drawings for all design/engineering requirements.

### VIEW A



### VIEW B

### VIEW C



## SPECIFICATIONS

| Axes | Maximum motion range [°] | Maximum speed [°/sec.] |  | Allowable moment [N•m] | Allowable moment of inertia [kg•m²] |
|---|---|---|---|---|---|
|  |  | FS100 | MLX200 |  |  |
| S | ±180 | 197 | 157.6 | – | – |
| L | -100/+155 | 175 | 175 | – | – |
| U | -165/+255 | 205 | 205 | – | – |
| R | ±200 | 400 | 400 | 39.2 | 1.05 |
| B | -50/+230 | 400 | 400 | 39.2 | 1.05 |
| T | ±360 | 600 | 600 | 19.6 | 0.75 |

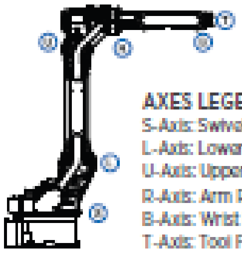
|  |  |
|---|---|
| Controlled axes | 6 |
| Maximum payload [kg] | 20 |
| Repeatability [mm] | ±0.06 |
| Horizontal reach [mm] | 1,717 |
| Vertical reach [mm] | 3,063 |
| Protection (IP rating)<br>Standard | IP54 Body; IP67 Wrist |
| Weight [kg] | 268 |
| Power requirements | 1- or 3-phase;<br>200/230 VAC at 50/60 Hz |
| Power rating [kVA] | 2.0 |

## OPTIONS

Extended length manipulator cables

MotoPick™ - scheduler and picking software integrated with vision and conveyor tracking

MotoSight™ - easy to integrate vision software



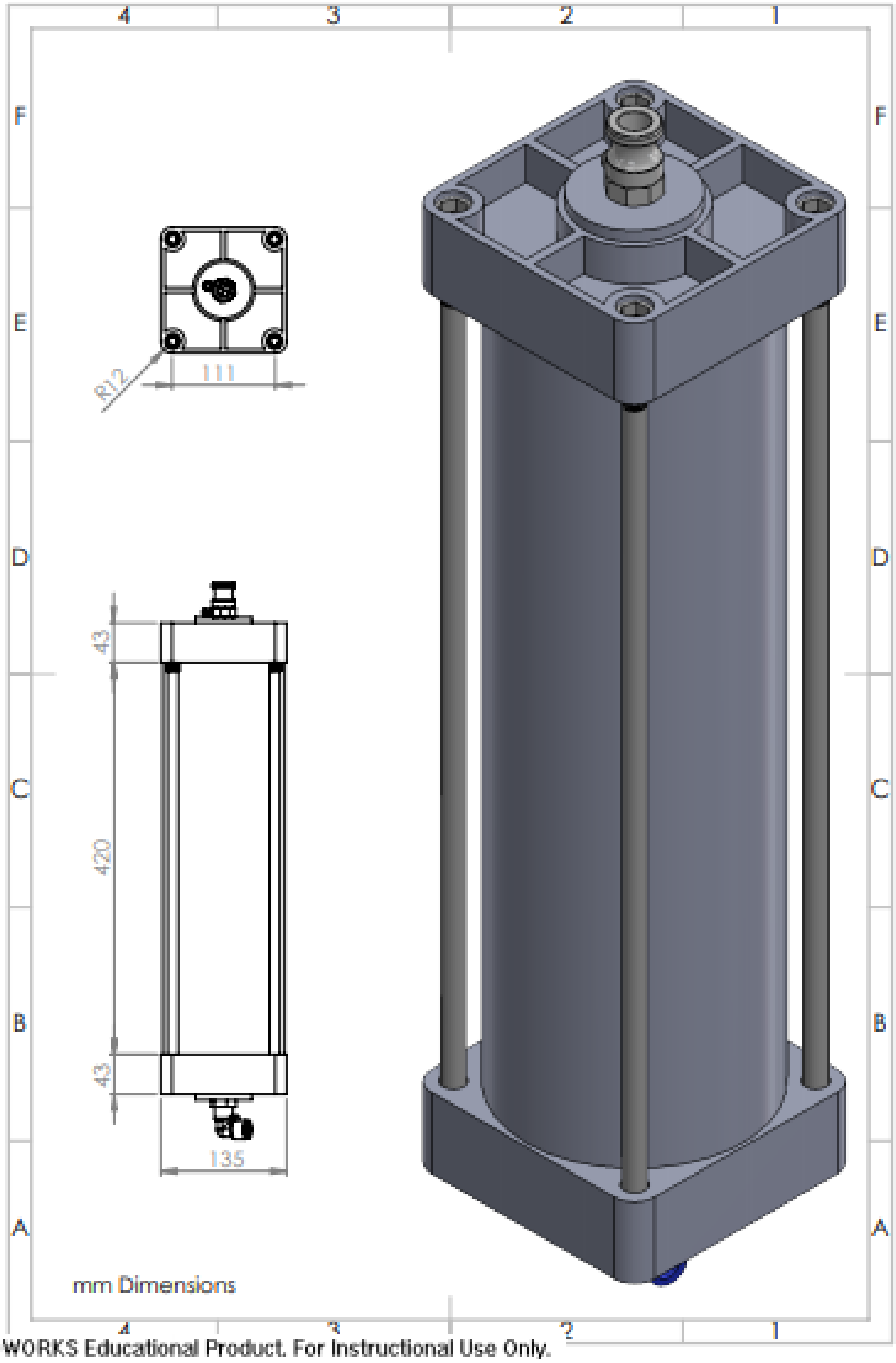
**AXES LEGEND**
S-Axis: Swivel Base
L-Axis: Lower Arm
U-Axis: Upper Arm
R-Axis: Arm Roll
B-Axis: Wrist Bend
T-Axis: Tool Flange

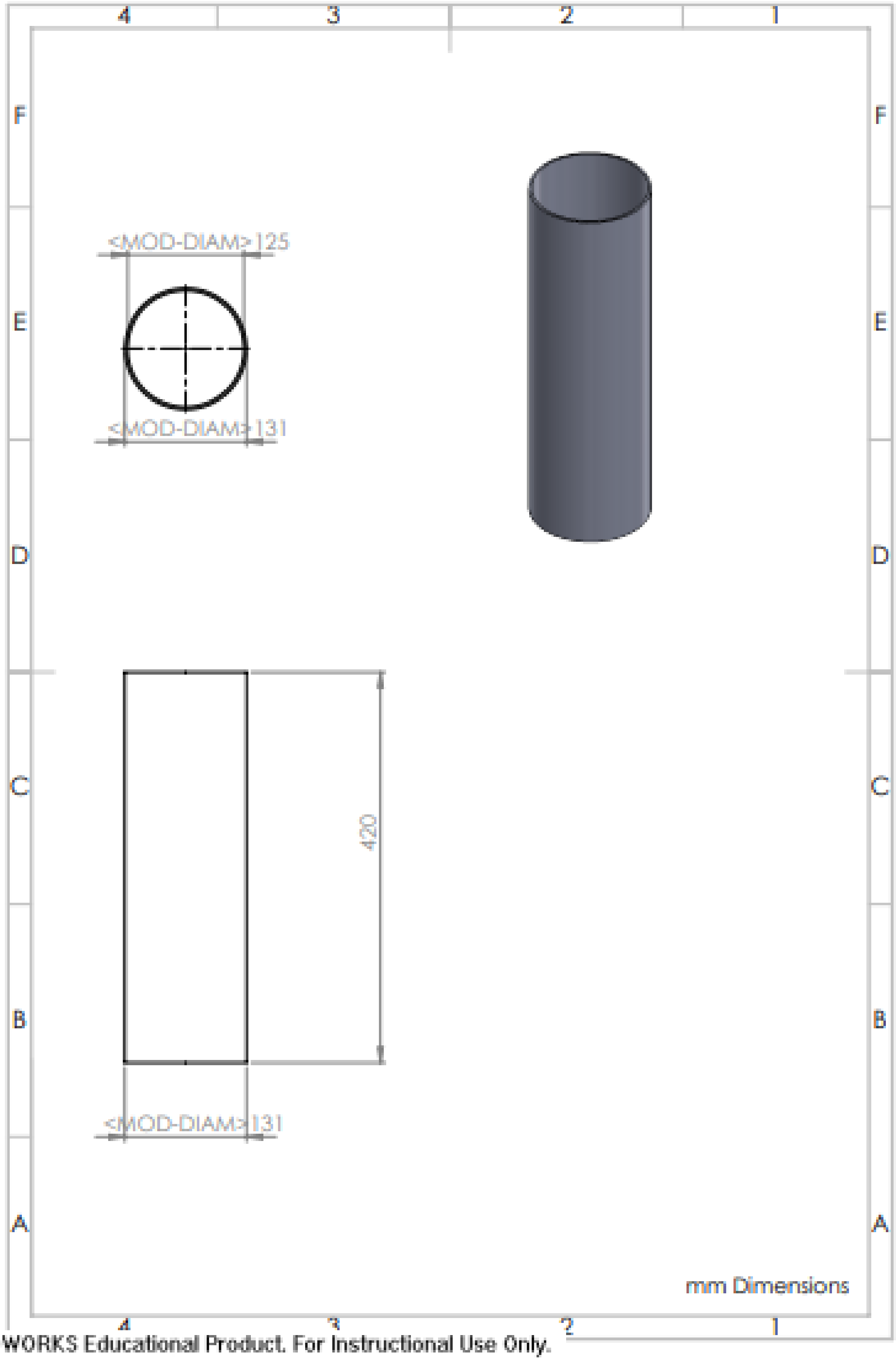
**Yaskawa America, Inc.**
**Motoman Robotics Division**

100 Automation Way
Miamisburg, OH 45342
Tel: 937.847.6200
Fax: 937.847.6277

**motoman.com**

# Technical Sheet of Cylinder




4
3
2
1
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A
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420
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mm Dimensions

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