Design and development of a Table Top Prototype of a 3D Printer for the Construction Industry

Thesis submitted for the undergraduate degree in Mechanical Engineering

at the

University of Central Punjab

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Department of Mechanical Engineering

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ABSTRACT

The success of growing industrialization throughout the world may be attributed to automated procedures that result in faster and less expensive manufacturing techniques. In several industrialized nations, the practice of mixing and pouring concrete on-site has increasingly been replaced by prefabricated building techniques during the last three decades. Advanced technology assists the construction sector by reducing labour needs and construction time, saving money, improving project quality, and lowering environmental effects. This study discusses the current state of 3D printing research applications in the construction sector and a prognosis and development strategy.

DEDICATION

"Dedication, Determination, and Hard work will feed life into your dreams."

LaDonna M. Cook

First of all, we thank ALLAH for His countless blessings and for reuniting and renovating through these ages that have allowed me to grow to this stage of learning awareness and principles.

We dedicate our thesis to our parents, siblings, supervisor, and research fellows for supporting us with love and helpfulness

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CHAPTER ONE: INTRODUCTION

1.1 Objective

Extrusion printing in particular, which is the foundational 3D printing technique, is incredibly flexible, making it feasible to adapt to a variety of materials based on certain properties that are necessary to meet the process requirements. Concrete is a strong contender for considering throughout the mix design process. The following objectives will be answered by the study after analysis:

- Development and manufacturing of a table top 3D concrete printer for the construction industry.
- Mixing design and properties of fresh concrete for high-performance printing.

1.2 Introduction

The process of making a 3D object via additive manufacturing, also designated as 3D printing, includes building up layers of material under the direction and control of a computer code to create a physical structure. Since it adds material in sequential patterns to establish the required structure opposite to subtracting or machining material to construct a component [1], 3D printing, also designated as additive manufacturing tends to create a structure from an STL file (geometrical representation) of the required structure by sequential addition of material.

The main areas in which it is in use are:

- Rapid Prototyping
- Fabrication of Specialized parts for the aerospace industry, military applications, and biomedical engineering
- Home use
- Future applications include medical, printing body parts, and construction of buildings.

Researchers worldwide have become interested in additive manufacturing over recent years because of its potential to fabricate a 3D design into an actual product. The world is using 3D printing extensively nowadays. The applications of 3D printing technology in the agriculture sector, healthcare sector, automobile industry, and aerospace are rising. It enables mass customization and the manufacturing of any type of open-source design [2].

The method of 3D printing includes using a 3D printer to create three-dimensional structures using 3D digital drawings [3]. The application of 3D printing, which has been restricted to industrial and manufacturing design before, is now expanding to sectors including construction and medical [4].

For the building and construction industries, 3D concrete printing (3DCP) is one of the computerized construction techniques that open up infinite possibilities for fabricating concrete structures with complex geometry. Due to the reduction of formwork costs, which account for 35–60% of the total cost of the concrete building, 3DCP is thought to lower construction costs. As 3DCP gains speed, numerous new developments and useful applications are frequently announced [5]. Construction will be transformed by the adoption of 3D concrete printing (3DCP), innovative technology, and computerized manufacturing methods.

When compared to the traditional construction method, 3DCP enables considerable reductions in construction wastes, cost of labor, time, and hazards related to construction.

It also allows architects the potential to create complex structures [3]. Conventional manufacturing processes, known as "Subtractive Manufacturing." Subtractive manufacturing processes include machining processes such as drilling, milling, and cutting.

This kind of procedure generates a lot of waste because in most cases, material that is removed during the process cannot be utilized in any way and is simply disposed of as scrap.

Construction 3D printing technology provides numerous avenues for the construction of complex structured buildings and can successfully resolve many problems that occur with conventional construction methods. One of the most important types of construction 3D printing techniques is with using concrete [6].

1.3 Applications

The applications of 3DCP are as follows:

- ✓ The 3DCPs are used to build houses by depositing a mix of recycled raw materials and rapid hardening cement.
- ✓ It is used in the development of the contour crafting process. Concrete was printed in layers by the 3D printer using nozzles. Thus, the inner and outer skins of the home's wall are constructed from layers of concrete. The manufacturer then either adds more concrete or an insulator to cover the space between.
- ✓ 3D concrete printers are also used for structures such as bridges, which have to withstand more stress.

1.4 Advantages of 3DCP

The advantages of 3D concrete printing are:

- ✓ Acceleration in construction speed, in comparison to conventional ways.
- ✓ Improved control over the process to avoid material wastage.
- ✓ Reduced to almost no use of forms and scaffolding of wood and steel.
- ✓ Less capital cost for construction.
- ✓ The use of 3D printing technology in construction will eliminate the need for the design of reinforcements required in normal construction and will make use of reprocessed materials/goods.
- ✓ Execution with high precision in details and also improving quality of architecture and structural strength.
- ✓ Possibility of construction of structures in narrow spaces, otherwise not possible in conventional ways.
- ✓ Possibility of fabrication(printing) of complex structures with reasonable expenditure [4].

1.5 Limitations of 3DCP

- ✓ Costly equipment and raw materials are two factors that limit 3D printing in general. It will be challenging to compete with mass production because this leads to expensive parts. Moreover, it costs more if the part is complicated and requires the use of a CAD designer to build what the customer desires. [1]
- ✓ In the computer, the desired building's three-dimensional CAD model is created, and the model is then put through a sequence of steps. To create a format for the numeric control software, a 2-d file of specific thickness is first created along a defined way, in STL format. Finally, the numerically controlled system directs the

mechanical device to print building sections layer by layer, which is then gathered to create the building.

- ✓ The concrete mixture required for 3DCP is a major constraint, as this requires a special mix of various chemicals that suit the process. The desirability of a specific mixture depends on the workability and buildability after deposition. The development of equipment is not a major issue as much research is not required in that area but the only big hurdle is the attainability of an optimal mixture.

1.6 Types of 3D Printer:

According to ASTM Standard F2792, numerous 3D printing techniques have been developed with diverse capabilities. The applications of additive manufacturing technology are expanding beyond prototyping to include a wider variety of product manufacturing [8]. The various techniques of 3D printing are as follows:

The following are the most important 3D Printer types:

i. Binder Jetting
ii. Direct Energy Deposition
iii. Material Extrusion
iv. Materials Jetting
v. Powder Bed Fusion
vi. Sheet Lamination

1.6.1 Binder Jetting:

Binder jetting is a fast manufacturing, 3D printing technique that joins powdered particles together by applying a liquid binding agent precisely to one area of the workpiece. The binder fluid is shot onto the distributed powder to form the first layer [9]. Different components of the binder jet are shown in Figure 1.1 and Figure 1.2 shows a schematic diagram of binder jet printing.

Using binder jetting we can make sand-based products on a large scale like casting patterns, cores and molds, raw-sintered goods, or comparable items could be produced. Materials available for printing through binder jetting include ceramics, polymers, sands, metals, hybrids, etc. Sand has the advantage of not requiring any further processing. Furthermore, because there is a fusion of powder particles during this process, it is easy, swift, and inexpensive. Last but certainly not least, binder jetting can print exceedingly huge items.

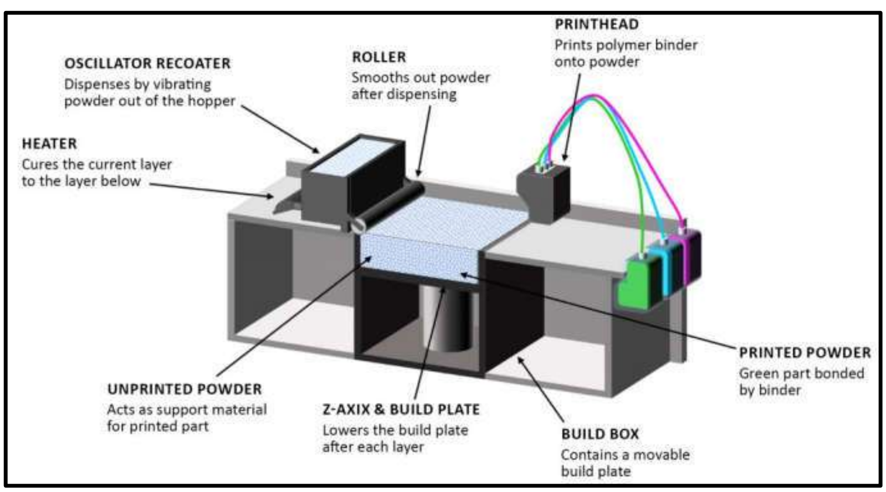


Figure 1.1: Binder Jetting 3D printing

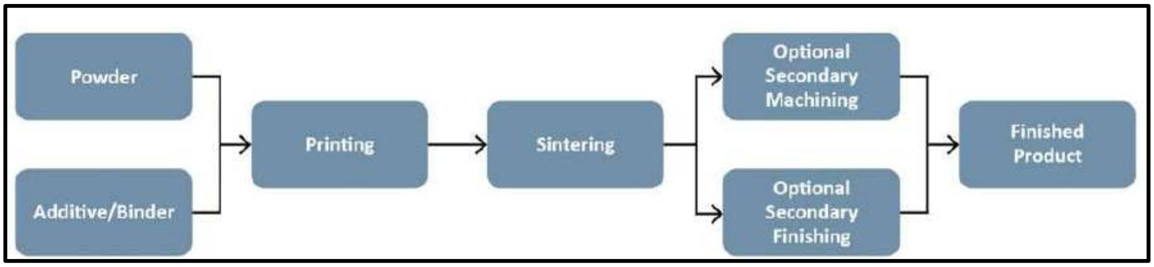


Figure 1.2: Schematic Flow Diagram of Binder Jetting Printing

1.6.2 Direct Energy Deposition:

A relatively complex technique for printing commonly deployed to fix or replace material in existing components is direct energy deposition [10]. Directed energy deposition can manufacture high-quality objects since it has great control over the grain structure. Direct energy deposition works similarly to materials extrusion, except for the fact that the nozzle can travel in any direction and is not restricted to one axis. As shown in Figure 1.3, although the process is applicable with ceramics and polymers, metals and metal-based hybrids are most typically used, either in wire form or powder form. This technology's examples include laser-engineered net shaping and laser deposition. Laser deposition technology is becoming more and more popular in manufacturing, oil and gas sectors, aerospace, and transportation since it can provide scalability and is quite diverse in functionality for a single system.

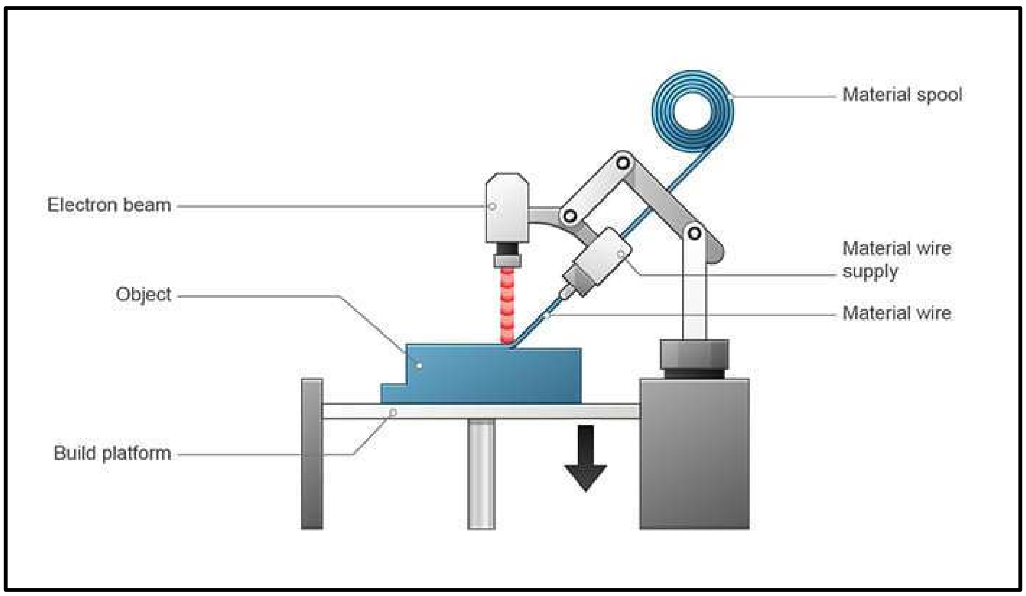


Figure 1.3: Direct Energy Deposition Printing

1.6.3 Material Extrusion:

Printing many materials and colors of plastics, food, or living cells is possible with 3D printing using extrusion-based technology [11]. This technique is extensively used and reasonably inexpensive. Additionally, this method can provide product components that are completely working. Figure 1.4, shows fused deposition modeling (FDM), the first illustration of a material extrusion system. FDM extrudes a hot thermoplastic filament to create a part layer by layer [12].

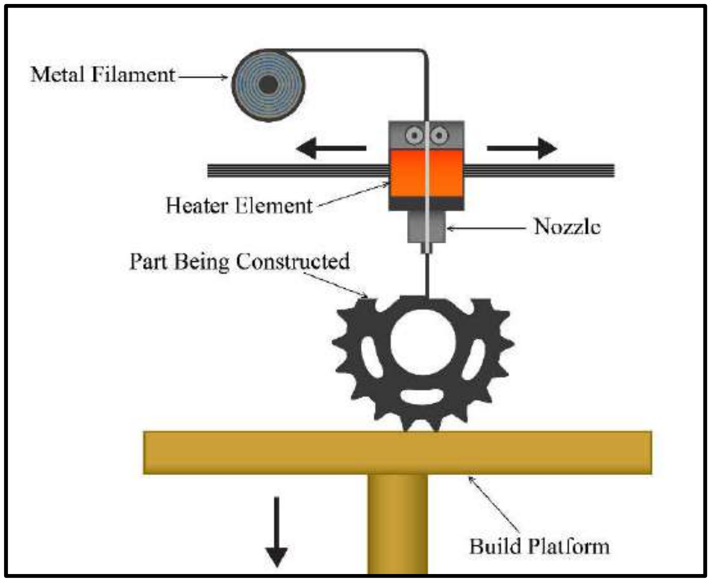


Figure 1.4: Material Extrusion Printing

1.6.4 Materials jetting:

The ASTM Standards describe material jetting as a 3D printing technique where the material is precisely placed in droplet form. As given in Figure 1.5 In material jetting, a part is built up layer by layer as a printer sprays a mist of a photosensitive chemical that solidifies when exposed to ultraviolet (UV) light. Additionally, items created with this process have great dimensional accuracy and smooth finishing. Material jetting offers a variety of materials for printing which include composites, hybrids, polymers, and ceramics [13].

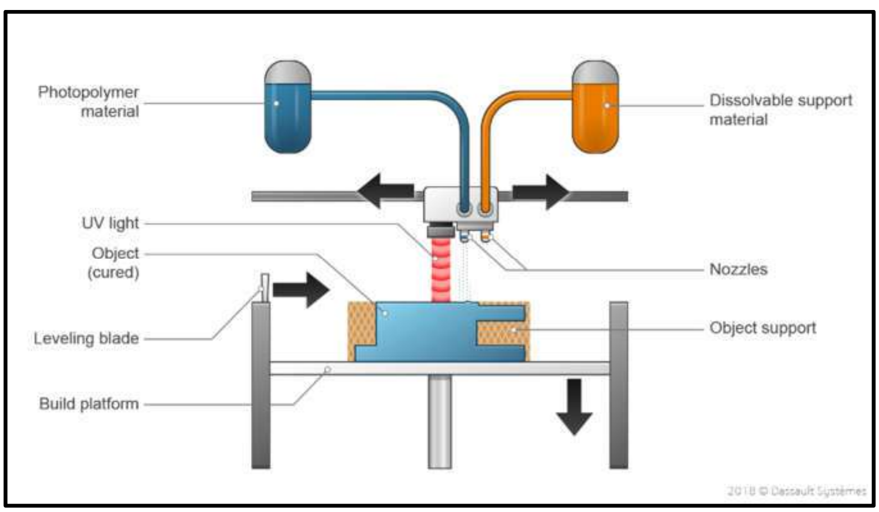


Figure 1.5: Material Jetting Printing

1.6.5 Powder bed fusion:

The powder bed fusion procedure includes electron beam melting (EBM), selective laser sintering (SLS), and selective heat sintering (SHS) printing processes. In this method, a laser or an electron beam is utilized to melt or fuse the material powder. Some of the materials used in this process are metals, ceramics, polymers, composite materials, and hybrids. Lasers are used in the most popular type of powder-based 3D printing, known as selective laser sintering (SLS) figure1.6. A 3D printing method known as SLS produces items rapidly, accurately, and with different degrees of surface finish [14].

Selective laser sintering may be used to create items made of metal, plastic, and ceramic materials. SLS produces a 3D object, using a strong laser to sinter polymer granules. A head thermal print is used in the SHS technology, another component of 3D printing, to melt the thermoplastic powder and produce 3D-printed objects. Last but not least, the material can be heated more effectively due to electron beam melting.

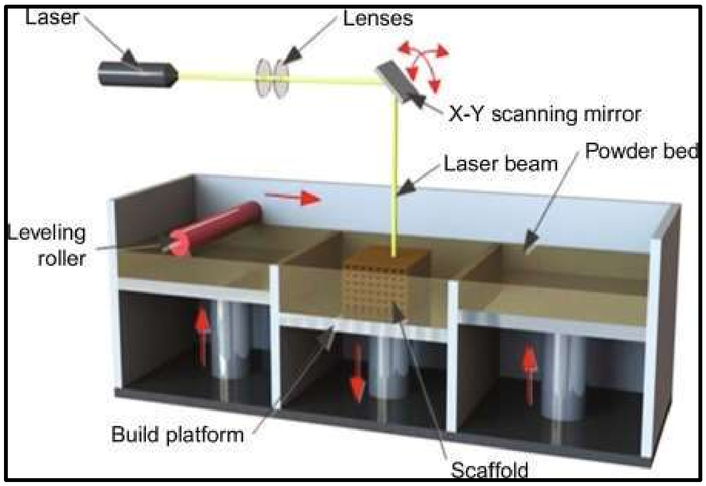


Figure 1.6: Powder Bed Fusion Printing

1.6.6 Sheet lamination:

As defined by ASTM, sheet lamination is a 3D - printing technique in which an object's component is created using a printing method in which sheets of various materials are fused. As given in Figure 1.7. Laminated object manufacturing (LOM) and ultrasonic additive manufacturing (UAM) are two examples of 3D printing technology that use this method. Full-color printing capabilities, cost, convenience of material handling, and recycling of excess material are benefits of this technology. Complex geometrical parts can be produced using laminated object manufacturing (LOM) for a cheaper cost of fabrication and shorter production time. Sound is used in a cutting-edge procedure known as ultrasonic additive manufacturing (UAM) to join layers of metal removed from a simple foil sheet [15].

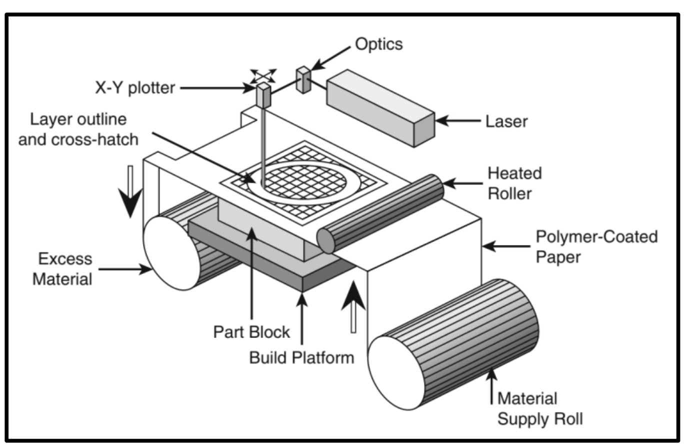


Figure 1.7: Sheet Lamination Printing

1.7 Concrete 3d Printing Technology:

Although there are numerous other 3D printing technologies for building, only the 3D concrete printing technology can be easily scaled up and can acclimatize to the customs of traditional concrete construction. Concrete 3D printing is a popular building 3D printing technology due to the support method's simplicity and speed.

1.8 3D Concrete Printing Equipment:

Three components make up the system for the 3D concrete printing setup: the frame, the operating system, and the concrete feeding system and extrusion system as the gantry system is shown in figure 1.8. Concrete extrusion and printing device movement are both managed by the operating(control) system. Concrete is mixed uniformly, which is then transported to the extrusion mechanism and extrudes the concrete via the screw.

The concrete feeding pump, the feeding pipe, the frame, the printing head, and the computer control system are only a few examples of the parts of the concrete 3D printing equipment system that are shown in figure 1.9 [16]. The concrete 3D printing system is introduced in detail, including the feeding and extrusion system, frame, and process control. Each component of the 3D concrete printing system is examined in further detail, along with its operating principle and standard structural measurements.

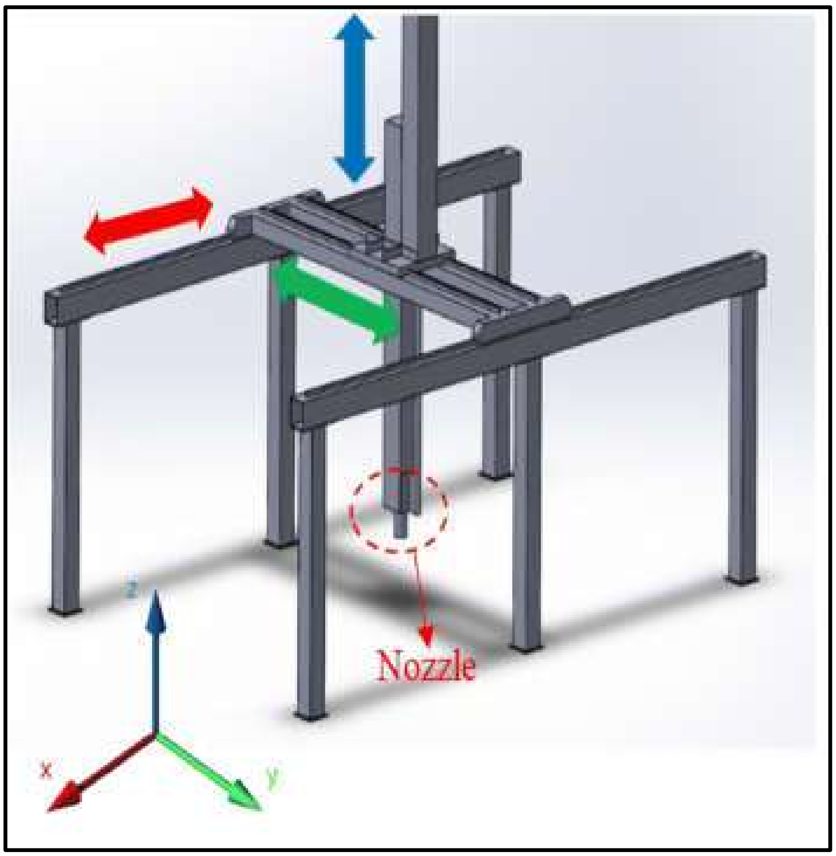


Figure 1.8:3D Printing Gantry System Schematic Diagram

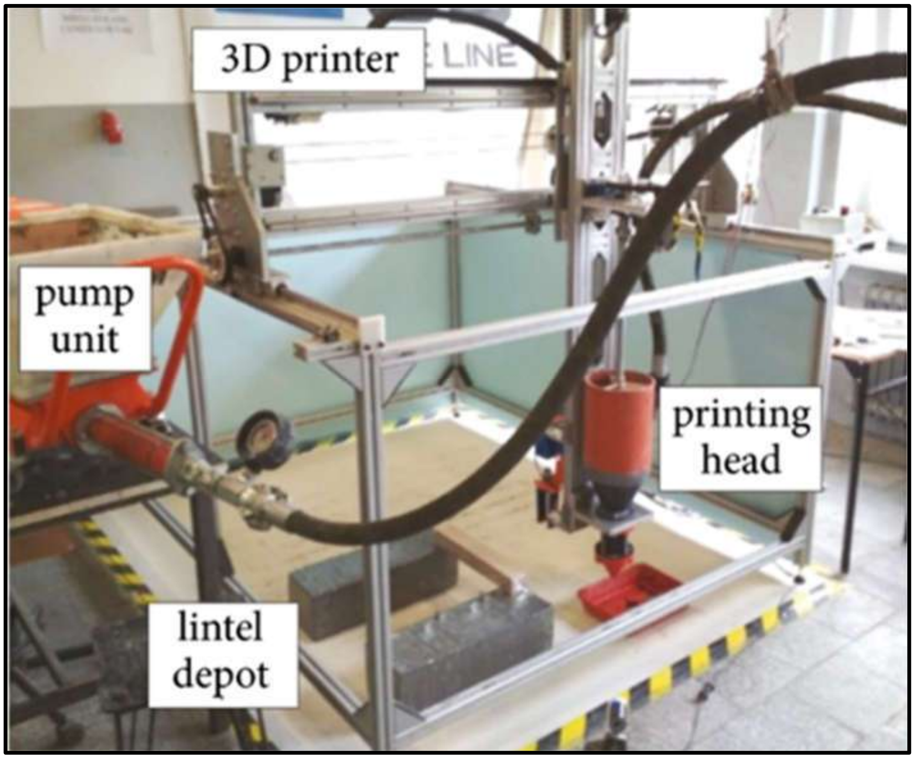


Figure 1.9: A Typical 3D Concrete Printer

1.9 Components of 3D Printer:

The components of the 3D printer are listed in figure 1.10 as follows:

i. Stepper Motor
ii. Extruding
iii. Feeding system
iv. Pipe mechanism
v. Frame
vi. Gantry system
vii. Control system
viii. Hooper system

Printing Process of the 3D concrete printer uses the stepper motor to move the print head (extrusion system) along the predetermined path, following the instructions from the 3D model and slicing software. The software controls the movement of the print head, guiding it to deposit the concrete layer by layer, building up the desired 3D structure. The concrete is extruded through the nozzle as the print head moves, and each layer is carefully deposited on top of the previous one. The stepper motor's precise movements ensure that the layers align accurately, resulting in a stable and well-defined structure. By accurately controlling the stepper motor and extrusion system, the 3D concrete printer can create complex geometries.

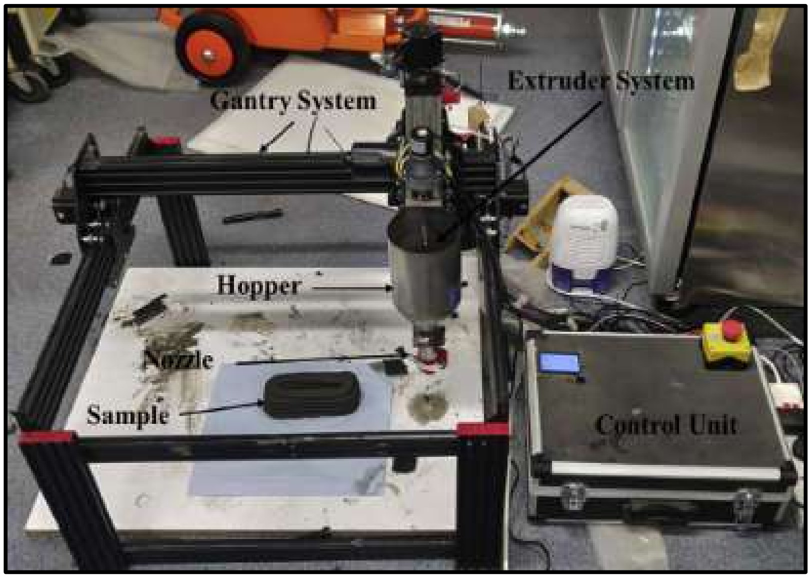


Figure 1.10: Labeled Diagram of 3D Printer Components

These are described one by one as follows:

1.9.1 Stepper Motor:

Stepper motors are DC motors with numerous coils that enable them to move in incremental steps. These coils are arranged in groupings termed 'phases'. The motor activates one phase at a time when it needs to rotate one step [17]. These motions may be highly accurate when controlled by a computer. They are ideally designed for positioning, speed control, and low-speed torque. Figure 1.10 shows a cutout model of a stepper motor with a motor.

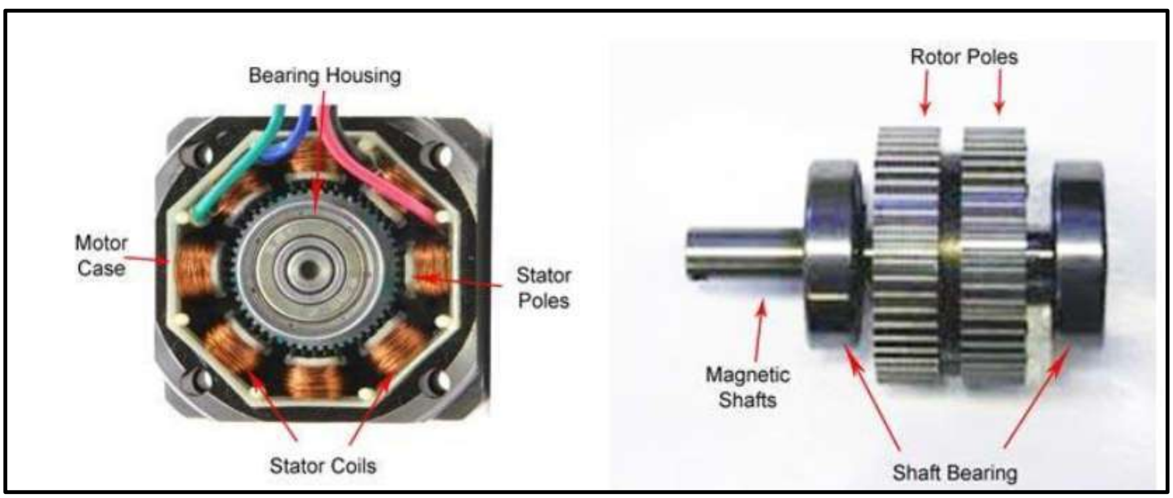


Figure 1.11: Cut-out Model of Stepper Motor with Motor

1.9.2 Extruding system:

The extrusion mechanism of a 3D printer is a critical component of the whole process. Many factors affect the extrusion of cementitious-based materials [18]. There are two types of extrusion systems:

- Screw pump type
- Direct screw type

These are described one by one as follows:

1.9.2.1 Screw Pump Type:

The rotor is covered with a tight stator made of rubber (labeled as a closed screw, as related to a straight screw), and a strong motor pushes the material out of the nozzle tip as shown in Figure 1.11. It requires great fluidity or flowability of the material for ease of pumping, resulting in a significant droop after printing and making it difficult to preserve the structural geometry as required by the printing. With nozzle tips that range from 30 mm to 60 mm and a maximum fluidity mortar, the screw pump is most frequently used in large-scale printing. The extruding process between the tightly wrapped rubber and metal screw generates a lot of heat, which accelerates cement hydration and shortens the settling time.

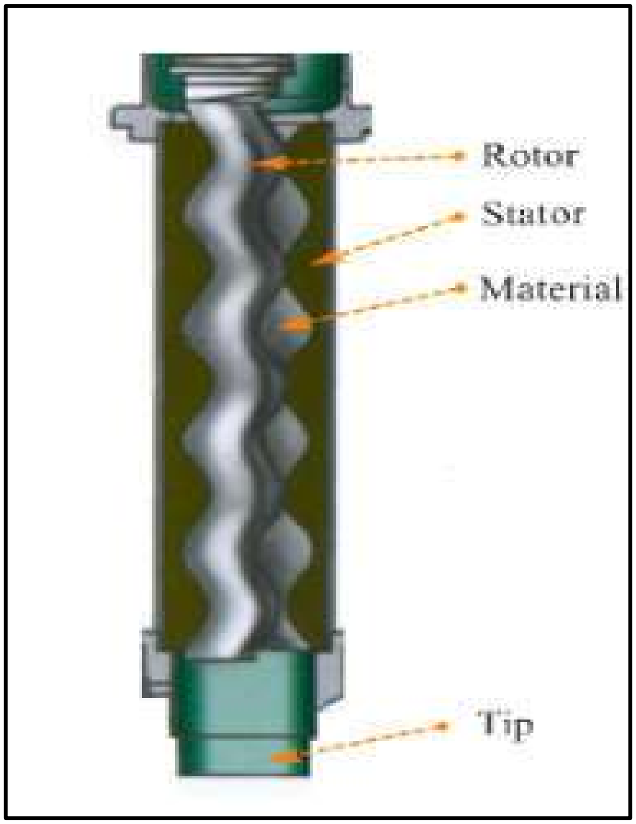


Figure 1.12: Screw Type Extrusion System

1.9.2.2 Direct Screw Type:

The material is extruded from the feed hopper to and out of the nozzle tip by an open screw (as opposed to the preceding SP's closed screw). The DS extruders are easy to use, handle, and maintain. It may be mounted on a tabletop gantry with manual feeding as shown in Figure 1.13 with labelled parts. Two DS extruders may combine two materials to provide graded outputs. The material is not exposed to high pressure in the extrusion cavity as in SP because the cavity created by the screw rod and the outside wall is not sealed [18].

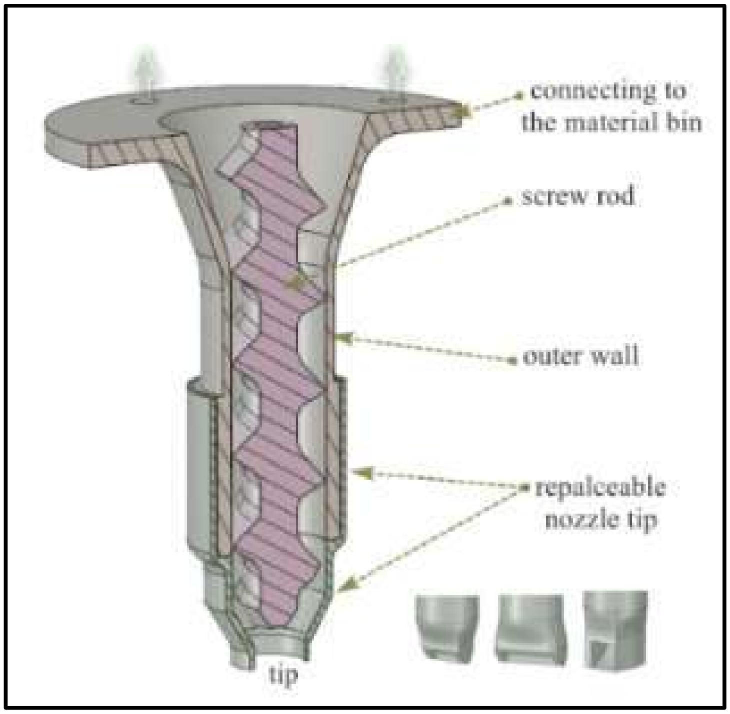


Figure 1.13: Direct Screw Type Extrusion

The nozzle mechanism is the most important. It mixes digital processes with construction materials to produce a cementitious component. It is important to quantify the extruding process. Following the nozzle motion speed or pump pressure, the material extruding speed should be freely and quantitatively changed. The DS is ideal for 3DCP research, while the SP is ideal for large-scale printing, which requires a fast extrusion speed, a strong motor, and a big nozzle tip [19].

1.9.3 Nozzle Design:

To create a good print, the size of the nozzle plays an important role in molding the material flow and influencing the buildability of the printed structure. The nozzle size may be changed depending on the created item, such as its dimension and required resolution [17]. The printed components were printed in a zigzag pattern on a path. More fine details are printed on an item when the nozzle diameter is smaller figure 1.14. However, as seen, this comes at the expense of a reduced buildability factor. A bigger nozzle, on the other hand, will generate a coarser structure but increased buildability. The 20 mm nozzle was utilized throughout this investigation to produce the highest buildability results.

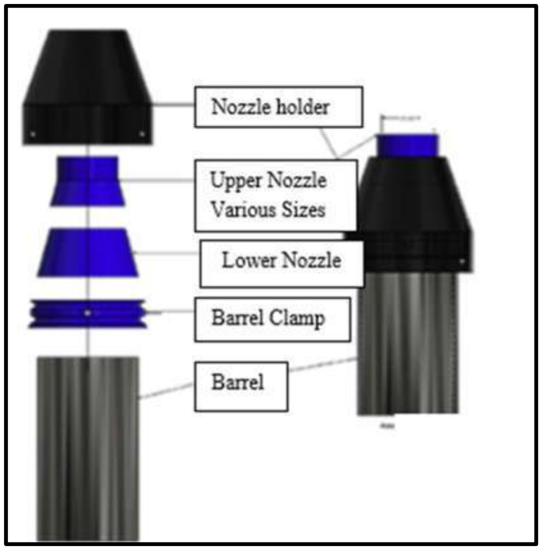


Figure 1.14: Exploded & Assembled view of Nozzle

1.9.4 Pipe Mechanism:

The difficulties between the pumping and deposition processes in 3D concrete printing can be resolved by using a twin-pipe pumping (TPP) system with a helical static mixer. In this method, a cement-based mixture (without an accelerator) and a mixture based on limestone powder (with an accelerator at its highest concentration) are brought separately and merged in the helical static mixer just before extrusion. [20].

1.9.5 Gantry System:

The gantry is the framework component of 3D printers that supports the printer head along the X/Y axis as it travels around to print the object on the build surface (similar to an arcade claw game). Its printer head is usually supported by three gantries in 3D printers [21]. Stepper motors move and track the gantries using digital pulses. By using pulses to control the motor at a very small fraction of a spin, stepper motors provide high-resolution movement. As the printer head advances along the concrete surface, the gantries support it as shown in Figure 1.15.

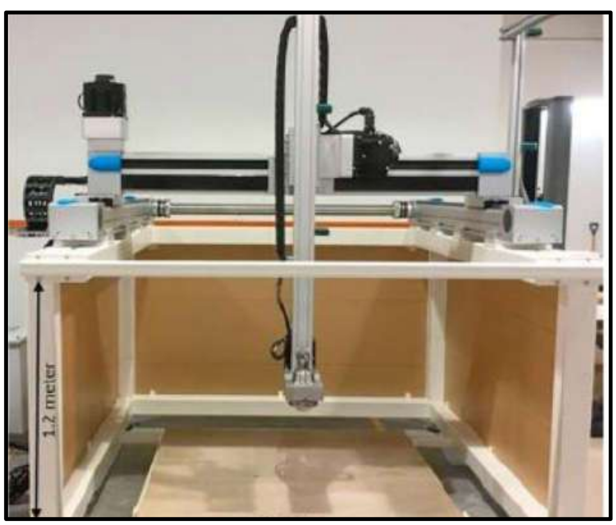


Figure 1.15: Gantry System

1.9.6 Control System:

A 3D printer for concrete structures prints in three stages: preparation for printing, material preparation, and lastly printing. During the printing preparation step, a required component for printing is developed as a 3D CAD model and converted to STL file format. The printing path of the component is derived from the file to construct a G-code file. The printer's printing preparation stage is done after the G-code is written and entered as shown in Figure 1.16. The next step is to mix concrete or cementitious ingredients for printing. The material is continuously supplied to the hopper to supply the pump and nozzle [22].

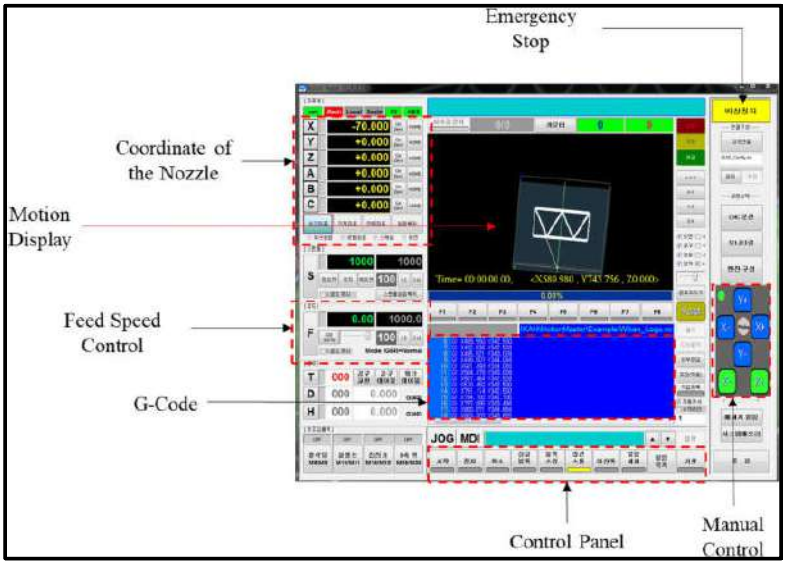


Figure 1.16: CNC Control Panel Used in 3D Concrete Printing

1.9.7 Hooper System:

To get appropriate conditions for extruding concrete-like materials, such as non-Newtonian, pseudo-plastic fluid that show shear thinning behavior, agitating equipment is necessary. Agitation enhances the pumpability of cementitious materials by decreasing the value of effective shear stress due to a reduction in internal particle friction. As a result, a scraper was created and attached to the hopper as can be seen in Figure 1.17 [23].

Figure 1.17: Hooping System for Better Pump Ability

CHAPTER TWO: LITERATURE REVIEW

2.1 3D Concrete Printer

Additive manufacturing has gained popularity in recent times due to its potentiality of transforming CAD drawings into solid objects by depositing layer upon layer of the material to form a complete geometry. Additive manufacturing or 3D printing was previously limited to manufacturing in the industry using resins, carbon fiber, graphite, graphene, nylon, ASA (Acrylic Styrene Acrylonitrile), ABS (Acrylonitrile Butadiene Styrene), and metals as material, but now this technology is approaching the construction sector.

In the 1990s it was referred to as Contour Crafting. Initially, it was limited to only cement paste extrusion but later expanded to the use of cementitious materials to build large structures. There are two basic types of 3D concrete printers. One is the fixed or gantry-type printer and the second is the robotic arm printer. The key components of a 3D printer include a concrete storage tank, a pumping mechanism, a hose, an extruder(nozzle), and a robotic arm or Frame (gantry style) that serves to move the nozzle in abscissa (x), ordinate (y), and applicate (z) directions. Both configurations of the 3D concrete printer, fixed and robotic arm type have been successfully used in both research and practical applications.

Undoubtably, the field of construction constitutes one of many mega industries in the world with a major contribution to the world economy, contributing almost $10 trillion in annual income, or nearly 6% of the global GDP. In the last few decades with the growth of technology, the construction industry has undergone countless advancements. From a business point of view, construction companies are always in search of ways to enhance productivity and reduce costs at the same time. According to studies conducted, the annual growth rate in the construction sector is not satisfactory. The machinery and tools used in construction are certainly improving but the basic procedure is still the same, thus limiting the growth in this sector. The addition of the technology of 3D printing to the field of construction is a major step towards a revolution in this sector.

Initially, the concept came from Pegna for using 3D printing in construction. Khoshnevis from the University of Southern California came up with the concept of contour crafting that utilizes a gantry system (frame type) for concrete extrusion.

The gantry-type arrangement has the advantage of trowels, that are linked to the nozzle to smooth out the surface of the concrete during extrusion [24]. Contour crafting was the first method to be used for the on-site printing of complex structures. The main benefits of this system are the surface smoothness of the printed structure and high fabrication speed. Out of many benefits, there is one major drawback that only vertical extrusion is possible, limiting the diversity in design. Materials used in printing were concrete, polymer, and ceramic. Some issues in this process were the possibility of weak interfacial zones due to a lack of adherence between layers and the weak mechanical characteristics of extruded cement. The mixture prepared was not adequate for the process, due to which it was limited to printing of only medium-sized structures.

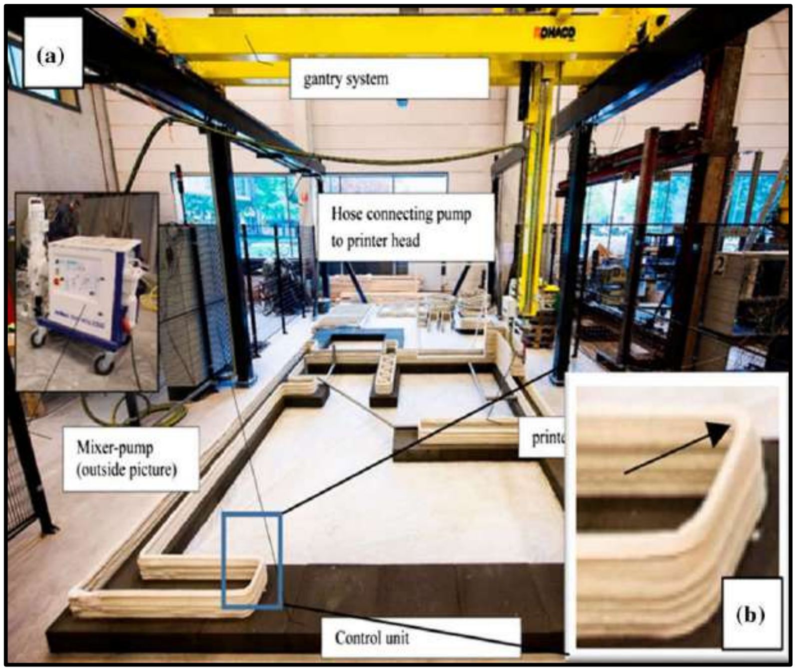


Figure 2.1: Gantry System of 3D Concrete Printer

2.2 Concrete Ratios

The development of an adequate concrete mixture for 3D concrete printing is a big constraint that has limited the growth in this sector. In a research project [25], a concrete mixture for 3D printing was developed using DuraPozz Class F fly-ash, CEM II 52.5 N (a type of cement containing 6 to 20% limestone extender) and Ferro-Atlantica Microsilica fume was utilized as extenders to achieve the required rheology of concrete for optimal printing results. As illustrated in table 1, the aggregate used has a 4.75mm maximum particle size and is continuously graded. A high-range water-reducing chemical admixture Chryso Premia 310 superplasticizer is also added.

Table 2.1: Composition of different elements in concrete

Constituent		Kg
1.	Cement	579
2.	Fly Ash	165
3.	Silica fume	83
4.	Aggregate	1167
5.	Water	261
6.	Superplasticizer	1.48% by mass of the binder

For this research, a rectangular structural wall element of dimension 630 × 230 ×500 mm was designed for printing. The wall comprises a W-shape infill as shown in Figure 2.2.

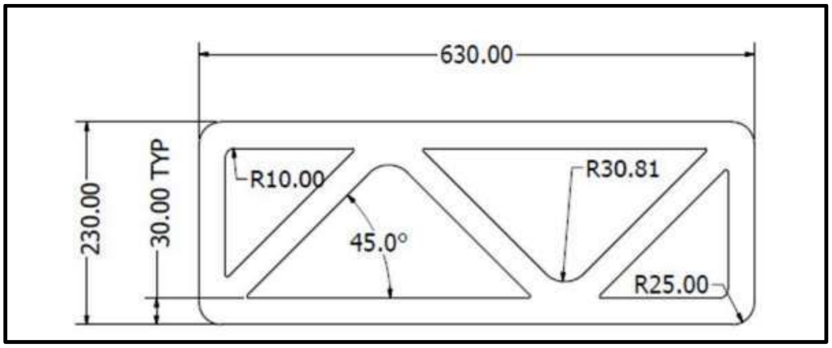


Figure 2.2: Rectangular Wall with Dimensions.

The basic parameters for accessing the desirability of the mixture of concrete for 3D printing are the dynamic and static yield stress of the concrete mixture. For observing the thixotropic behavior of the concrete mixture, tests were conducted on the extruded mixture at different intervals of time. The limitation in this process is that we cannot test for rheology and printing at the same time, these need to be done separately. The tests were conducted on different batches to account for variations in rheology, for this purpose five batches of concrete were prepared. For testing, we need to place the printed structure under the rheometer after specific intervals of time to check the value of static yield stress to judge the behavior of the concrete mixture. The static yield stress for concrete mixture is the maximum stress needed to start the flow of mixture and it also determines the strength of the printed concrete layer and whether it can bear the weight of successive layers or not.

The strength of each layer is important but most importantly the strength of the lowest layer should be adequate to withstand the buckling caused by the weight of successive layers. The total length of the print path for this object equals approximately 2378 mm and is the same for every layer. The layer of filament with a 30mm width is selected and the printing speed is in the range of 40-100mm/s. The height range for feasible filament layer height is 8 to 15 mm. The nozzle is circular having an opening of 25mm diameter, so a filament having an almost rectangular cross-section is achieved through it. It can be deduced that high stability can be achieved using smaller filament layer heights. The printed wall labeled with layer number is shown in Figure 2.3.

Figure 2.3: 3D Printed Structure of The Wall.

A total of 45 filament layers were deposited in 21 mins and the total height of the wall was about 360mm. The structure was stable until the deposition of the 45th layer, but a collapse occurred due to plastic yielding, plastic yielding is confirmed by the appearance of surface cracks. The height of the building obtained practically was about 360mm, which is almost 3 times less than the predicted height of 960mm. The difference between predicted height and experimental is not unexpected since the magnitude or extent of variation calculated through finite element analysis was about 43% and 37%. The root cause for this deviation in behavior is due to variations in the properties of the constituents of the mixture overtime.

The behavior of the printed structure is shown in Figure 2.4. A total of four images have been taken after the complete printing of the structure, it can be seen in successive images that the collapse is starting at the bottom layer and gradually the entire structure comes down.

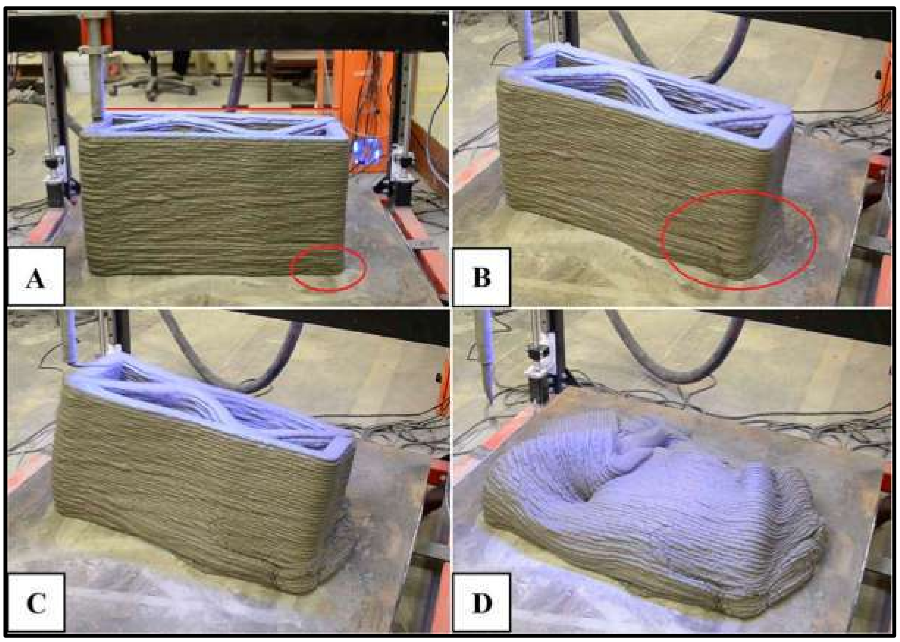


Figure 2.4: Behavior of 3D Printed Wall.

The most basic method used to select a mixture for 3D concrete printing is by trial and error. Two modes of failure [26] that are most likely to occur are elastic bucking and plastic collapse. Elastic buckling is a form of failure characterized by loss of geometric stability in the printed structure and plastic collapse is due to the application of stress on the bottom wall beyond the material yield strength. Both these failures are illustrated in Figure 2.5.

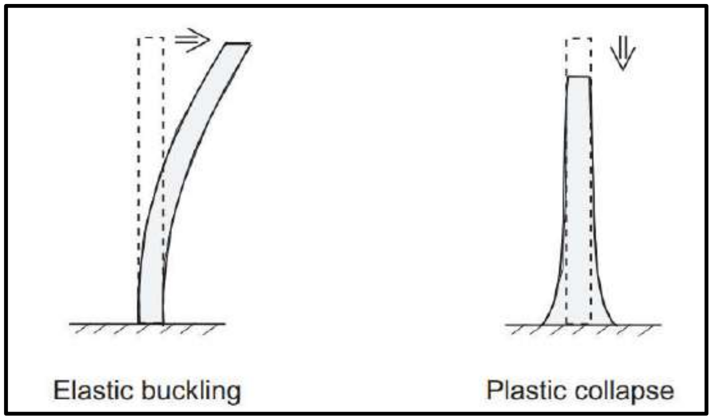


Figure 2.5: Modes of Concrete Failure

Plastic collapse can be characterized that it occurs using compressive failure. The minimum wall length printed determines whether the failure is due to elastic buckling or plastic collapse. Elastic buckling has only a very slight negative impact on the structure. For straight walls, the effect of elastic buckling can be disregarded, but it has a big impact on shell-type wall structures.

2.3 Gantry system for 3D concrete printers

For accessing the feasibility of different concrete mixtures for 3D printing, research [27] was conducted using an extrusion-based 3D printer named Velleman K8200. Resolution for the x, y, and z axes was 0.015 mm and 0.781 mm, respectively, and a maximum printing speed or travel speed of 300 mm/s. The printing area measured 20×20×20cm and a 3mm diameter nozzle was used. The travel and feed rate were kept at 65 and 25 mm/s. For analyses of the rheological characteristics of concrete mixtures provided in Table 2, the HR-2 Hybrid Rheometer was used.

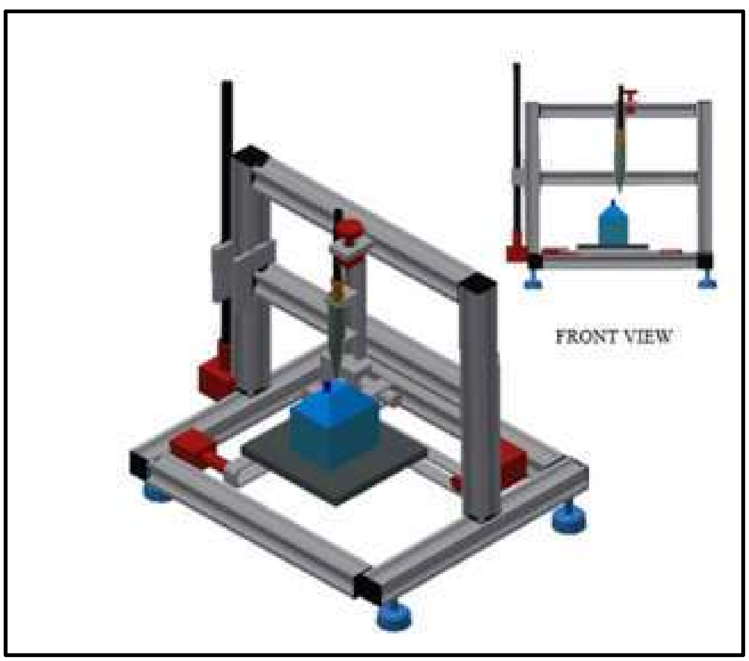


Figure 2.6: Velleman K8200 3D printer

As illustrated in Table 2.2, mixtures were prepared using standard type II Portland cement, silica fume, and polycarbonate superplasticizer in six different ratios. The ratio of water-to-cement (W/C) was kept constant for all mixes at 0.3 [27].

The presence of a superplasticizer served to increase the mixture's workability and worked as a viscosity-modifying agent (VMA). To increase cohesiveness between mixture constituents to improve the mechanical properties of the mixture densified silica fume was added.

Table 2.2: Water to Cement ratios of different elements

W/C ratio	Cement(g)	Silica Fume (g)	Superplasticizer (g)	Water(g)
0.3	95	5	1.5	28.5
	97.5	2.5	1.5	29.25
	100	0	1.5	30
	95	5	2.5	28.5
	97.5	2.5	2.5	29.25
	100	0	2.5	30

The rheological characteristics of the concrete mixture are susceptible to change by numerous factors like mixing additives, the proportion of constituents and mixing time, etc. To avoid variation in rheological properties a standard procedure of mixing had to be obeyed. For the first step, a dry mix of cement plus silica is prepared followed by the addition of water and superplasticizer in the second step. The pressure required for extrusion needs to be calculated to ensure adequate extrusion. Not only pressure but there should be tight adhesion between mixture constituents for adequate extrusion.

It is observed that incase of insufficient adhesion between constituents resulted in the extrusion of only silica and water leaving behind the other constituents. To avoid this type of failure we need to select a mixture with optimal cohesive forces between constituents.

The mixture for 3D concrete printing must contain fine-grained particles whose combination provides the required strength, resistance to frost-enhanced adhesion, and appropriate curing speed. For cohesion between particles, we need to add a binder, blast furnace slag is a low-cost option with desirable characteristics [28]. In addition to interacting with calcium hydroxide and promoting the production of additional hydro-silicates, blast-furnace slag raises the carbonization coefficient value of concrete mixtures and mortars, which benefits the environment. To analyze the characteristics and behavior of extruded mixtures, a printer for testing at the laboratory level was designed and assembled as shown in Figure 2.7.

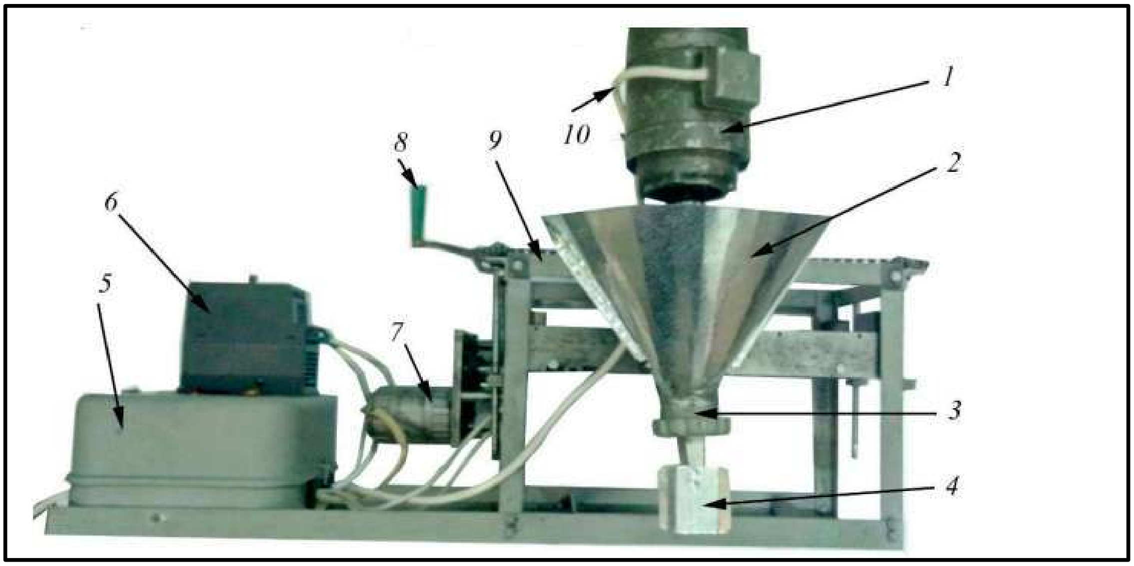


Figure 2.7: Laboratory 3D Printer. 1- Electric motor of the extruder; 2-hopper of building mixture; 3-Auger;4-Mouthpiece;5-Control Panel; 6-Frequency Converter of Electricity;7-Reverse Motor moving the Extruder in the Horizontal Direction;8-Manual Drive moving the Electric Motors

The main constituents selected for concrete mixture in this research [28] are granulated blast furnace slag (GBFS), Na_2SO_4 hardening accelerator (HA), Cement–slag binder content (Bnd). If the role of each constituent is observed individually the structural strength of the concrete mixture increases as we increase the amount of GBFS. The suitable mixture for 3D printing is obtained when granulated blast-furnace slag is roughly 30-40% of binder and hardening accelerator (sodium sulfate) for about 1-2% of binder. The compressive strength as well as the structural strength of concrete increases by increasing the amount of hardening accelerator–Na2SO4 in the mixture. If we increase the percentage of GBFS above 40%, extrudability increases but also strength is compromised. Another important observation is that the efficacy of HA (hardening accelerator) increases when the ratio of GBFS is low in the binder.

2.4 Design of optimal concrete ratios

A mathematical model was developed for selecting an optimal concrete mixture for 3D printing [29] to calculate static and dynamic yield stress values of different concrete mixtures with the same type of constituents mixed in different ratios, Table 2.3 shows percentages of different elements used for each concrete mixture.

The main constituents of the concrete mixture are OPC (ordinary Portland cement), silica fume, water, fly ash, and sand. For the research, the constituents were kept the same and difference in rheological characteristics (static yield stress, dynamic yield stress) was observed for changing the proportion of constituents. The goal is to obtain a certain ratio of concrete that provides a balance between the high value of static and low-value dynamic yield stress to achieve the desired characteristics of a concrete mixture.

Table 2.3: Different Percentages of Elements used for Concrete Mixture

Sr. No.	Cement (%) (x_1)	Sand (%) (x_2)	Fly ash (%) (x_3)	Water (%) (x_4)	Silica fume (%) (x_5)
1	0.160	0.210	0.280	0.330	0.020
2	0.120	0.230	0.300	0.330	0.020
3	0.120	0.210	0.300	0.350	0.020
4	0.120	0.240	0.250	0.350	0.040
5	0.120	0.210	0.280	0.350	0.040
6	0.160	0.210	0.260	0.350	0.020
7	0.140	0.226	0.266	0.339	0.029
8	0.160	0.240	0.250	0.330	0.020
9	0.160	0.210	0.250	0.340	0.040
10	0.140	0.210	0.300	0.330	0.020
11	0.120	0.260	0.250	0.350	0.020
12	0.160	0.210	0.260	0.330	0.040
13	0.120	0.260	0.250	0.330	0.040
14	0.160	0.220	0.250	0.330	0.040
15	0.160	0.210	0.250	0.350	0.030
16	0.140	0.260	0.250	0.330	0.020
17	0.120	0.210	0.300	0.330	0.040
18	0.120	0.260	0.270	0.330	0.020
19	0.160	0.220	0.250	0.350	0.020
20	0.150	0.210	0.250	0.350	0.040
21	0.140	0.226	0.266	0.339	0.029
22	0.140	0.226	0.266	0.339	0.029

The only characteristics that are important for the selection of concrete mixture as mentioned before are dynamic and static yield stress. A certain value of dynamic yield stress is required for pumpability and static yield stress is crucial for buildability, but if any value of either static or dynamic stress is above the optimal or required value, it can cause irregularities.

A high value of static yield stress can lead to low pumpability and a high value of dynamic yield stress leads to a loss in buildability. These characteristics are opposite of each other but are at the same time important.

The mixture we require should have a specific value of static and dynamic yield stress that make it useful in the sense that it has the strength and compactness required to stay in place and sustain the weight of successive concrete layers and also be pumpable. The magnitude of Static yield stress is generally higher than dynamic yield stress.

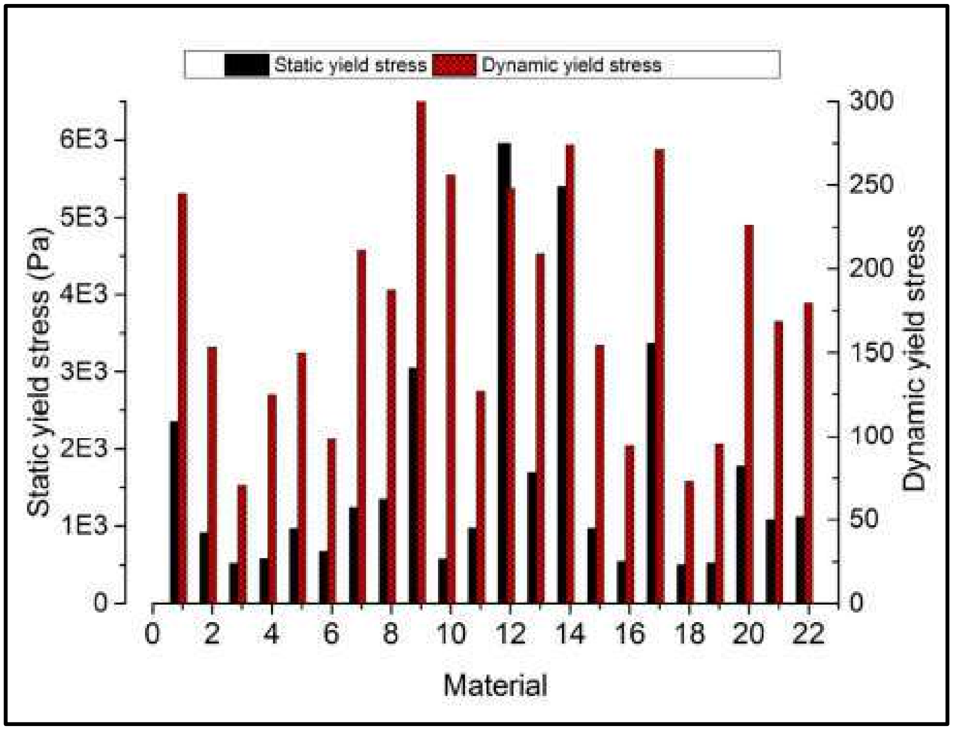


Figure 2.8: Rheological Properties of Various Mixtures.

Figure 2.8 shows the static and dynamic yield stress of all the concrete mixtures (Table 3). The variation in static and dynamic yield stress depicted in Figure 2.8 is useful to select the appropriate mixture for 3D concrete printing. The best content selected from this study is 0.150–0.155 of cement and 0.215–0.230 of sand to get a value higher than 4880 Pa for static yield stress and lower than 220 Pa for dynamic yield stress.

From all the mixtures shown in Table 3, the mixture with the most desirable characteristics was M19. Silica fume is a binder in the mixture for promoting cohesion, strength, and impermeability. Increasing water content leads to a decrease in static and dynamic yield stress and static yield stress increases by increasing cement content. Apart from the ratios in Table 3, another mixture is proposed in the research which includes 0.148, 0.221, 0.261, 0.33, and 0.04 ratios of cement, sand, fly-ash, water, and silica fume.

2.5 The desirability of Concrete Mixture

The desirability of a concrete mixture is based on the following properties:

1. Pumpability is defined as the desirability of pumping the concrete mixture through a 3D printer pump.
2. Printability or extrudability, is the ease of pumping mixture through the nozzle.
3. Buildability is the resistance to deformation offered by deposited material upon application of a load of successive layers.

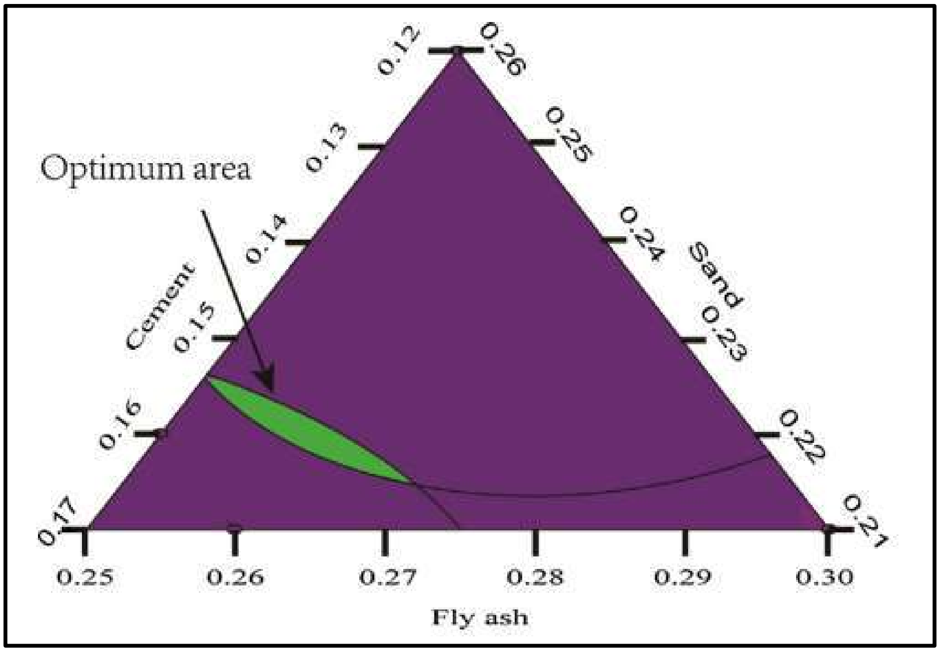


Figure 2.9: Optimization Mixture for the Material Used in Concrete Mixtures

For the selection of a desirable ratio of constituents for a concrete mixture of concrete figure 2.9 can be utilized, as the green region indicates the optimum area for the selection of desirable fractions of cement, fly ash, and sand. Any ratio selected from this optimum area is most likely suitable for 3D printing. The behavior of concrete during pumping is determined by analyzing the characteristic of the slip layer that forms between the concrete and the pipe surface [31]. Another research used multiple concrete mixtures based on the use of course and fine particles and types of cement to study the effect on slip layer formation. It was observed that the thickness of the slip layer was directly dependent on the quantity of cement, water-to-cement ratio, and superplasticizer added to the mixture. As we increase the concentration of fine sand in the mixture, the slip layer thickness decreases. The diameter and length of the pipeline can be used to alter the thickness of the slip layer.

A tribometer was selected for assessing the rheological characteristics of the slip layer required to form an optimum working mixture of concrete and SCC (self-consolidating concrete) to investigate the suitability of concrete for 3D printing. The tribometer consisted of a conical-shaped inner cylinder as shown in figure 2.10. The calculated values of parameters for the rheology of the slip layer of different concretes were applied to the mathematical model for pumping prediction to predict the behavior of concrete during pumping to assess the workability of different mixtures.

The testing was carried out using a 30m pipeline with diameters of 125 and 100mm. All parameters were kept constant, and only the diameter of the pipe was altered to observe the difference between the behavior of concrete during pumping. The comparison between both pipes showed that pumping pressure doubled with a 20% increase in pipe diameter. If a narrow pipe is used, we require a higher pressure for pumping, consequently, we need a higher-power pump. The diameter of the pipe should be appropriate to avoid energy wastage. The extrusion speed also increases in the case of a narrow pipe.

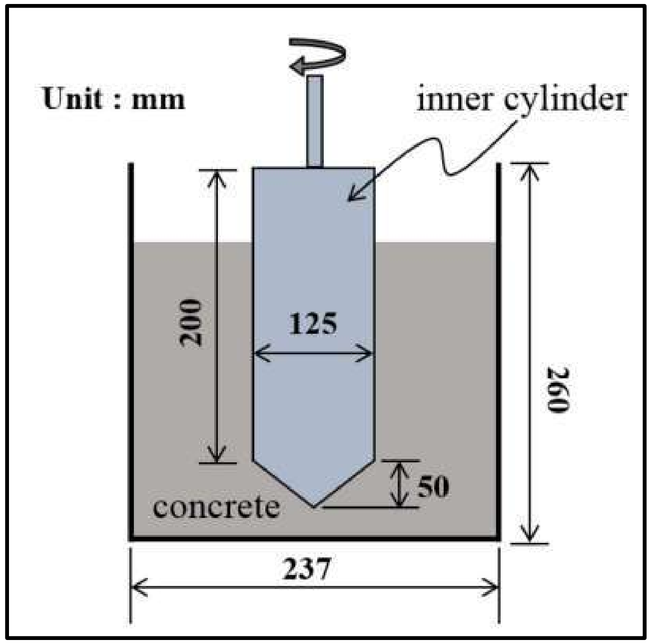


Figure 2.10: Schematic Description of Feys' Tribometer

Six different concrete mixtures were prepared and experiments were performed on those mixtures to evaluate the pumping performance [32]. The parameters defined for the mixtures as 10, 20, or 25mm were set for maximum particle size of coarse aggregate at each of two nominal strength values of 24Mpa and 50 MPa. To keep the same slump flow of 600mm the amount of superplasticizer was adjusted. The rheological characteristics of the different concrete mixtures and related slip layers are written in table 4. The viscosity of the slip layer and concrete increases as the size of the coarse aggregate increases. With the increase in aggregate size, the yield stress of both concrete and slip layers decreased. In the case of a mixture with large aggregates, we need to add a larger quantity of superplasticizer for increased need of compactness in the mixture, but excessive amount of superplasticizer decreases the yield stress which compromises buildability.

The value of pressure required per unit length to achieve a pumping value of 30 m^3 /h was computed concerning the measurement of rheological characteristics to examine the effects of an increase in the size of coarse aggregate. Compressive strengths of 24 and 50 MPa are denoted by S24 and S50 and A10, A20, and A25 are used to denote different sizes of coarse aggregate of 10, 20, and 25 mm, respectively [32]. The mixture with a coarse aggregate of size 25mm requires almost double the value of pressure in comparison to the mixture with a 10mm aggregate. The conclusion drawn from this study shows that the size of coarse aggregate used in a mixture has a certain effect on the pumping of concrete.

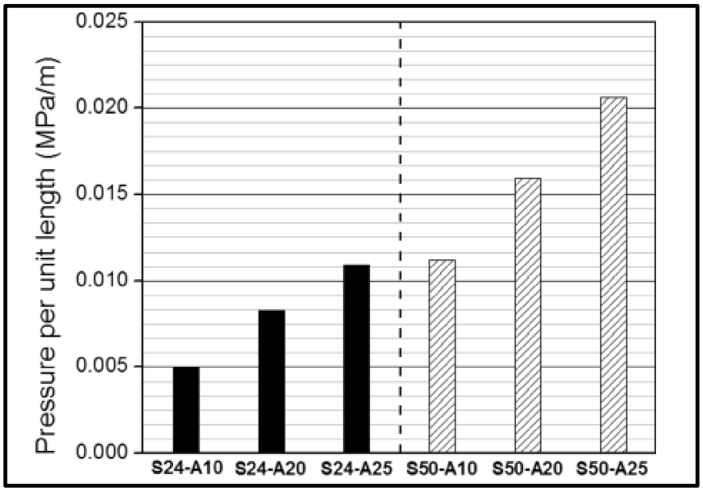


Figure 2.11: Pressure Required Per Unit Length for 30 m^3/h of Pumping

Table 2.4: Yield stress and Viscosity of Concrete and slip-layer at different aggregates and design strength

Design strength (MPa)	Maximum aggregate size (mm)	Concrete		Slip-layer	
		Yield stress (Pa)	Viscosity (Pa s)	Yield stress (Pa)	Viscosity (Pa s)
24	10	300.0	8.0	15.0	0.5
	20	200.0	10.0	12.0	0.8
	25	150.0	13.0	5.0	1.0
50	10	100.0	25.0	11.0	1.3
	20	80.0	30.0	10.0	2.0
	25	80.0	40.0	5.0	2.5

Jeon et al, a researcher performed tests [33] to evaluate the rheological characteristics of concrete and respective slip layers for concrete mixtures with high strength of various types with different mineral admixture content. Again, the use of rheological measurements was done to assess the pumping performance. The pumping performance for three mixtures was evaluated, by using silica fume (SF), zirconia silica fume (ZSF), and SF0 as a control mix with no mineral admixture, figure 2.11 shows the results of the pumping performance of these mixtures. Each mixture was pumped through 500m by 15MPa of pressure and it was observed that the ease of flow for concrete improves by increasing the quantity of silica fume. Zirconia silica fume increases the flow rate of concrete almost twice when compared to the same amount of normal silica fume in a mixture.

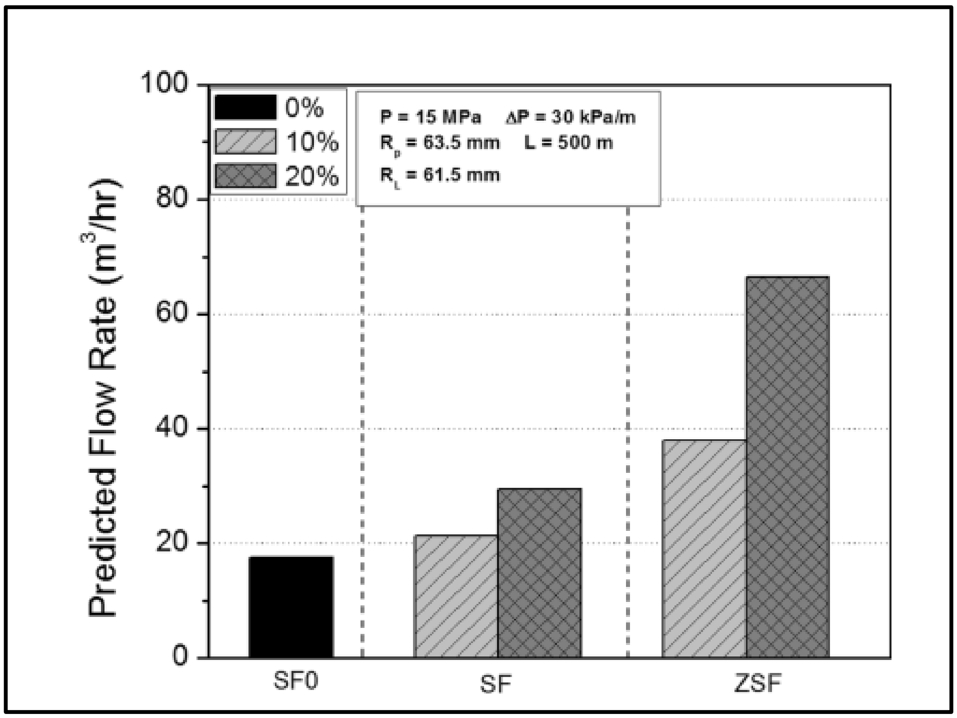


*Figure 2.12: Calculated Flow Rate for SF And ZSF Test Series *SF Is Silica Fume; ZSF is the Zirconia Silica Fume.*

Ten concrete mixtures were prepared with varying amounts of superplasticizer to study its effect on pumping performance. The results of a test for slump flow and rheological property estimation of these mixtures are given in table 5. It was observed that slump flow increases by increasing the amount of superplasticizer whereas the viscosity decreases. Pumping prediction was done using the rheological characteristics of concrete and slip layers. Figure 2.12 illustrates the results of flow rates of all the mixtures at compressive strengths of 50, 80, and 100 MPa respectively. It can be seen under the same value of compressive strength the rate of flow increases with the amount of superplasticizer. For 50MPa the increase in flow rate in quite large, the behavior of mixtures is the same at other values of compressive strengths but the rate of increase is less.

Table 2.5: Yield Stress and Viscosity of Concrete and Slip-Layer at Different Dosage of Superplasticizer and Design Strength

Design strength (MPa)	Dosage of superplasticizer (%)	Concrete		Slip-layer		Slump flow (mm)
		Yield stress (Pa)	Viscosity (Pa s)	Yield stress (Pa)	Viscosity (Pa s)	
50	0.80	144	53.4	72.0	2.49	370
	1.00	74.0	43.0	9.0	1.98	485
	1.10	41.0	44.0	77.0	1.56	540
	1.27	16.0	61.1	25.0	0.60	655
80	1.10	84.0	107	32.0	4.06	450
	1.25	2.0	94.0	40.0	2.92	575
	1.40	0.1	79.0	5.0	2.98	665
100	1.10	13.4	121	15.3	4.77	515
	1.20	4.0	112	21.5	3.99	585
	1.40	0.1	77.0	0.1	3.22	695

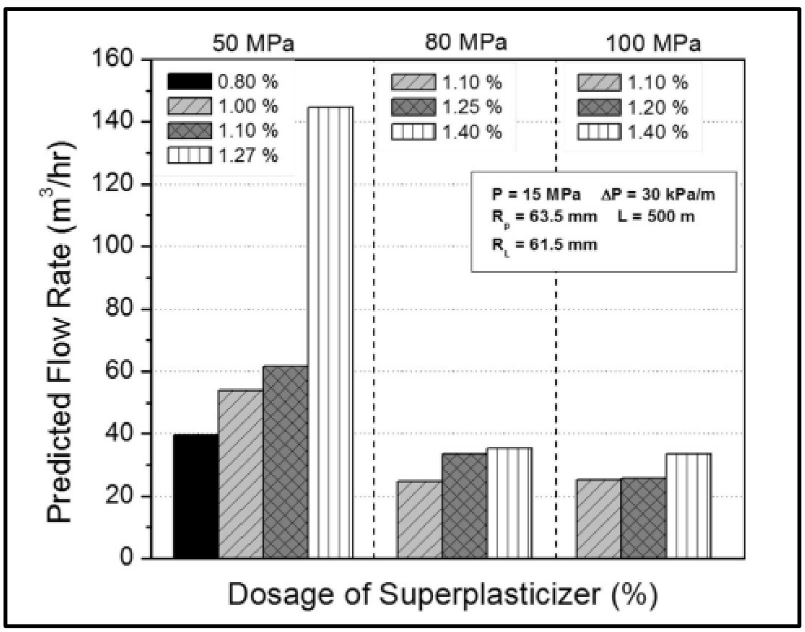


Figure 2.13: Calculated Rate of Flow for SP Test Series Against Different Pressures.

From all the tests conducted it was observed that pumping performance was reduced as the maximum coarse aggregate size increased. Keeping the pressure condition the same it was seen that the mixture with 10mm coarse aggregate showed almost twice the flow rate compared to the mixture with 25mm size coarse aggregate. Also, the effect of quantity and type of silica fume and fly ash were examined. The use of silica fume improved pumping performance and the application of zirconia silica fume was twice as better in comparison to regular silica fume and an increase in dosage of superplasticizer also showed improvements in pumping performance.

CHAPTER THREE: DESIGN AND CALCULATION OF 3D CONCRETE PRINTER

3.1 Design and Calculations

The design of the nozzle is selected from the research paper [17]; there are four distinct types of nozzles according to the size of the printer we are using or the thickness of the layer needed. The given diameter of nozzles is 9mm, 20mm, 25mm, and 44mm.

So, for table top 3D printer the suitable size of the nozzle is 9mm with a deposition speed of 50mm/s

3.1.1 For nozzle:

circular diameter = d = 9 mm

The deposition speed needs to be between 50mm/s to 60mm/s.

Working area

Nozzle diameter = 9mm

Deposition speed = 50mm/s = 0.05m/s

Settling time is the total time for the layer of concrete to be hard enough to bear the weight of the second layer

Settling time = 15min = 900sw

Safety time = 2 min = 120s

Total time=1020s

Total Required Distance = Deposition speed × total time ------------- (1)

So,

Total required distance $= 0.05 \times 1020$

Total required distance = 51 meter

For a square perimeter = 4x(Length)

So, L = Perimeter/4

L = 51/4

L = 12.75m

To decrease the cover area, we will deposit the layer in the loop to increase the travel time

So, for that

L=12.75m

Will reduce by a factor of 4

L = 12.27/4

L = 3.1m

This is the total length for the nozzle to cover before deposing the second layer of concrete

Now we have to select the suitable motor for the gantry system for that we have to calculate the given factors.

3.1.2 For Stepper motor:

Quantity 6 (two for x-axis, two for Z axis and one for y-axis and one for Nozzle)

So, Step angle = 1.8 degrees

Steps per revolution = $\frac{360}{1.8} = 200\ steps\ per\ revolution$

Motor driver micro steps = $\frac{1}{16}$

So, for micro-steps per revolution = 200× 16 = 3200 micro-steps per revolution

Input voltage of the motor = 12V

Current (I) = 2 A

Holding torque = 40Ncm = 0.040Nm

Weight of the motor = 400 grams

3.1.3 Calculations for X and Y-axis Motor steps per mm:

Belt pitch = 2mm

No. of teeth on the pulley = 20

$$\textbf{\textit{Steps per mm for X and Y axis}} = \frac{\boldsymbol{motor\ steps\ per\ revolution \times driver\ microsteps}}{\boldsymbol{belt\ pitch \times number\ of\ teeth\ on\ the\ pulley}} \qquad \textbf{\textit{(2)}}$$

So, putting values in above equation (2),

$$= \frac{200\times 16}{2\times 20}$$

Steps per mm for X and Y axis $= 80\ steps\ per\ mm$

3.1.4 Calculations for Z-axis motor steps per mm:

For a T8 rod

Threaded pitch = 2mm

$$\textbf{\textit{So, steps per mm for the Z axis}} = \frac{\boldsymbol{motor\ steps\ per\ revolution \times driver\ microsteps}}{\boldsymbol{thread\ pitch}} \qquad \textbf{\textit{(3)}}$$

So, putting values in the above equation (3)

Steps per mm for Z axis = $\frac{200\times 16}{2}$

Steps per mm for Z axis = $= 1600\ steps\ per\ mm$

3.1.5 *Calculating power of Nema 17:*

Total rated voltage = 4V

Total rated current per coil = 1.2 A

So, the number of coils = 6

Total current = $6 \times 1.2 = 7.2A$

Total power = $4\times 7.2 = 28.8\ W$

$No.\ of\ stepper\ motors\ used$=6

$Total\ power\ for\ frame$=6×28.8

$Total\ power\ for\ frame$ =172.8W

For choosing the best stepper motor our selection depend upon two factors.

1. Speed (RPM)
2. Torque (Nm)

As they all have the same speed category of 50mm/s to 60mm/s. For torque, we need to find the weight on each axis.

Torque on the x-axis:

3.1.6 *For Torque XY axis:*

Friction coefficient of threads = f = 0.1

Friction coefficient of collar = fc = 0.15

Pitch=P=2mm

α=0

The mean diameter of rod=d_m=d-P/2

dm=8-2/2

dm=7mm

l=2P

l=4(2) mm

l=0.008m

The total mass of structure for XY axis=1.5Kg

Total Weight= 1.5×9.81N

F = 14.715N

3.1.7 For calculation of torque:

As we are given the relation:

$$T=\left(\frac{Fdm}{2}\right)\times\frac{(l+\pi dm\, fsec\alpha)}{(\pi dm-flsec\alpha))} \text{-------------} \quad (4)$$

Putting values in equation (4)

$$T=\frac{14.715\times0.007}{2}\times\frac{(0.008+\pi\times0.007\times0.1\times\sec(0)}{(\pi\times0.007-0.1\times0.008\sec(0)}$$

$$T= 0.024Nm$$

3.1.8 Torque on the z-axis

The total mass of structure for Z axis=3Kg

Total Weight= 3×9.81N

F=29.43N

For the calculation of torque

$$T=\frac{Fd_m}{2}\left(\frac{l+\pi d_m f sec\alpha}{\pi d_m-flsec\alpha}\right) \text{-----------} \quad (5)$$

$$T=\frac{29.43\times0.007}{2}\left(\frac{0.008+\pi\times0.007\times0.1\times\sec(0)}{\pi\times0.007-0.1\times0.008\sec(0)}\right)$$

$$T=0.05Nm$$

For the x, y, and z-axis, the Nema-17 stepper motor is the best to meet our design requirements and cost.

3.1.9 For Extruder:

For motor speed, we know the relationship as:

$$\textit{Motor Speed}=\frac{f\times e\text{-}step}{\textit{motor steps per rev}} \quad \text{---------} \quad (6)$$

Where f is the print speed (mm/min)

e-step is a setting in the printer’s temporary electronic memory that is related to the extruder (steps/mm)

So, the stepper motor in this work, moves 1.8 degrees per full step and has a reduction ratio of 1:100.

As stepper motor steps per revolution are calculated as:

Stepper motor steps per revolution = $\frac{360}{1.8}\times100$

Stepper motor steps per revolution = 20000 steps per revolution

So, for predicting the volumetric extrusion rate (Q predicted);

$$Q_{Predicted} = f \times e\text{-}step \times 1\ \frac{\text{Lead Screw travel Speed (mm/rev)}}{\text{stepper motor (steps/rev)}} \times \frac{1}{5} \times \frac{\pi}{4} \times (\text{PVC internal diameter})^2 \times min\ 60\ s \quad (6)$$

For that extrusion characteristics are given:

Stepper motor (steps/rev) = 20000

Gear reduction ratio= 1:30

Lead screw travel speed (mm/rev) = 1/6

PVC internal diameter (mm)= 101.6

So, by putting values we have the relationship:

$$Q_{Predicted} = f \times e\text{-}step \times 1\ \frac{1/6\ \text{mm/rev}}{20000\ \text{steps/rev}} \times \frac{1}{5} \times \frac{\pi}{4}\ (101.6\ \text{mm})^2 \times min\ 60\ s$$

Putting values in the above equation as:

f= 60mm/sec= 3600mm/min

e- steps = 1600

$$Q_{Predicted} = 3600 \times 1600 \times 1\ \frac{1/6\ \text{mm/rev}}{20000\ \text{steps/rev}} \times \frac{1}{5} \times \frac{\pi}{4}\ (101.6\ \text{mm})^2 \times min\ 60\ s$$

$$Q_{Predicted} = 4.670\ mm^3\ /\text{sec}$$

3.1.10 *Frame structure:*

The material we are using for the frame is aluminum 2020 profile because it allows easy installation and provides the path in which the gantry system will be installed.

So, after the selection of the frame material aluminum 2020, we have done an analysis that

1) How much deflection is on the bars after the installation of the nozzle?
2) The maximum stress introduces in the bars.

So, the analysis of the aluminum profile is conducted on ANSYS to find the total deflection and the maximum stress.

Given that

Weight of the 15cm nozzle + concrete inside the nozzle = 2.5kg

Weight of the motor and the aluminum profile = 1.8 kg

1) Total deformation:

The total deformation of the framre is analyzed on ansys. So, the results are shown it the figure 3.1 below as:

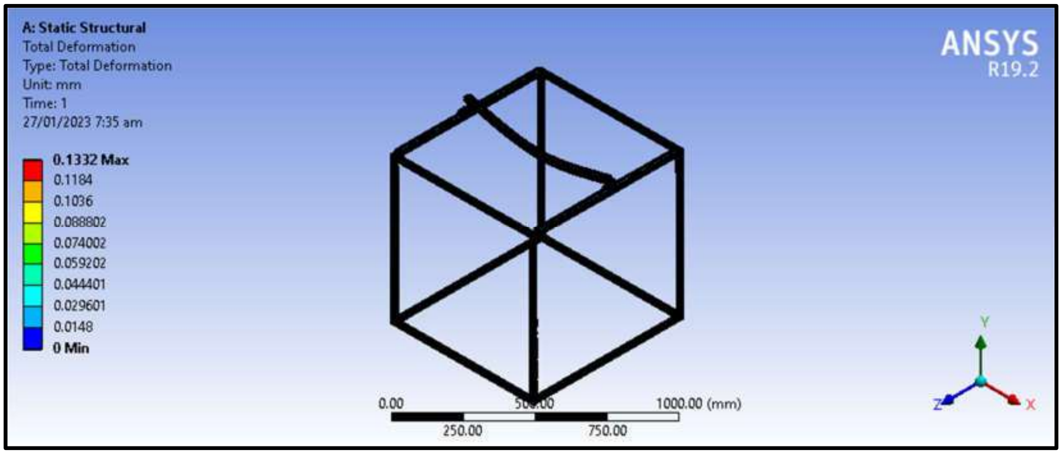


Figure 3.1: Total deformation at a Load of 50N

According to the analysis, the maximum deformation in the frame is about 0.133mm which will not affect the layers of the concrete.

2) Maximum stress:

The maximum stress introduces in the bar after the maximum weight of 50N

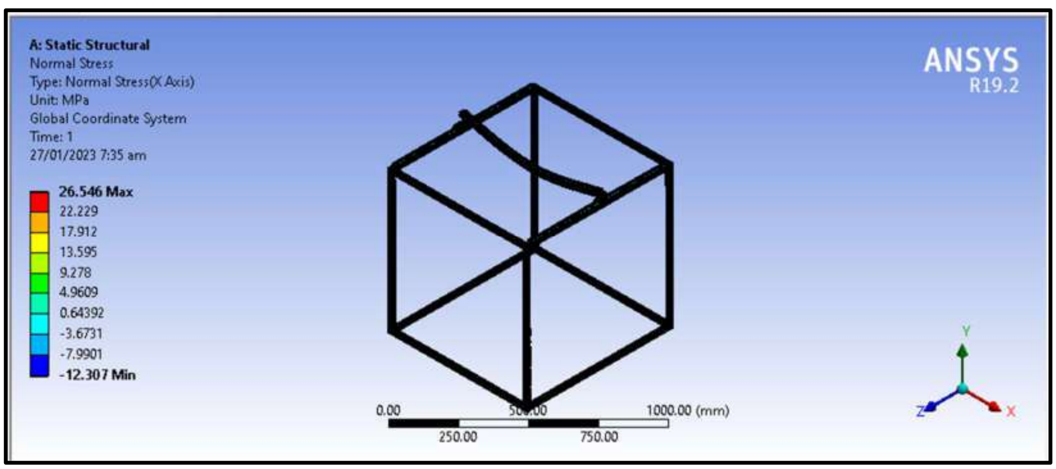


Figure 3.2: Maximum stress in the aluminum profile

The maximum stress on the bar is about 26.5MPa whereas the (t-slot) Aluminum profile can bare the total stress of 120MPa.

3.2 Designing:

The main components including any part that contributes to its movement along the x, y, and z directions. The print bed and print head move according to the controller board's commands to create a 3D-printed structure.

3.2.1 Aluminum profile (T- slots):

These T-slot designs are as straight as they can be. Bent or twisted profiles are undesirable for the frame since they will unbalance the entire structure. These profiles have the least amount of variation. T-slot aluminum is a material that is highly durable, versatile, and affordable for customized constructions and frames like these. We are using T slots of 20 by 20mm.

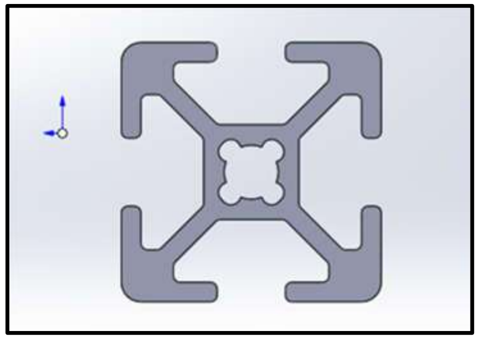


Figure 3.3: Front View of 20x20mm aluminum profile (T- slots)

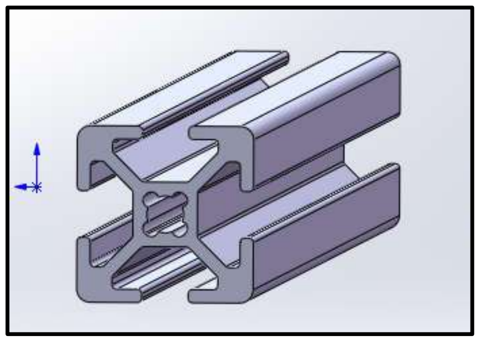


Figure 3.4 Isometric View of the 20x20mm aluminum profile (T- slots)

3.2.2 Stepper motor:

Stepper motors are the most common form of motors found in 3D printers. They are useful for 3D printing since their ease of use and great precision without the requirement for high-end feedback sensors. Most 3D printers used NEMA-17 stepper motors as shown in figure 3.5, which come in three common types based on torque rating: 20-25, 40-45, and 50-56 N-cm. the motor which we are going to use is a stepper motor with torque ranging from 40-45 N-cm. Because these motors are often used in 3D printers, they are referred to as the usual option of motors. They provide adequate torque to move heavy objects at regular speeds. These motors can be found in practically every other 3D printer on the market.

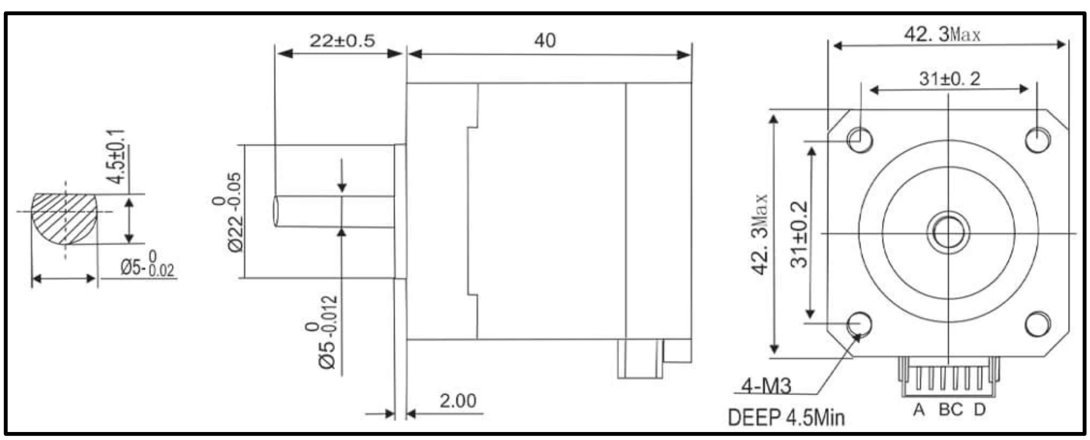


Figure 3.5: Drawings of the Stepper Motor Nema-17

3.2.3 Feeding System:

The feeding and extrusion system seem to be responsible for uniform concrete mixing, transporting it to the extrusion mechanism, and extruding it via the screw. A typical diagram of the extruding system is as follows:

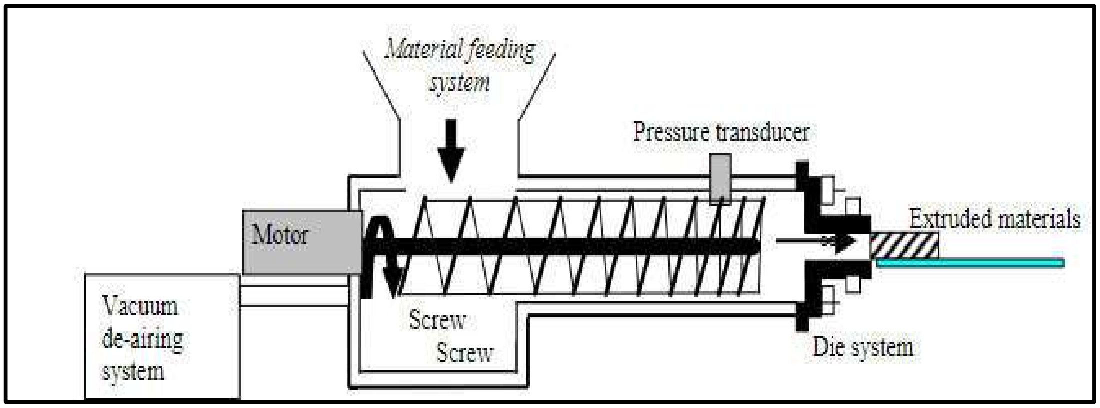


Figure 3.6: Feeding System for the Extruder

We are using a screw-type feeding system because the advantage of a screw-type feeding system over pump type feeding system is that it provides constant extrusion of the mixed concrete. That's why it's better to use a screw-type feeding system instead of a pump type.

3.2.4 Nozzle Design:

The nozzle is the main and most important part of 3d printing. As the material is extruded through the nozzle which we are using is about 9mm in diameter. because the larger diameter will cause a better deposition of material. There is a motor above the nozzle head to move the screw inside that nozzle, so the material is extruded layer by layer continuously through itas shown in figure (3.7).

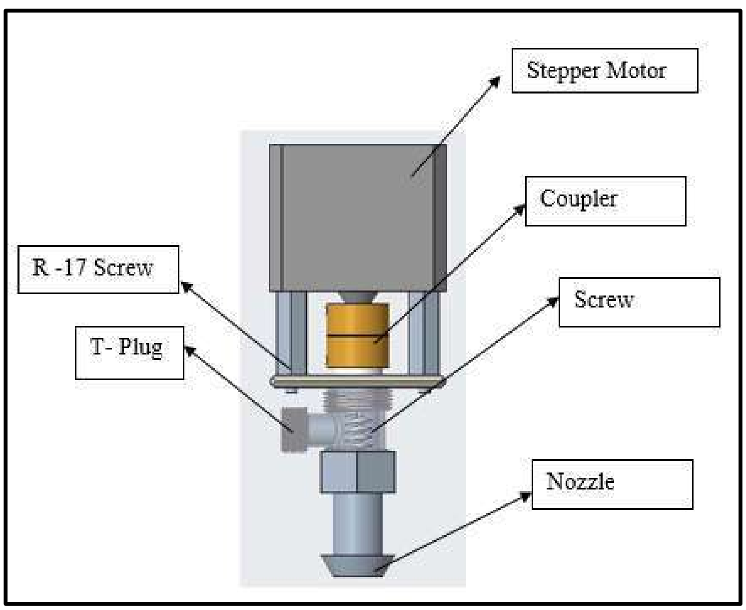


Figure 3.7: Schematic View of the Extruder

3.2.5 Frame*:*

Since we are using a fixed frame type of 3D printer. So, the structure that is created should be within the frame limit. The size of the frame is 0.8m× 0.8m × 0.8m. There is a gantry system above the frame head. The frame is made up of T- slots aluminum bars. The screws are also attached to each end of the frame for the movement of the gantry system in the x, y, and z directions. The frame which we have designed is as follows in figure 3.8.

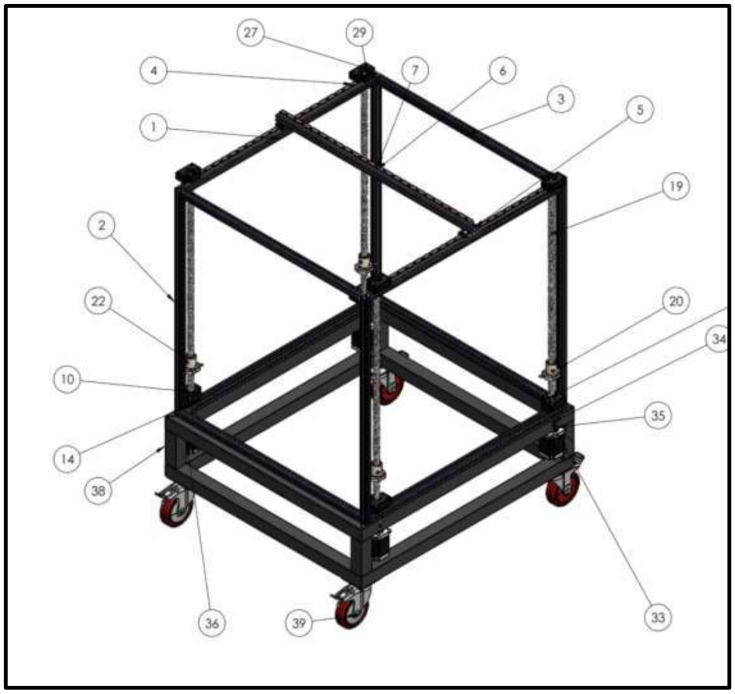


Figure 3.8: Labelled Figure of the Frame excluding nozzle

Table 3.1: Components of the Frame of a 3D Printer

ITEM NO.	3D concrete printer parts	QTY.
1	2020 aluminum extrusion T slot 700mm	4
2	2020 aluminum extrusion T slot 720mm	4
3	2020 aluminum extrusion T slot 660mm	4
4	Rail	2
5	MGN_12_H_SLIDER	2
6	20 20 aluminum extrusion T slot 720mm ABOVE SLIDER	1
7	rail above slider	1
8	Bracket (BK12)	4
9	7001 CE_P4A_PART1	8

10	7001 CE_P4A_PART2	8
11	7001 CE_P4A_PART3	96
12	Bracket (BK12)	4
13	Bracket (BK12F)	4
14	Bracket (BK12)	4
15	Bracket (BK12)	8
16	M12x1.0	4
17	ISO 4762 M4 x 10 - 10N	16
18	DIN 913 - M4 x 5-N	4
19	1605-400	4
20	1605-3	4
21	SFU1605 Washer Front	4
22	SFU1605 Washer Back	4
23	A M6x1.00	4
24	Ø 2.50	4
25	ISO 4027 - M3 x 5-C	8
26	ISO 4027 - M3 x 2.5-C	8
27	BF12	4
28	6000-2RSH_PART1	4
29	6000-2RSH_PART2	4
30	6000-2RSH_PART3	28
31	Circlip DIN 471 - 10 x 1	4
32	D30L35	4
33	D30L35-6.35	4
34	D30L35-10	4
35	ISO 4762 M4 x 16 - 16N	8
36	57BYGH627	4
37	ISO 7045 - M3 x 30 - Z - 25C	16

38	The base of the 3D printer	1
39	Castor Wheel for base	4

3.2.6 Base Frame:

The frame on which the wheel and 3D printer frame are attached.

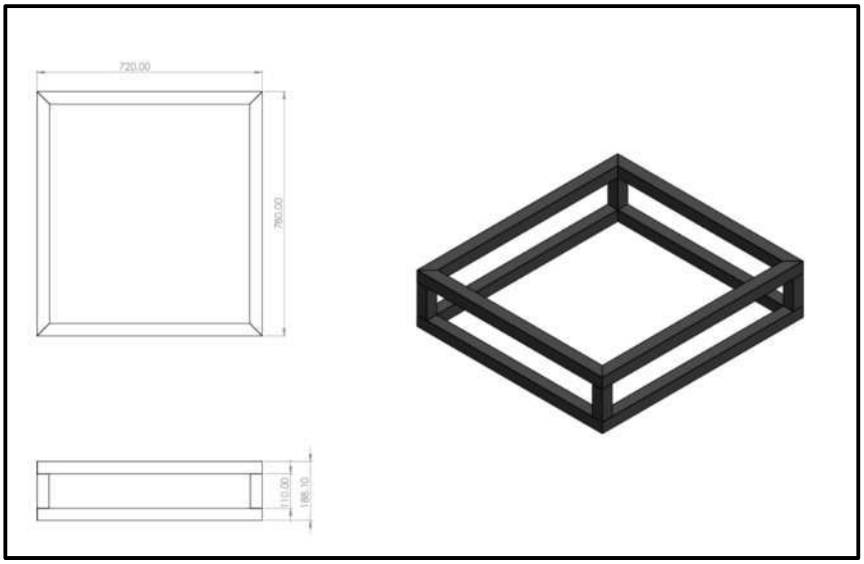


Figure 3.9: Drawings of the Base of the 3D Printer

3.2.7 Castor Wheel:

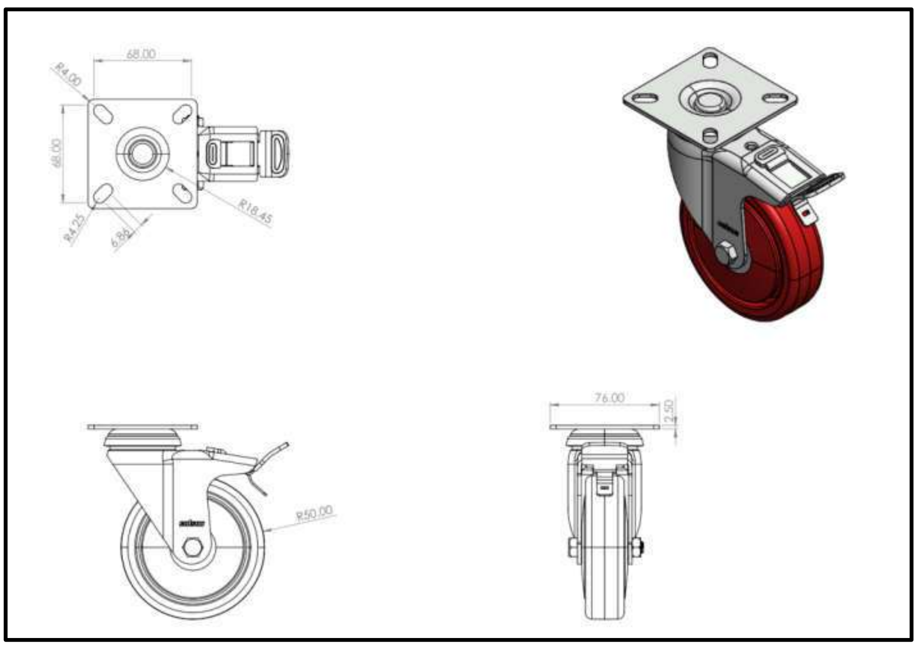


Figure 3.10: Drawings of the Castor wheel

3.2.8 Lead screws:

The screws are used to move the gantry along the x, y, and z directions. The motors are attached with the screws to move it and eventually the gantry system of the printer. The gantry system allows it a multi-axes movement so, with the help of it the nozzle can easily move in all three dimensions. With a total length of 747mm.

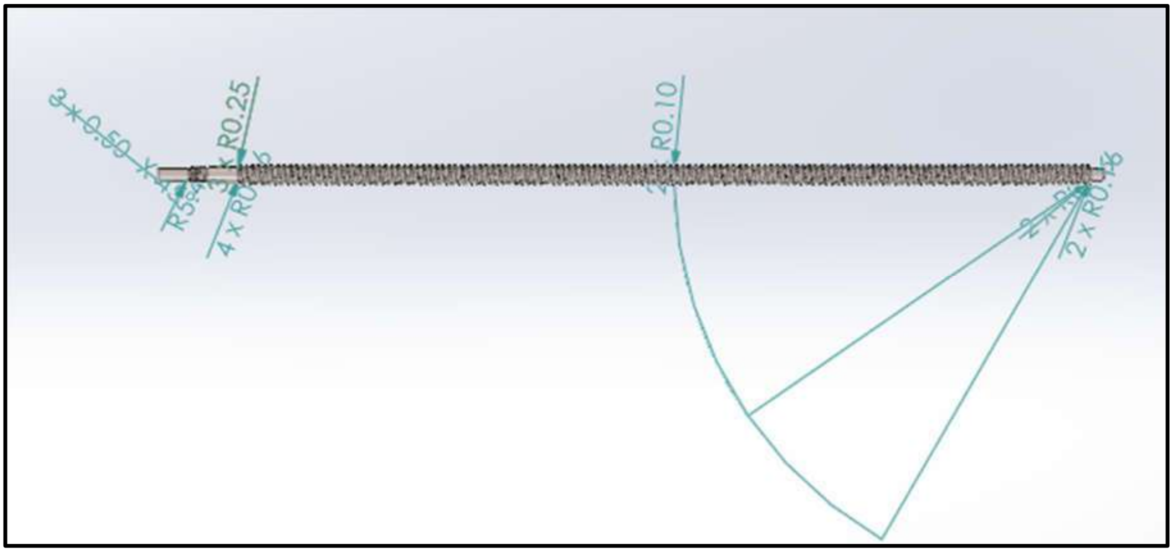


Figure3.11: Ball Screw of the 3D Printer

3.2.9 Lead screw holder:

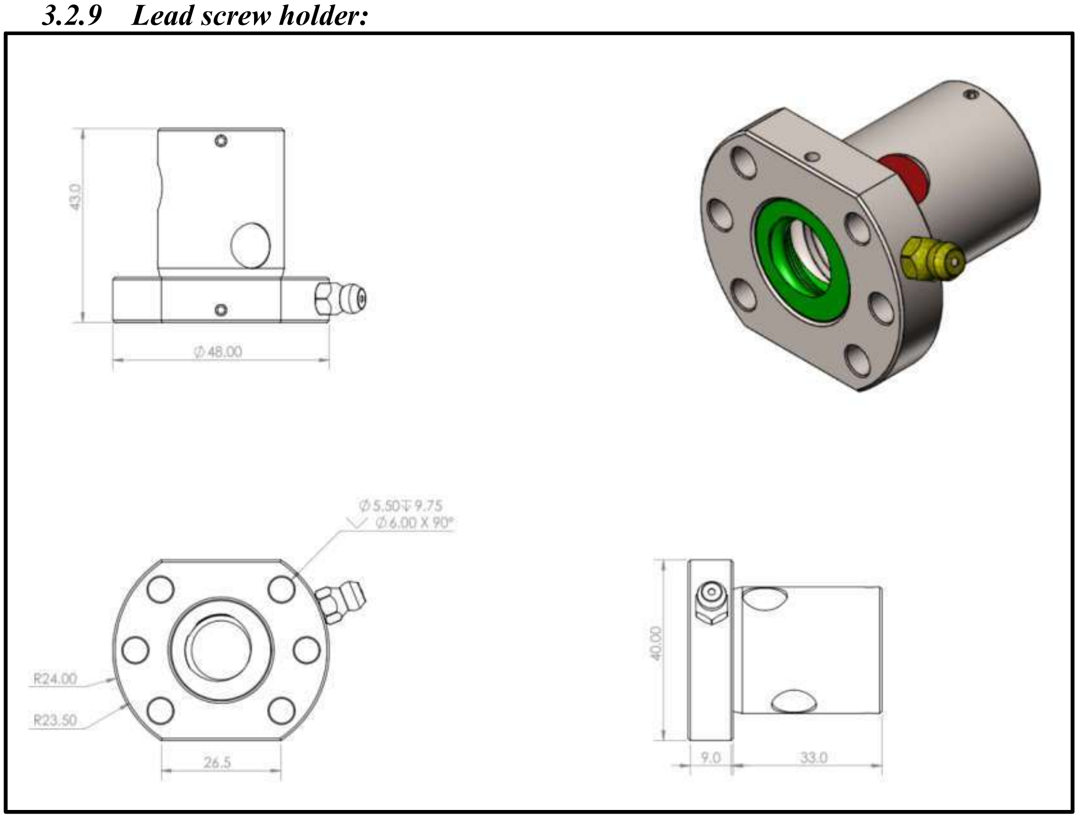


Figure 3.12: Ball Screw for the 3D Printer

3.2.10 Bearing Block:

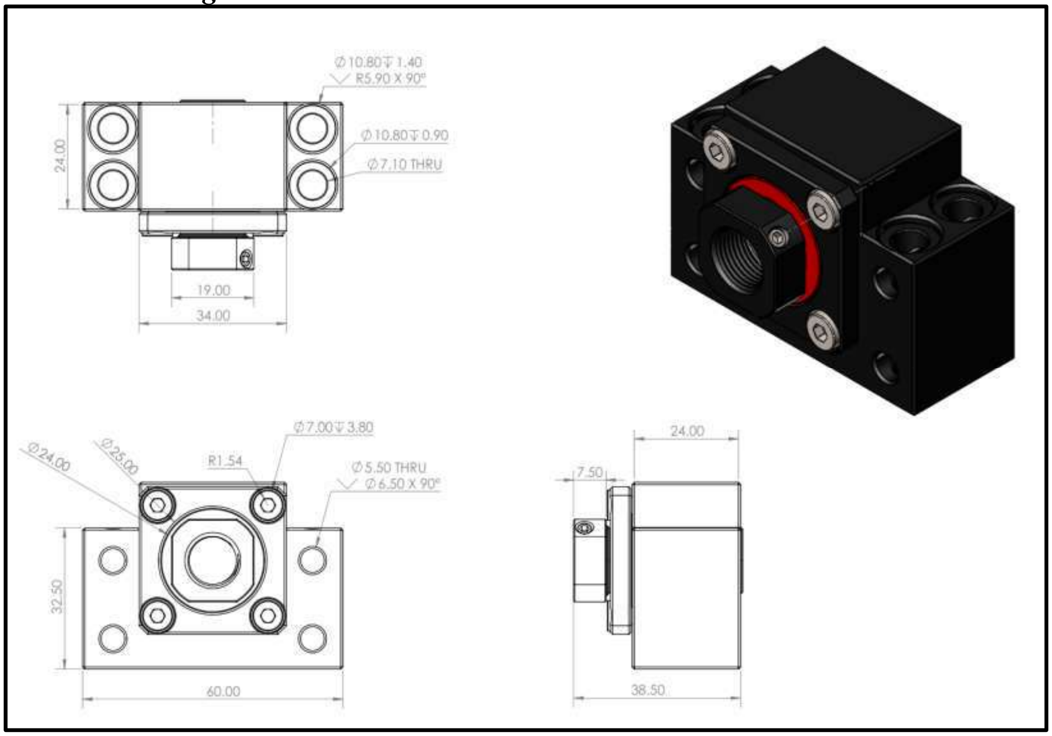


Figure 3.13: Bearing Block of the 3D Printer

3.2.11 Coupling:

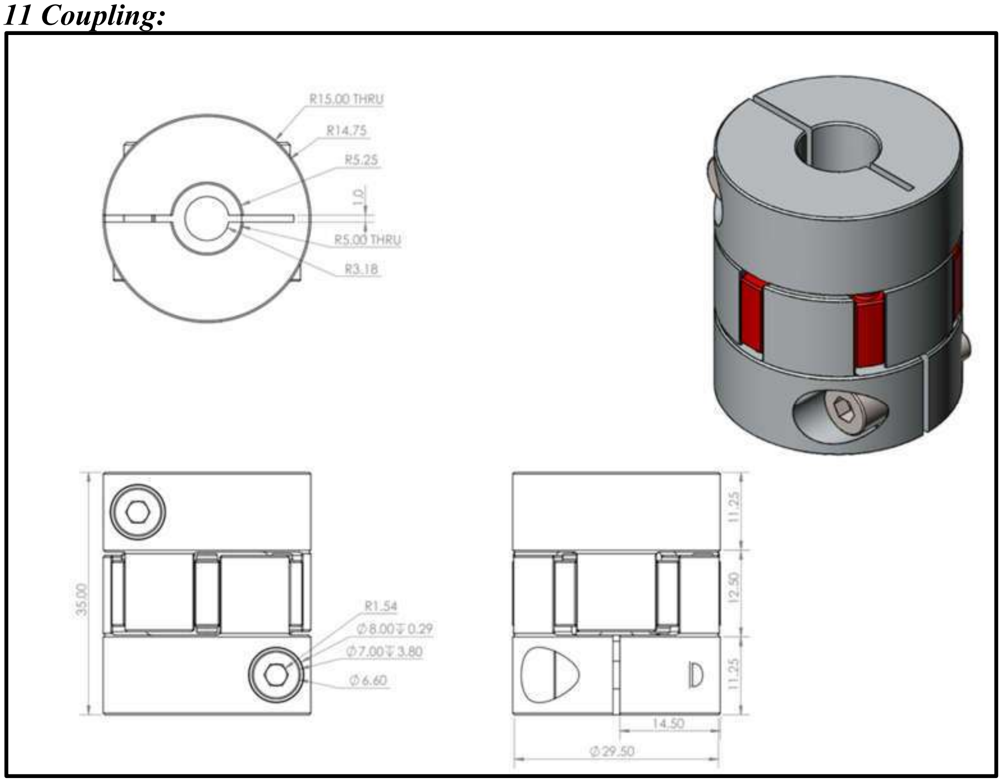


Figure 3.14: Drawings of Coupling

3.2.12 Slider:

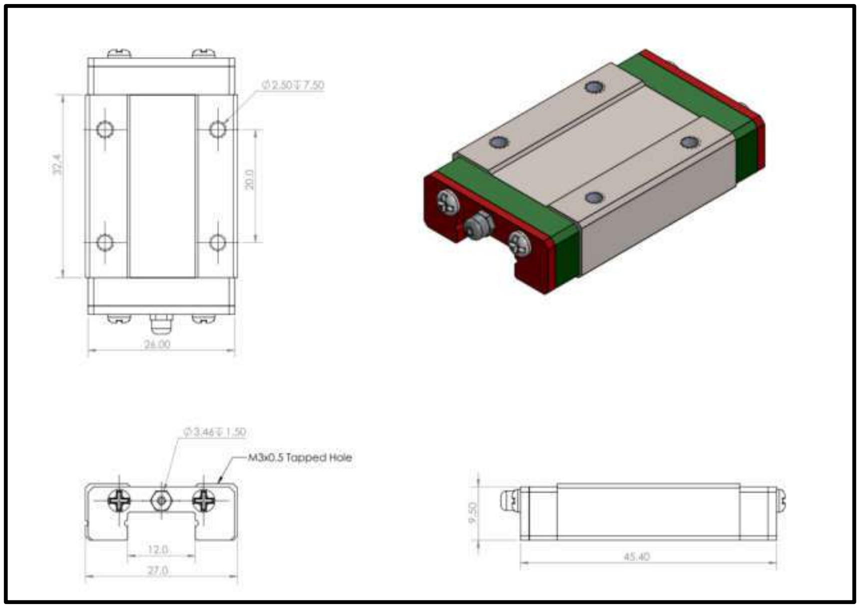


Figure 3.15: Slider with Drawings

3.2.13 Sub-assemblies:

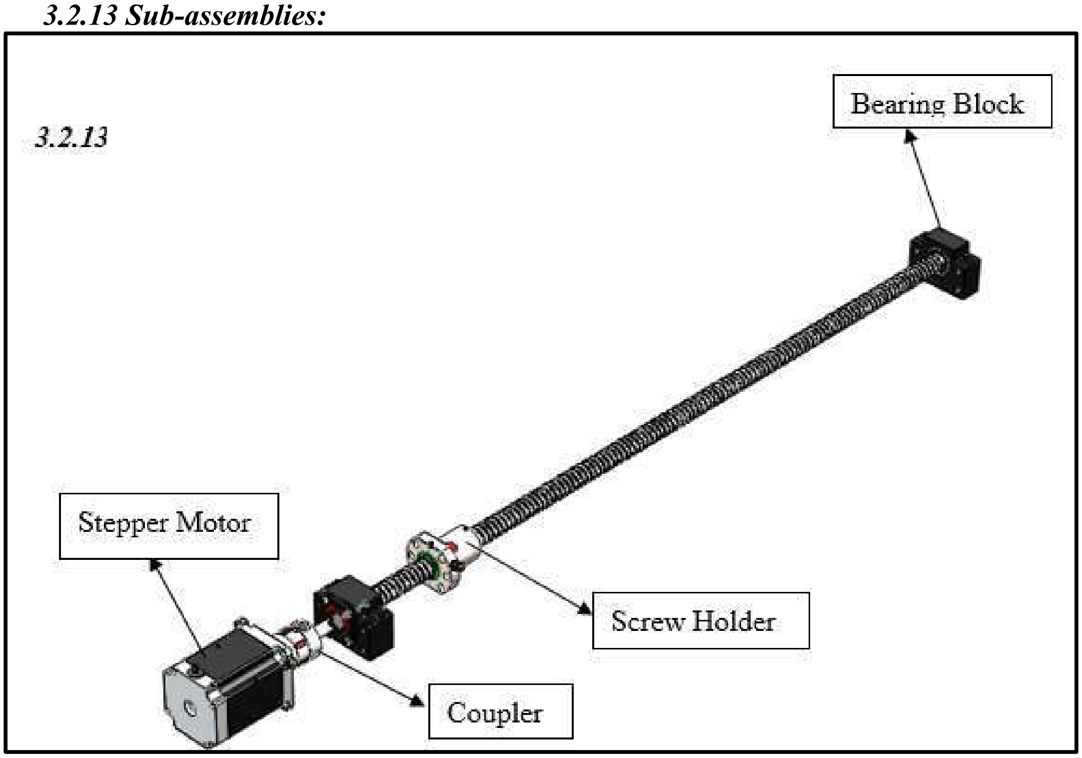


Figure 3.16: Isometric View of the Sub Assembly of the Ball Screw with Stepper Motor (Nema-17), Bearing Block, and Coupler

3.2.14 Final assembly:

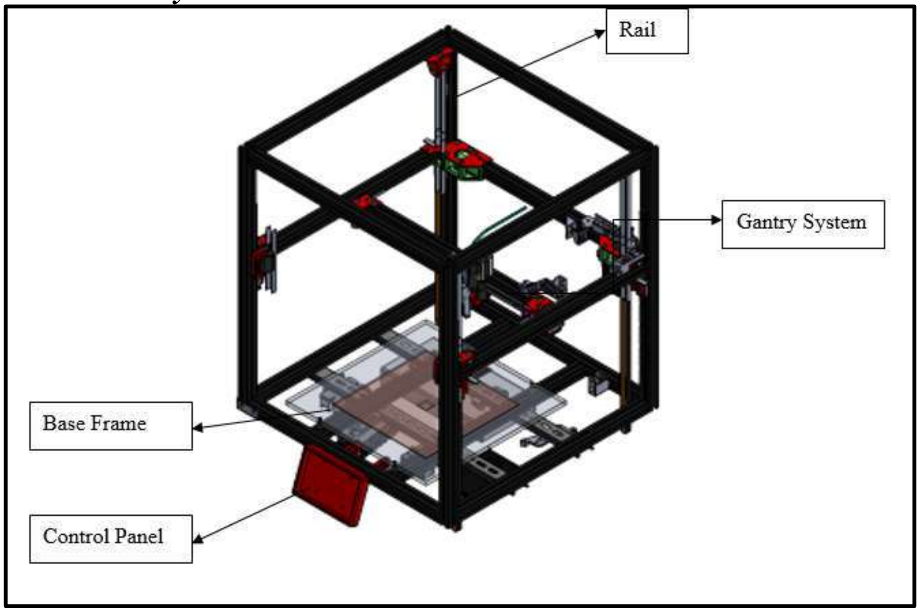


Figure 3.17: Complete Assembly of the Frame

The drawing with a dimension of the frame in the right-side view is shown in Figure 3.17.

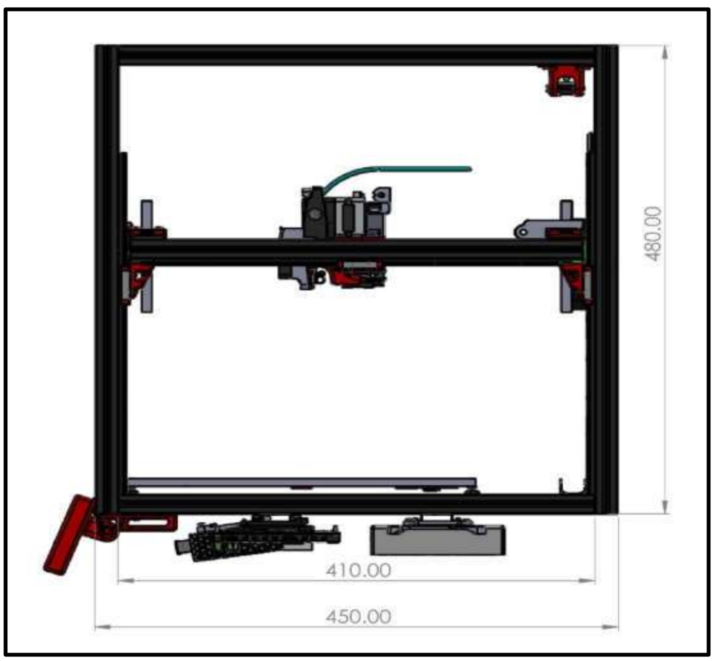


Figure 3.18: Right Side View with Dimensions (All Dimensions in mm)

The different views of the frame as an isometric view, the top, and the right-side view are shown below in Figure 3.19.

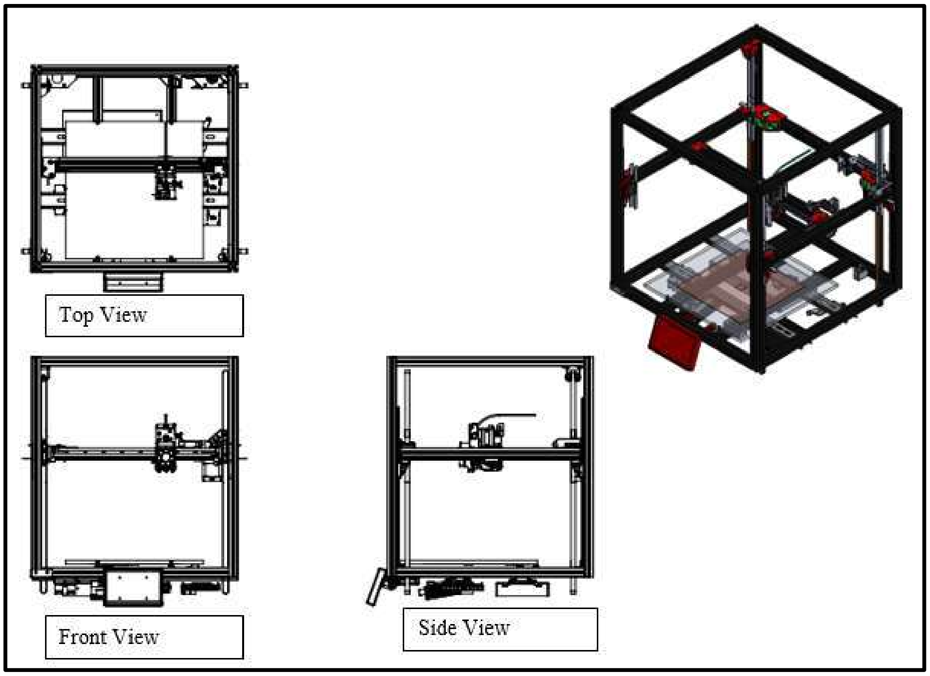


Figure 3.19: Top, Front, Isometric, and Side View of Frame

3.2.15 Extrusion System:

Two types of extrusion systems are used commonly for pumping of concrete screw type and injection type. Extrusion driving forces are provided by the extrusion mechanism for concrete extrusion. It explains the process of extruding FCP from the extruder entrance to the outlet exit figure 3.20. Extruder mechanisms are classified into three types: (1) Primary motive, (2) ram extrusion, and (3) screw extrusion.

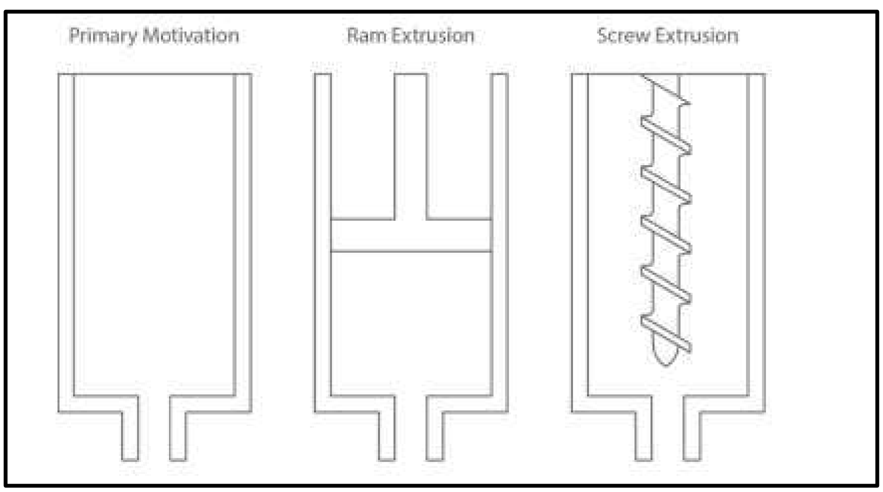


Figure 3.20: The Schematic Sketches of Extruder Mechanisms: Primary Motivation, Ram Extrusion, and Screw Extrusion

In a screw-type injection system, there is a screw that is attached to a motor which rotates it and concrete is extruded through the nozzle. But the only problem is that in a screw-type system, the extrusion may vary as it is observed that the properties of concrete vary when it moves continuously its shear force and viscosity change so, that's why the extrusion system we are using is injection type. In an injection-type extrusion system, there is a pipe that is hollow from the inside and inside it, there is a round shape material which is commonly made up of plywood.

So, the purpose of this is to pump the concrete through the nozzle. There is a screw attached to it. Which is connected to a stepper motor (Nema 17). The purpose of the stepper motor is to rotate the screw and ultimately the plywood rubber will move. Figure 3.21 shows the design of the injection-type extrusion system.

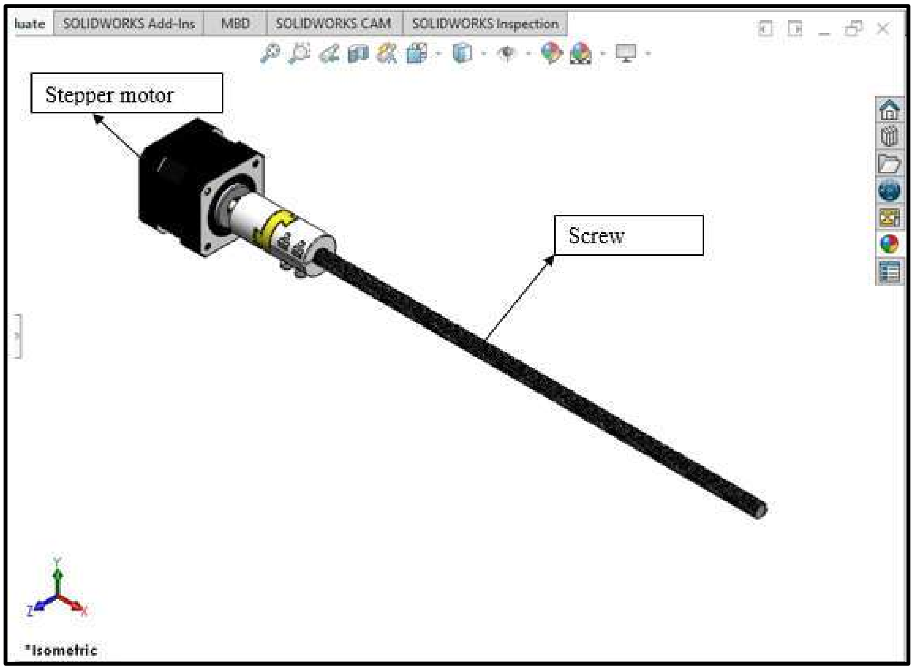


Figure 3.21: Sub Assembly of Extrusion System with Stepper Motor and T8 Screw

3.2.16 Final Assembly of extrusion system:

The final assembly of the extrusion system is shown in the figure 3.22. The final assembly contains the screw which is attached to a stepper motor that rotates the screw and the screw is attached to the solid material (rubber) in the barrel which pushes the concrete in the barrel and then towards the concrete is pumped through the nozzle.

The extrusion system of a 3D concrete printer is a crucial component responsible for depositing and shaping the concrete material to create the desired 3D printed structure. It typically consists of the following main elements:

- ***Extruder:*** The extruder is the primary component that pushes the concrete material through a nozzle or a series of nozzles. It often includes a motor or a screw mechanism to control the flow and pressure of the material. The extruder is responsible for accurately positioning the nozzle and controlling the amount of concrete being extruded.
- ***Nozzle:*** The nozzle is the opening through which the concrete material is extruded. It plays a significant role in determining the layer thickness, printing speed, and overall quality of the printed structure. Nozzles can vary in size and shape, depending on the specific requirements of the printer and the desired output.

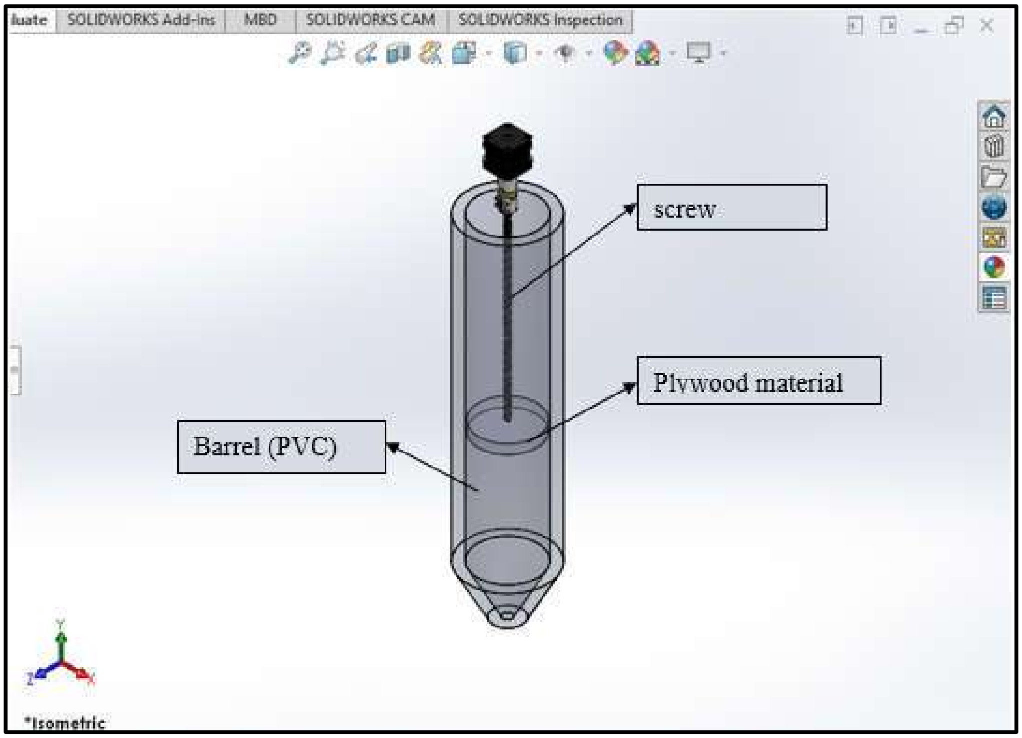


Figure 3.22: Final Assembly of Injection Type Extrusion System

- ***Material Supply System:*** The material supply system is responsible for storing and feeding the concrete mixture to the extruder. It typically consists of a hopper or a container where the concrete is placed. Depending on the design, the system may also include mechanisms such as agitators or mixers to ensure a consistent and homogenous material flow.
- ***Control System:*** The extrusion system is controlled by a computer or microcontroller that interprets the 3D model data and sends commands to the extruder. The control system regulates parameters such as the extrusion speed, nozzle movement, and layer height. It ensures precise coordination between the extrusion system and the motion control system of the 3D printer.
- ***Support Structures:*** Some 3D concrete printers may include additional support structures to aid the extrusion process. These structures can provide stability to the printed layers, especially in the case of overhangs or complex geometries. Support structures can be temporary and removed after printing or integrated into the final structure.

It's important to note that the specific design and features of the extrusion system can vary between different 3D concrete printers. Manufacturers often optimize their systems for specific applications, such as large-scale construction projects or architectural prototyping, resulting in variations in extrusion mechanisms, nozzle designs, and control systems.

CHAPTER 4: FABRICATION OF MECHANICAL STRUCTURE AND COMPONENTS

4.1 Design and Construction of Printer Frame:

One of the very first tasks that we performed was to design and construct the printer's body out of aluminium. Aluminium was preferred for frame design for its low cost and ease of working. We used a standard aluminium tube of 19mm ×19mm to assemble a square frame Fiure4.1. The frame is held together with screws at each corner. The dimension of the frame is 600× 600× 500 mm.

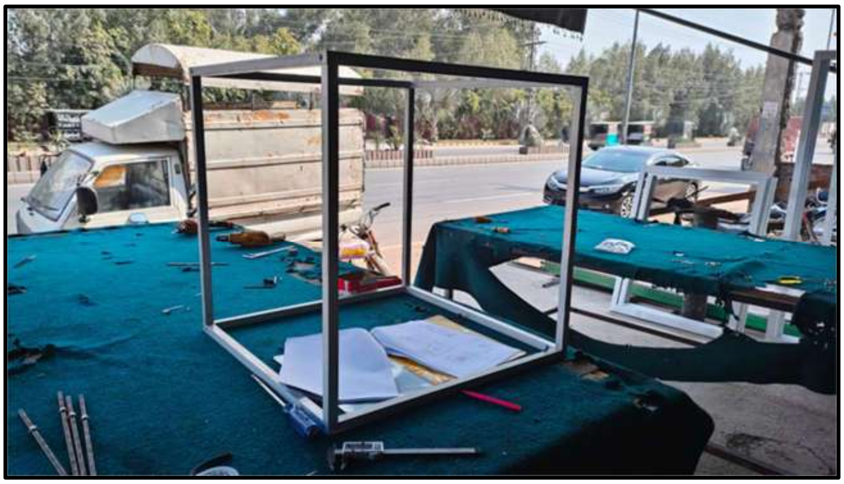


Figure 4.1: Aluminum Frame

4.2 Welding of Stainless-Steel Rods:

The gantry was made with square shaped stainless-steel tube of dimension 3/4' x3/4', the reason we selected stainless steel for the base frame is directly attached to the nozzle and requires structural integrity to resist any vibration as concrete is being deposited layer by layer figure4.2. So, the frame should be capable enough to withstand the weight of the concrete-filled nozzle. The working area we are left with is 350×350×350mm, the stainless-steel tubes are welded together to form the base frame. We use electric-arc welding to weld these tubes by using welding rods for SS.

Figure 4.2: Welding for Stainless Steel Frame and Motor Brackets

4.3 Fabrication of the Gantry System:

In the fabrication of the gantry system, for the support of the legs of the gantry, we use aluminium section (used in window frames) pieces from scrap, this forms the path for movement of the base frame on the z-axis. The pieces are cut and bolted in the center of the axis accordingly, and smooth stainless steel(8mm) rods are inserted in the aluminium brackets. The two stainless steel rods were passed through two holes on the side faces of the two brackets by keeping the distance between rods equal throughout the length to ensure precise movement along the axis of the frame (figure 4.3). This moves the gantry on the z-axis.

Figure 4.3: Z-Axis path

Similarly, For the rails on the x and y-axis, small pieces of aluminium are used and aligned such that there is no difference between alternate axes that can restrict ease of movement. figure 4.4

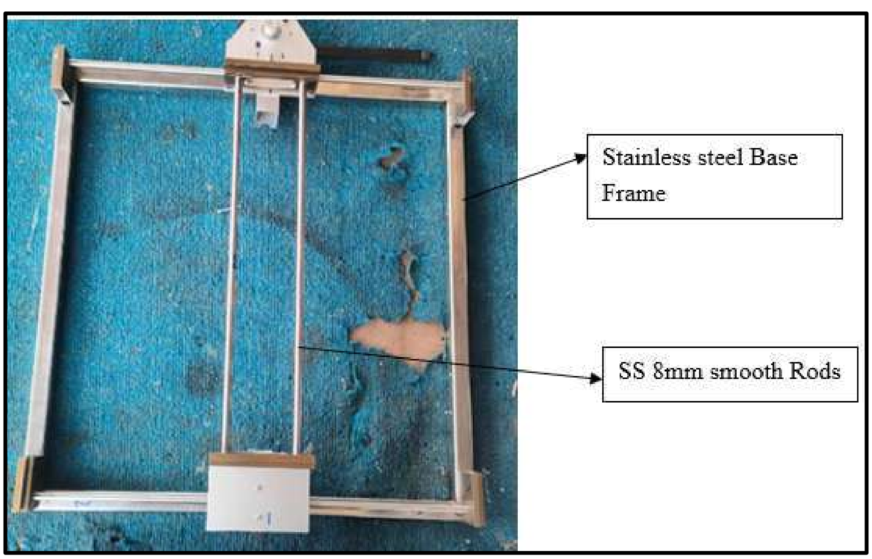


Figure 4.4: Y- Axis Arrangement

Then, afterward, the base frame is fitted into the main frame to check whether it is dimensionally correct or not, it is verified by observing the movement of the frame, because if there is any misalignment in the assembly or distances between the rods are inconsistent it will lead to the failure in the movement of the whole gantry system (figure 4.5). Since the motion of the nozzle is linked with it so if there is any misarrangement in the assembly it will cause a lag in the motion, and the required speed of the nozzle for printing will not be achieved and ultimately there will be failure in the printing process.

Figure 4.5: Gantry System without Motor Installation

4.4 Fabrication of Corner Brackets, Motor Block, and Pulley:

Aluminium plates were used as brackets for the rails of the x-axis on the edges of the gantry frame. SS rods were force-fitted in the aluminium brackets to avoid any play, which would have caused misalignment between adjacent rails that would result in obstruction in movement in the x-axis. Two Nema 17 motors were fitted using motor mounting brackets fitted just below the rods. A T8(SS) rod was connected to the motor shaft using flexible coupling and the other side of the T8 rod was force-fitted in another aluminium plate.

Then we made two additional blocks named motor block and pully block using the same material(aluminium). These blocks are responsible for the movements of the nozzle along the Y-axis and had to be mounted on the fixed rails of the X-axis using linear bearings. Both these blocks move along these fixed rods. On the motor bracket, mounted the stepper motor, and on the shaft of the motor, a pulley (GT2) was connected. The pulley was connected to the motor shaft using a timing belt. figure 4.6

Again, we used two SS smooth (8mm) rods to form rails of the Y-axis on which the nozzle is to be mounted. The nozzle mounting plate is fitted with four linear bearings for movement along the rails. Alignment is again crucial in these rails for easy movement of the nozzle along the Y-axis.

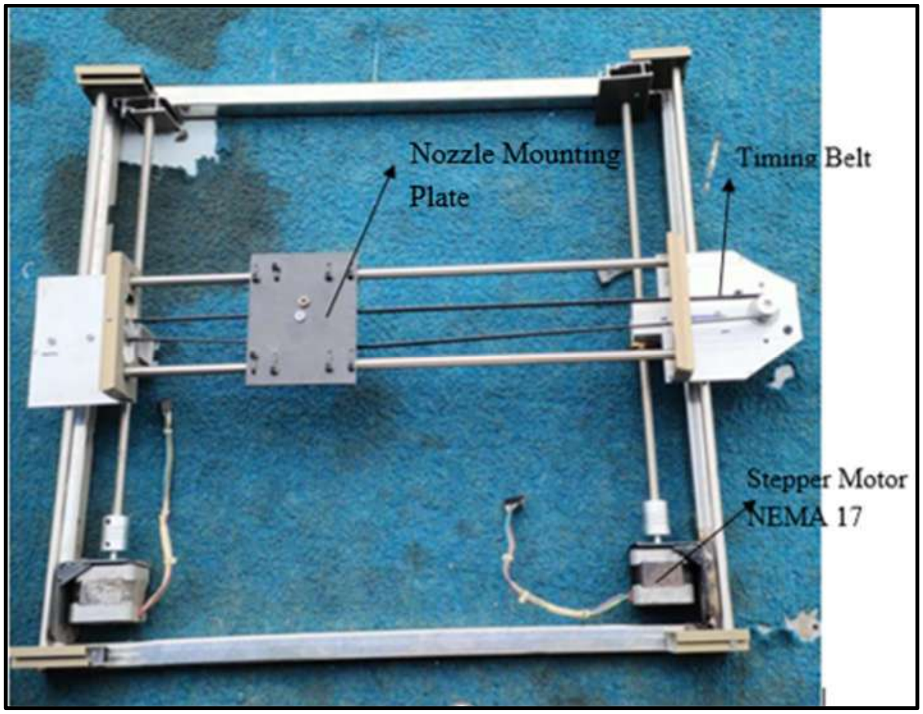


Figure 4.6: The Complete Fabrication of Y-Axis with Stepper Motors and Timing Belt

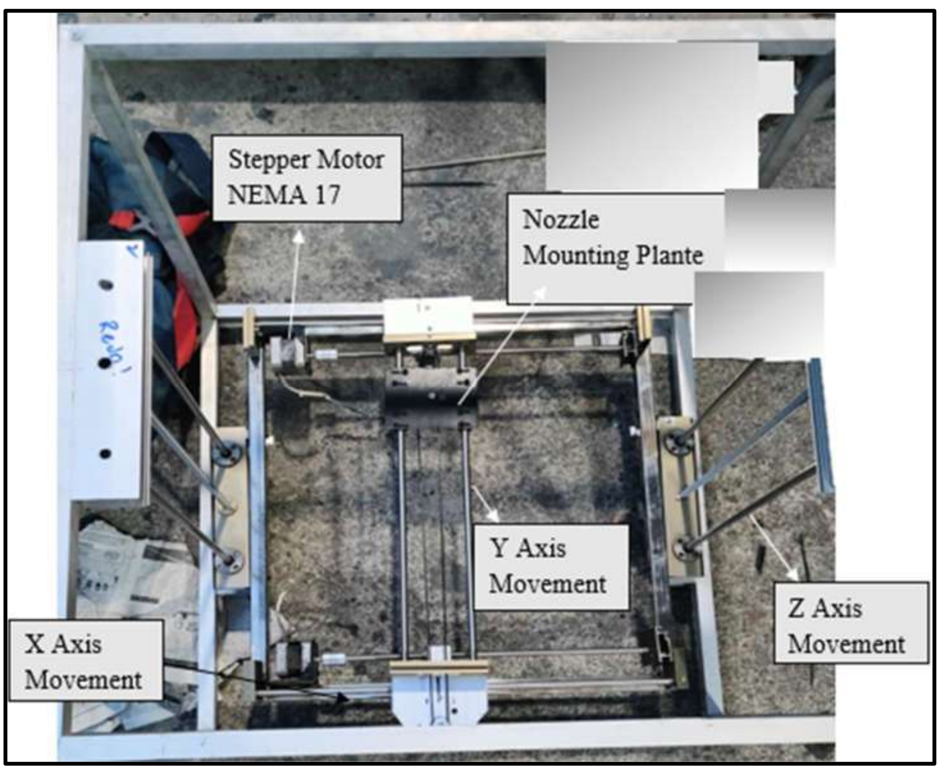


Figure 4.7: Complete Fabrication of Gantry System Assembled View

4.5 Extrusion system:

For the fabrication of an injection type extruder, we use a PVC pipe for the housing to contain the concrete, the size of the pipe will determine the quantity of concrete for one batch. The plunger consists of a round plate of compressed plywood with a layer of rubber attached to the bottom of the plate. The wooden plate is connected to the power screw via a bearing using iron glue (Magic Depoxi steel). A lead screw is used to drive the plunger along the pipe. The screw is attached to the wooden plate via a bearing so that only the translatory motion of the screw is transmitted to the plunger.

The main purpose of using a bearing between the screw and plate is to cancel out the rotational motion of the screw since rotational motion will result in excessive friction between the cylinder's internal surface and plunger rubber, this can affect the working efficiency of the system and can increase the torque requirement for the process, and also wear and tear in rubber will reduce the life of the rubber.

A stepper motor will be used to drive the power screw, the shaft of the motor is connected to the screw with a rigid coupling. figure 4.8. So, we can say that the motor will drive the screw and the screw will provide translatory motion to the plunger which will ultimately extrude the concrete.

Figure 4.8: PVC Pipe Extruder with Rubber Inside for Concrete Extrusion

4.6 Fabrication of Nozzle:

The type of nozzle we are using is made of parts used for gas pipe fittings. It includes the stepper motor Nema 17, Long bolts, rigid coupling, tee-shaped 3-way fitting, and hose barb fitting. So, the basic principle is that the motion of the motor will drive the screw inside the nozzle which will cause the deposition of the concrete layer through that nozzle opening. So, we went to Brandreth Road to get these parts since these parts were not available in the required dimensions at a local market.

Some of the parts were purchased from the sanitary shop like tee-shaped 3-way male fitting of ¼'' of SS (figure 4.9), screw PCB standoffs hexagonal Spacers M3 male× Female 40mm as shown in figure 4.10, were required initially but due to their unavailability we had to use simple M3 50mm bolts, while the other remaining parts like M8 tap bolts hexagonal selftapping wood screws of 304 stainless steel, SS ¼'' nut, hose barb fitting adapter ¼'' 3mm figure4.11 were purchased from Brandreth road.

Figure 4.9: Tee-Shaped 3-Way Male Fitting of ¼'' of SS

Figure 4.10: Screw PCB Standoffs Hexagonal Spacers M3 Male× Female 40mm

The extrusion of the concrete is through the nozzle end which in our case is the hose barb fitting adapter indicated in (figure4.11).

Figure 4.11: SS ¼'' Nut, Hose Barb Fitting Adapter ¼'', 3m

So, the complete fabrication of the nozzle for the extrusion, which is in our case is hose bard fitting indicated in (the figure4.12) with a screw inside for mixing.

Figure 4.12: The Final Fabrication of The Nozzle with Motor Mounting Plate and Coupling

4.7 Installation of Worm Gear:

For the extruder the stepper motor was insufficient in providing necessary torque for pushing the concrete so we had to install a worm gear between the screw and the motor with a gear ration of 1:30 to supply the required torque. Two sleeves with shaft key pins were fabricated for the worm gear apparatus to attach the stepper and the lead screw. As shown in figure 4.13.

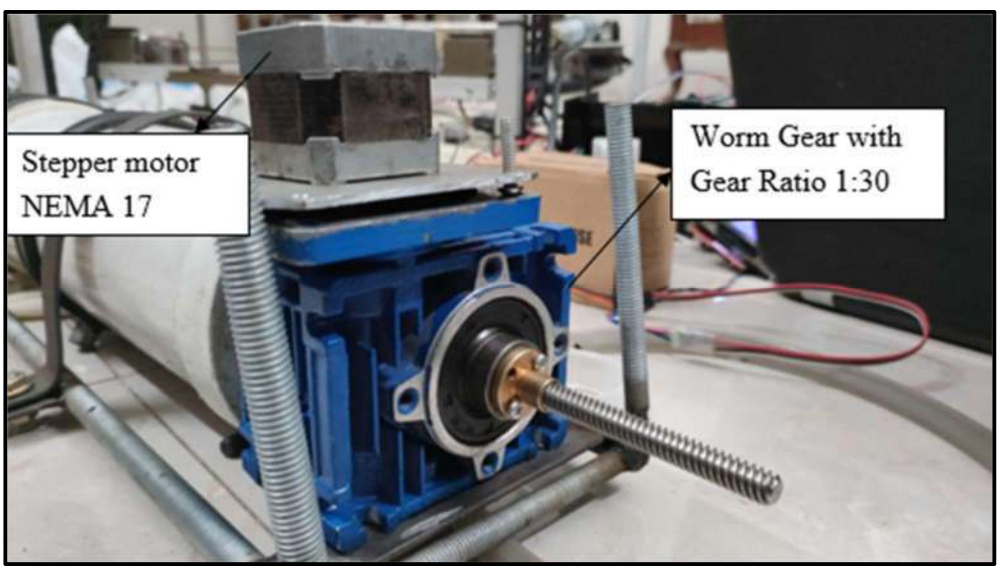
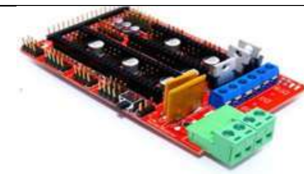


Figure 4.13: Installed Worm Gear with Extruder

4.8 Electrical Parts with Description:

Table 4.1: Electronic Operating System Parts and Accessories

Sr. No	Electronic Operating System Parts and Accessories	Pictures
1	NEMA 17 stepper motor	
2	Arduino Mega R2560 R3 ATMEGA16U2	
3	RAMPS Shield 1.4 3D Printer Control Board	
4	RAMPS 1.4 3D Printer 2004 LCD Controller with SD Card Slot	
5	A4988 Stepper Motor Driver	
6	3D Printer Mechanical Limit Switch Module Board V1.2 end stop	
7	Rigid Coupling 5×8mm Shaft Coupler	

8	Flexible Coupling 5×8mm Shaft Coupler 5mm to 8mm	
9	LM8UU Linear Ball Bearing Bushing CNC 8×15×24mm for 3D Printers	
10	GT2 Timing Pulley 5mm 20 Teeth	
11	GT2 Timing Belt GT2-6mm 16 Teeth	
12	6Volt DC Gear Motor	

4.9 Installation of the RAMPS and Arduino Mega:

The first thing that we had to decide to install the Arduino and Ramps was to decide their location. Once the location was decided, the wires coming from all components were extended so that they can reach RAMPS Figure 4.14. For the wires coming from moving components, we had to take into consideration that they should not stretch too much upon reaching their extreme positions.

Figure 4.14: RAMPS Board

Secondly, we have to solder all the required connectors that are compatible with it. It is pressed against the Arduino Mega so that the pins coming out of it are inserted into the Arduino Mega, with the same sequence. One of the most difficult tasks that we faced while making printer connections is the connection of all wires to the RAMPS one wrong connection will lead us towards a short circuit of the RAMPS board and it will be useless.

But the use of web sources and one of our friends from the electrical engineering department helps us in making the right connections. The circuit diagram of the RAMPS Arduino Mega also helps us in making the right connections. Figure 4.15 indicates the location of the connection of every component on RAMPS. As figure 4.15 shows the circuit diagram of RAMPS connections. This is one of the approaches to easily connect the circuit. But one of the wrong connections will cause a short circuit in the board.

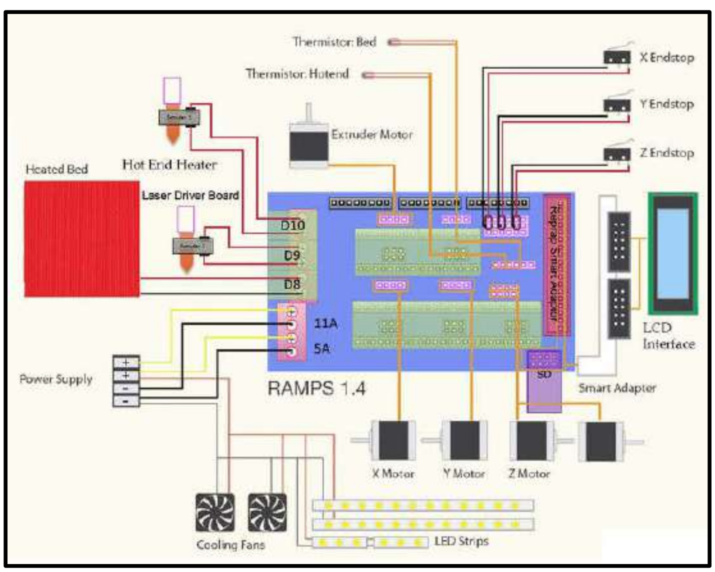


Figure 4.15: Circuit Diagram Indicating Various Connections Between the Components and RAMPS

A typical RAMPS 1.4 is shown in Figure 4.16, so it should be used with proper connection in our project. Each part in the board has its specification so the connections should be made right.

Figure 4.16: the 1.4 RAMPS Board

After the connections were made, now we have to configure and set up the software. so, the following step was followed:

Firstly, we installed Arduino IDE Figure 4.17. As IDE stands for Integrated development environment which is integrated into the program for Arduino microcontroller. It is the most widely used software for 3D printers. It communicates with RAMPS to install the firmware.

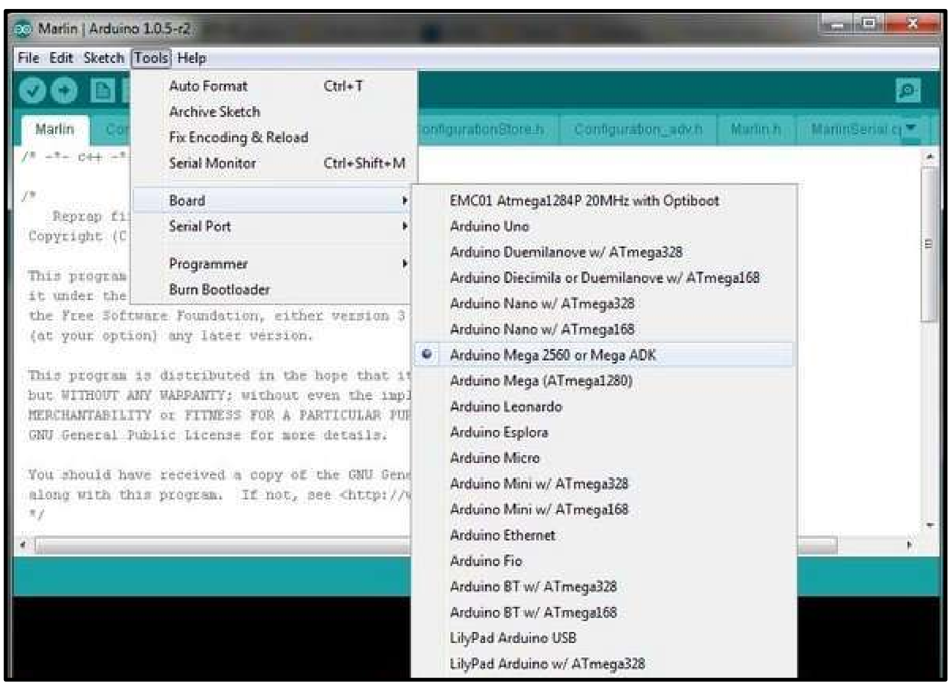


Figure 4.17: A Snapshot of Arduino IDE Software

After the Arduino IDE is installed, we connected Arduino Mega with a computer to verify that it is in working condition. Then we open Marlin firmware figure 4.18 on Arduino IDE and update it. Marlin is a firmware for RepRap single processor electronics, supporting RAMPS, Rambo, Ultimaker, BQ, and several other Arduino-based 3D printers' Figure 4.18. So, a file can be given to it in the form of a USB or from an SD card. It consists of a long series of codes that default values of various parameters of the printer. For example, the default acceleration of X, Y, and Z axis motion. Furthermore, default extruder heating temperature, Bed heating temperature, etc.

```
Send: M503
Recv: echo:; Linear Units:
Recv: echo:  G21 ; (mm)
Recv: echo:; Temperature Units:
Recv: echo:  M149 C ; Units in Celsius
Recv: echo:; Filament settings (Disabled):
Recv: echo:  M200 S0 D1.75
Recv: echo:; Steps per unit:
Recv: echo:  M92 X80.00 Y80.00 Z400.00 E93.00
Recv: echo:; Max feedrates (units/s):
Recv: echo:  M203 X300.00 Y300.00 Z25.00 E60.00
Recv: echo:; Max Acceleration (units/s2):
Recv: echo:  M201 X500.00 Y500.00 Z100.00 E1000.00
Recv: echo:; Acceleration (units/s2) (P<print-accel> R<retract-accel> T<trav
el-accel>):
Recv: echo:  M204 P500.00 R800.00 T1000.00
Recv: echo:; Advanced (B<min_segment_time_us> S<min_feedrate> T<min_travel_f
```

Figure 4.18: Marlin firmware Code and Some Default Values

So, in our case, we have to turn off the heating element since our printer is made to produce concrete structures so in that case, we off the heating elements. So, to calculate the x, y, and z axis there is also a manual control to control these axes .as shown in Figure 4.19.

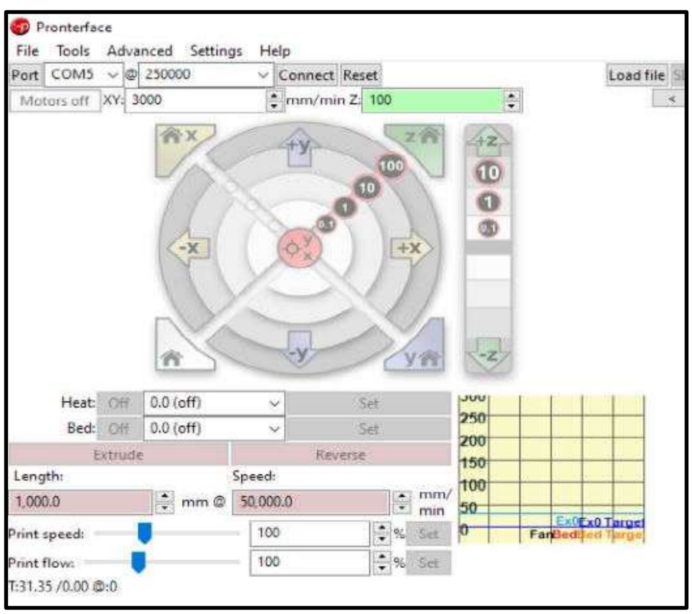


Figure 4.19: A Snapshot of Manual Control Panel of Repetier Host Software

4.10 Final Assembly of the 3D Concrete Printer:

The final assembly of the 3D concrete printer is shown in the figure below 4.20. The only change is that we have changed the stain less steel base with aluminium. Since the base frame of SS is heavy and the frame is getting load and can undergo bending so, to avoid that we have replace it with aluminium with same dimensions.

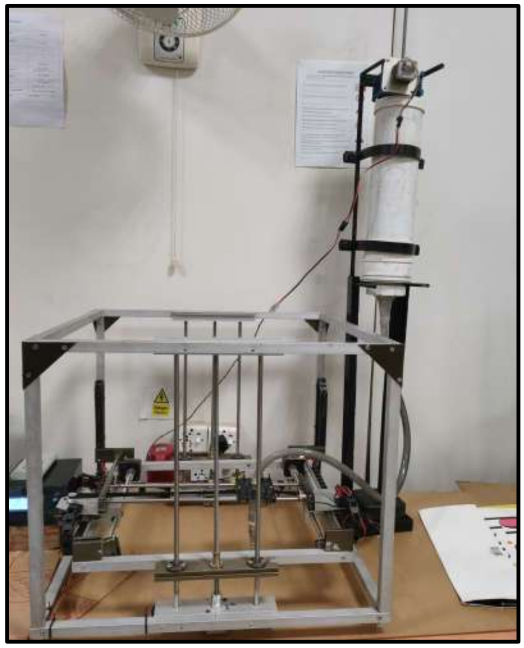


Figure 4.20: Complete Assembly of Frame

4.11 Selection of the right Concrete mixture:

The concrete we need for this application must have the required characteristics like adequate flowability since it needs to be passed through the extruder and nozzle, certainly, the viscosity for this mixture needs to be less than that of a regular concrete mixture. For achieving the desired characteristics, we need some additional chemicals for the mixture. The constituents we are using include ordinary Portland cement (OPC), Fly ash, silica Fume and water. Silica fume and fly ash are unique in this mixture also coarse aggregate is not used in this mixture. The percentages of each constituent in the mixture are shown in the table below

Table4.2: Selected Percentages of Concrete Mixture

Material	**Selected Percentage (%)**
Cement	0.16
Sand	0.220
Fly Ash	0.250
Water	0.350
Silica Fume	0.020

Rapid hardening cement is usually preferred for concrete printing, but with the addition of these chemicals like silica fume and fly ash, the required characteristics can be achieved. The mixture used for the experiment was acquired from a research project [29] and the results were satisfactory but just in case the mixture does not yield the desired characteristics, we also purchased a cement hardening accelerator. The role of the accelerator is to further reduce the settling time of concrete. As far as the availability of mixture components is considered some of the things like OPC, sand, and water are available easily as in Figure 4.21. But for silica fumes and fly ash, we have to towards Sheikhupura to get these two chemicals.

After getting these components we had to move towards testing the right mixture. As the concrete should be deposited layer by layer, the first layer should be strong enough to bear the weight of the second layer and should not fail due to buckling. For this purpose, silica fume is used which increases the early age strength of the concrete layer. According to the research, these constituents will reduce the settling time from 45 min to 15 mins, we can further reduce this time by using an accelerator in the mixture.

Figure4.21: Silica Fume and Accelerator for Concrete Mixture

4.12 Preparation of Concrete Mixture:

For preparation of adequate mixture, we need to first prepare the dry mix of all the constituents, before adding water. The proper procedure for this is to use a mixer at different speeds as used in the research. Since we couldn't obtain a mixer, the mixing was done manually. The dry mix was mixed for at least five minutes with a spatula. Uniformity of mixture was achieved after mixing for 4 to 5 minutes. When the mixture is thoroughly mixed, we need to add water just before the mixture is to be filled in the extruder.

As the addition of silica fume to the mixture decreases the settling time, we need to transfer the concrete mixture to the extruder as quickly as possible. The time gap in printing after the addition of water to the mixture should be minimized as much as possible.

For this purpose, first, the structure to be printed is prepared on the software, and data is transferred to Arduino via cable, the rest will be controlled using an LCD monitor. How this works is that first we will start the extruder motor and wait for the concrete to reach the nozzle, as the concrete approaches the exit point of the nozzle the program is initiated and the nozzle will start printing.

4.13 Testing of Concrete Mixture:

In the beginning, we started by printing manually using the same composition as mentioned in Table 4.1, only two layers were printed for observing the behavior of the printed layer. The behavior of the layer after five minutes is shown in Figure 4.21. The layer did not maintain structural integrity as can be seen in the figure the second layer spread completely. Failure due to spread can be accredited to an insufficient amount of silica fume and an excess quantity of water in the mixture. Another observation was that due to unequal distribution of water in the mixture.

The mixture first let out the water leading to failure which shows that appropriate time must be given for mixing after water addition. The reason for the presence of excess water is that fly ash absorbs excess water and maintains uniformity of water distribution in the mixture, so when we didn't give proper time for mixing after adding water, this led to water being separated from the mixture. This led to two different modes of failure.

First, only the water-rich mixture has extruded which led to the compressive failure of the deposited layer, then the remaining mixture was left with an insufficient amount of water for extrusion, as the mixture left with less water led to an increase in torque requirement so we had to terminate the whole process and revisit the mixture.

Figure 4.22: Behavior of Concrete Mixture when there is an Excess of Water in the Mixture

The priority was to ensure proper mixing of the mixture, if the same failure persisted in the following tests, then it would become crucial to change the percentages of mixture constituents. The next test was done after mixing water for at least 5 minutes, and the results of extrusion are shown in Figure 4.23. As can be seen in the picture at point the layer is set accurately and no failure was observed in the structure where the layer width is uniform.

At point 2 marked in Figure 4.23, the layer fell to a side because of the excessive weight of the layer as the thickness is not uniform as the speed of movement of the operator's hand is varying. It can be said that the only problem is the travel speed, the mixture itself is adequate for this process.

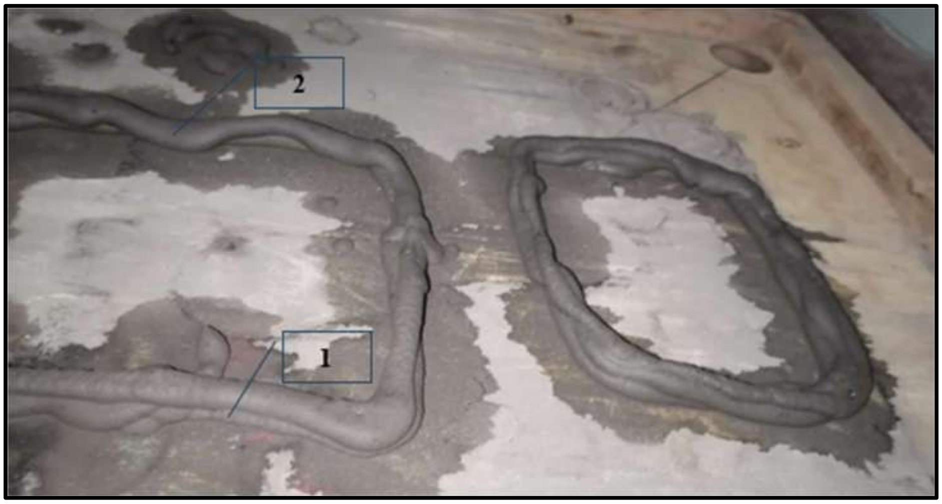


Figure 4.23: The Buildability and Sustainability of Concrete Layers

After several trials, we can make a square box finally. We face many problems during the extrusion of concrete through the nozzle. The proper flow of concrete is necessary for the extrusion of concrete. So, once the flow of the concrete is controlled, we can print the required structure. The structure that we have printed using the same designed ratios is as follows in Figure 4.24.

Figure 4.24: (a) The 3D Printer Pyramid-Like Shape (40 × 20mm) (b) The 3D Printer Pyramid-Like Shape (40 × 40mm)

So, in the next attempt, we have to change the dimension of the shape and print again the structure as given below in Figure 4.24.

CHAPTER 5: DISCUSSION

A 3D concrete printer is a machine that uses additive manufacturing techniques to fabricate large-scale structures or components using concrete or other cementitious materials. It represents an innovative construction approach, offering numerous benefits and possibilities for the industry. 3D concrete printing involves the layer-by-layer deposition of concrete or cementitious materials through a gantry system. The printer follows a predetermined design, which is given to it in the form of G and M codes. Extruding the material in a controlled manner to create the desired structure. The printing process can be either continuous or intermittent, depending on the specific printer and project requirements.

5.1 Material Considerations:

The choice of concrete or cementitious materials is crucial for successful 3D printing. Special formulations are often developed to optimize the material properties for printing, including flowability, setting time, and strength development. Various types of cement, aggregates, and additives can be used, depending on the desired characteristics and project requirements. Achieving a suitable and sustainable mixture is our main goal since the mixture should be workable and extrudable at the same time. Workability of the mixture refers to the buildability of the mixture, that the deposited layer must maintain its shape and bear the weight of the incoming layer without collapsing, and extrudability is the ease of pumping, the mixture should not be viscous to the extent that extrusion becomes difficult. So, we are using OPC, silica fume, fly ash, and water. Certain percentages of these chemicals are used for our mixture.

5.2 Challenges:

Despite the potential, there are still difficulties to be overcome with 3D printing of concrete. Since current printers frequently have size limitations, scaling up the technology for large-scale construction projects is one of the key limitations. Additionally, research is continually being done to ensure the long-term endurance and structural integrity of printed components. To improve the technology any further, it is necessary to pay attention to other issues such as material development, cost-effectiveness, and regulatory frameworks.

Overall, the future of 3D concrete printing holds immense potential for transforming the construction industry. As technology advances, addressing challenges, and exploring new applications, it is expected to see wider adoption and the emergence of innovative construction methods that revolutionize the way we build. However, there are still challenges to overcome for widespread adoption. Material development plays a critical role in optimizing the properties of 3D-printed concrete, such as strength, durability, and sustainability. Further advancements are needed to enhance the printability and performance of concrete mixes, as well as explore the use of alternative materials.

Automation and robotics are key areas for future development. Continued research in this field can lead to faster printing speeds, improved control systems, and the integration of 3D concrete printers with other construction processes. Scaling up the technology for large-scale projects, such as buildings and infrastructure, is another avenue of exploration. So, in conclusion, we can say that while there are some challenges to address, the prospects of 3D concrete printing are highly promising. With ongoing research and development, we can expect to see advancements in material science, automation, design optimization, and sustainability, leading to wider adoption and the transformation of the construction industry.

Chapter 6: CONCLUSION AND FUTURE DIRECTION

In conclusion, 3D concrete printing has demonstrated its potential to revolutionize the construction industry by offering increased efficiency, design freedom, and sustainability. Its benefits include reduced labor requirements, faster construction timelines, intricate geometries, and optimized material usage. However, there are still challenges to overcome, such as scaling up the technology, ensuring structural integrity, addressing material considerations, improving cost-effectiveness, and developing regulatory frameworks. Future work in 3D concrete printing should focus on several areas:

6.1 Scaling Up:

Advancements in printer design, gantry systems, and material delivery mechanisms are needed to enable the construction of larger and more complex structures. Research and development efforts should focus on improving the scalability and adaptability of 3D concrete printing technology.

6.2 Material Development:

Continued research in concrete mix designs and material properties is necessary to optimize the printability, strength, durability, and sustainability of 3D printed components. Exploring alternative cementitious materials and additives can lead to improved performance and cost-effectiveness.

6.3 Structural Integrity and Durability:

Further studies are required to ensure the long-term structural integrity and durability of 3D-printed concrete. Testing and validation of printed components under different environmental conditions, loading scenarios, and aging processes will help establish standards and guidelines for quality assurance.

6.4 Cost Reduction:

Efforts should be made to optimize the printing process, reduce material costs, and streamline workflows to enhance the cost-effectiveness of 3D concrete printing. Collaboration between researchers, industry professionals, and manufacturers can help identify cost-saving opportunities and improve economic viability.

6.5 Sustainability:

3D concrete printing could lead to more sustainable construction practices, as it typically uses less material than traditional construction methods. This could be combined with the use of recycled or more sustainable materials to further reduce the environmental impact.

6.6 Regulatory Frameworks:

Collaboration between industry stakeholders, researchers, and policymakers is essential to develop standardized guidelines and regulations that address the safety, quality, and compliance aspects of 3D printed structures. This will provide clarity and confidence for wider adoption and integration of the technology.

6.7 Affordable Housing:

As the technology matures, it could be used to provide affordable housing solutions in regions where construction costs are typically high or in developing regions where there's a significant need for rapid, cost-effective construction.

By addressing these areas of future work, 3D printing technology is rapidly advancing and is becoming a disruptive innovation in many sectors, including construction. 3D concrete printing is already showing potential in the construction industry, offering the possibility of reducing costs, saving time, increasing productivity, and minimizing environmental impact. 3D concrete printing can evolve into a mature and widely accepted construction method, offering sustainable, cost-effective, and innovative solutions for the built environment. Continued research, collaboration, and technological advancements will be instrumental in unlocking the full potential of this transformative technology.

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