DESIGN AND FABRICATION OF CIVIL 3D PRINTER

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Abstract

The advent of 3D printing technology has revolution- ized the construction industry, offering innovative so- lutions for rapid, cost-effective, and sustainable build- ing practices. This research paper presents a compre- hensive study on the manufacturing and fabrication of a 3D concrete printer tailored for large-scale construc- tion applications. The paper outlines the design princi- ples, mechanical and electrical systems, material con- siderations, and software integration necessary for the development of an efficient and reliable 3D concrete printer.

Key components of the printer, including the frame, extrusion system, and control mechanisms, are meticulously designed to ensure precision, stability, and durability. Advanced materials such as high-performance concrete mixes are formulated to meet the unique requirements of 3D printing, balancing workability, strength, and setting time. The integration of sensors and automation technology facilitates real- time monitoring and control, enhancing the accuracy and consistency of the printed structures.

The implementation phase involved extensive testing and validation, highlighting the printer's capability to construct complex geometries and large-scale ele- ments with minimal human intervention. Results indi- cate significant improvements in construction speed, cost savings, and material efficiency compared to tra- ditional methods. The paper concludes with a discus- sion on potential applications, challenges, and future directions for 3D concrete printing technology in the construction industry.

Introduction

The convergence of 3D concrete printing, stepper mo- tors, and advanced firmware and software technolo- gies such as Marlin Firmware, Pronterface, and Slic3r presents an exciting landscape for innovative research in construction technology. This intersection opens new avenues for exploring precision engineering and additive manufacturing in the realm of concrete con- struction. With its ability to revolutionize traditional construction methods, 3D concrete printing offers unparalleled opportunities for enhancing efficiency, sustainability, and design flexibility in building pro- cesses.

By harnessing the capabilities of stepper motors and sophisticated firmware and software platforms, researchers can delve into optimizing printing pa- rameters, refining material compositions, and stream- lining construction workflows. Stepper motors play a crucial role in controlling the movement of print- ing nozzles, ensuring accurate concrete deposition and the realization of complex geometries. Advanced firmware and software tools like Marlin Firmware, Pronterface, and Slic3r facilitate seamless communi- cation between computers and 3D printers, enabling precise control over printing parameters and translat- ing 3D models into printable layers.

This convergence sets the stage for investigating the transformative potential of additive manufactur- ing technologies in the realm of concrete construc- tion. Through meticulous research and development, researchers aim to redefine the future of building in- frastructure by leveraging the capabilities of 3D con- crete printing, stepper motors, and advanced firmware and software technologies. The ultimate goal is to advance construction practices, enhance sustainabil- ity, and drive innovation in the construction indus- try. Stepper motors play a critical role in the suc- cess of 3D concrete printing systems. These precise electromechanical devices convert digital signals into mechanical motion, providing accurate control over the movement of printing nozzles or extruders. Their ability to execute intricate movements with high pre- cision ensures the accurate deposition of concrete lay- ers, resulting in high-quality printed structures. More- over, stepper motors contribute to the versatility of 3D printing technology by enabling printers to produce a wide range of shapes and structures with fidelity, from simple geometries to intricate architectural forms.

Advanced firmware and software technologies, in- cluding Marlin Firmware, Pronterface, and Slic3r, complement the hardware components of 3D print- ing systems by facilitating seamless communication and precise control. Marlin Firmware serves as the firmware that controls the hardware components of the printer, while Pronterface acts as a user inter- face software that enables users to control printer settings and monitor the printing process. Slic3r, on the other hand, plays a crucial role in the slicing process by converting 3D models into a series of printable layers, providing instructions for the printer on how to construct the final object. Together, these firmware and software tools empower researchers to optimize printing parameters, refine material compositions, and streamline construction workflows, ultimately driving innovation in the field of construction technology.

This convergence of technologies sets the stage for investigating the transformative potential of additive manufacturing in the realm of concrete construction. Through rigorous research and development efforts, researchers aim to redefine the future of building infrastructure by leveraging the capabilities of 3D concrete printing, stepper motors, and advanced firmware and software technologies. The ultimate goal is to ad- vance construction practices, enhance sustainability, and drive innovation in the construction industry, ul- timately benefiting society as a whole

Litrature Review

Ayesha Siddika in his paper described that the Automatic construction systems have become the focus of the construction industry and research projects world- wide. Numerous technologies involving 3D printing (3DP) of concrete elements have been developed, and their application in construction projects has been growing. The 3DP in concrete construction is in- creasing due to its freedom in geometry, rapidness, formwork-less printing, low waste generation, eco- friendliness, cost-saving nature, and safety. Develop- ment of 3DP is not only limited to the earth but also gaining attention for building habitats in space.

Bos et al. (2016) discuss the significance of control systems in managing the extrusion rate, layer resolu- tion, and path planning. Advanced control algorithms are essential for achieving consistent print quality and preventing defects such as cracking and delamination. The integration of real-time monitoring systems and feedback loops has been proposed to enhance the reli- ability and accuracy of the printing process. Accord- ing to **Le et al. (2012)**, printable concrete must pos- sess specific rheological properties to ensure it can be extruded smoothly and maintain its shape upon de- position. The mix design typically includes a com- bination of cement, aggregates, additives, and water, with variations depending on the desired properties of the final structure. **Kazemian et al. (2017)** em- phasizes the role of additives, such as superplasti- cizers and accelerators, in enhancing the printability and setting time of concrete. Additionally, fiber rein- forcement has been investigated to improve the me- chanical strength and durability of printed structures. The balance between workability and strength is a key challenge, and ongoing research aims to develop op- timized mix designs that meet the demands of var- ious construction applications. A study by **Wolfs et al. (2019)** explores the use of Building Information Modeling (BIM) to streamline the design and print- ing process. BIM enables the creation of detailed dig- ital models that can be directly translated into print- ing instructions, reducing errors and enhancing co- ordination among project stakeholders. A case stud- ies by **Asprone et al. (2018)** illustrate the use of 3D printing for fabricating complex architectural el- ements, such as curved facades and intricate lattice structures. These projects showcase the design flexi- bility offered by 3D printing, enabling the creation of unique geometries that would be challenging or im- possible to achieve with conventional techniques. **Bos et al. (2018)** call for the development of industry stan- dards and testing protocols to validate the structural integrity of printed elements. Additionally, the envi- ronmental impact of concrete printing is a topic of growing concern. Research by **Paul et al. (2020)** ex- plores the potential for using alternative binders, such as geopolymer concrete, to reduce the carbon foot- print of 3D-printed structures.

Design and Fabrication of the 3D Concrete Printer

Frame and Structure

Figure 1: frame with all x,y,z setup

The frame and structure form the backbone of the 3D concrete printer,providing the necessary support and stability for all components. The frame is typi- cally constructed from strong, durable materials such as steel or aluminum, which can withstand the forces generated during the printing process and support the weight of the concrete being extruded.

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Materials

1. **Steel:** Known for its high strength and durability, steel is a common choice for the printer's frame. It can handle significant loads and provides excellent stability.
2. **Aluminum:** Lighter than steel, aluminum is also used due to its good strength-to-weight ratio. It is easier to work with and resistant to corrosion.

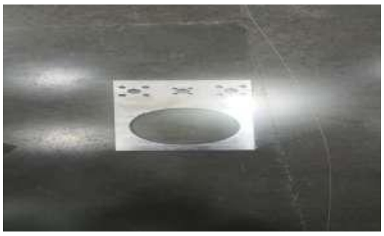

Figure 2: aluminium piece

Motion Control System

The motion control system is responsible for the pre- cise movement of the print head along the X, Y, and Z axes. This system uses stepper motors, linear guides, and control electronics to achieve accurate position- ing, ensuring that the concrete is extruded in the cor- rect locations.

Components

1. **Stepper Motors:** These motors provide precise control over the position of the print head. They move in fixed steps, which allows for accurate con- trol of movement.
2. **Linear Guides:** These guides ensure smooth and accurate movement of the print head along each axis.
3. **Control Electronics:** Microcontrollers and drivers manage the operation of the stepper motors, trans- lating digital instructions into precise movements.

Extrusion System

Figure 3: main extruder parts

The extrusion system is a critical component of the 3D concrete printer.responsible for delivering the concrete mix to the print bed in a controlled manner. This system must handle the unique properties of the concrete mix, ensuring consistent flow and preventing blockages.

Concrete Extruder Nozzle

Figure 4: all 3 nozzle

The nozzle design is crucial for controlling the flow of concrete.

- Material: Typically made from durable materials such as stainless steel to withstand abrasion and corrosion.
- Diameter: The nozzle diameter is selected based on the desired resolution and flow rate. Smaller diam- eters provide higher resolution, while larger diam- eters allow for faster printing.
- Shape: The shape of the nozzle affects the layering and surface finish of the printed structure. Common shapes include cylindrical and conical designs.

Pumping Mechanism The pumping mechanism must provide a steady and controllable flow of con- crete to the nozzle.

- Pump Type: Common types include peristaltic pumps and piston pumps. Peristaltic pumps are known for their ability to handle viscous materials and provide a pulseless flow, while piston pumps offer high pressure and precision.
- Flow Control: Precise control mechanisms ensure consistent extrusion rates, which are essential for maintaining print quality.
- Mix Agitation: Prevents settling of the concrete components and maintains a homogeneous mix. This can be achieved through mechanical stirrers or recirculation systems.

Materials and Components

Concrete Materials

Figure 5: All materila used in mix design

The concrete 3D printer is used to print the con- crete structures like walls, bricks, columns, beams, foundation etc. The materials used in concrete mak- ing include:

O.P.C. Cement

Figure 6: cement

O.P.C. Cement is used due to its good balance of strength and workability.

- Properties: Provides high compressive strength and adequate setting times.
- Role: Acts as the primary binder, giving the con- crete its structuralintegrity.

Figure 7: flyash

Supplementary Cementitious Materials (SCMs)

Fly Ash: Enhances workability and durability, and re- duces heat of hydration.

- Silica Fume: Increases strength and reduces perme- ability due to its fine particle size.
- Slag Cement: Improves resistance to sulfate attack and mitigates the risk of alkali-silica reaction.

Aggregate

Figure 8: quartz powder

Aggregates provide the bulk and strength to the concrete mix, ensuring stability and robustness of the printed structure.
Fine Aggregates: Quartz Powder(25 microns) Quartz Sand(1 mm)
Quartz Sand(2 mm)

Figure 9: quartz 1mm

Admixtures

Admixtures are added to the concrete mix to modify its properties and enhance performance.

- Superplasticizers
- Retarders
- Accelerators
- Viscosity Modifying Agents (VMAs)

Figure 10: fibers

Fibers

Fibers are added to the concrete mix to improve its tensile strength and ductility. Polypropylene Fibers

Mechanical Components

Mechanical components ensure the precise and smooth operation of the 3D concrete printer.

Stepper Motors:

Figure 11: Stepper Motor

Provide precise control over the movement of the print head along the X, Y, and Z axes.

Frame Materials

- **Aluminum Frame:** Lighter than steel, making it easier to assemble and transport, while still offering good strength and resistance to corrosion. Dimen- sions of frames are 1000mm* 1000mm*600mm. Dimension of bed is 800mm*800mm* 25mm.
- **Linear rail:**

It provides a smooth and accurate guiding sys- tem for the movement of the printer's components.

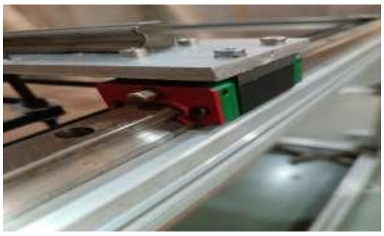

Figure 12: Guide Rail

- **Linear Guide ways:**

It provides high precision and stability for the movement of the print head or nozzle. These guide- ways consist of rails and bearing blocks that facil- itate smooth, low-friction movement along the X, Y, and Z axes.

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- **Guide ropes:**
  These guide ropes, typically made from high- strength materials, are tensioned to ensure smooth and precise motion along the required axes.

Wire Ropes

Extruder components

- **Nozzle:**
  The primary function of the nozzle is to extrude the concrete mixture in a precise structure.The dimension of nozzle used in the project is 20mm, 10mm, 6mm.

Figure 13: 3 extruder Nozzle

- **Auger Screw:**
  It is responsible for transporting and controlling the flow of the concrete mixture from the hopper to the nozzle. It operates by rotating within a cylindri- cal housing, effectively pushing the concrete for- ward. As the screw rotates, the helical flights of the auger move the concrete along the length of the screw. This action ensures a continuous and consis- tent flow of material, which is crucial for achieving uniform layer deposition.

Figure 14: Auzar Screw

- **Extruder body:** It houses the auger screw and fa- cilitates the transition of the concrete from the hop- per to the nozzle. The extruder body is designed to withstand high pressures and abrasive materi- als, maintaining the integrity and consistency of the concrete flow. As the auger screw rotates within the extruder body, it moves the concrete mixture for- ward, ensuring a continuous supply to the nozzle.

The dimension of the body are length 150mm, Di- ameter 78mm.

Figure 15: Extruder body

Electronic Components

Figure 16: Ar

Electronic components control the operation of the 3D concrete printer, ensuring precise movements and accurate extrusion.

Arduino Mega 2560 Microcontroller:

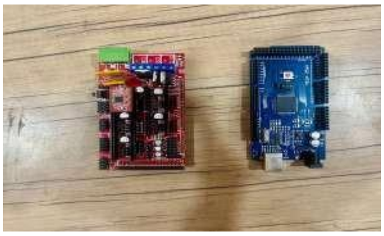


Figure 17: arduino and motor driver

Acts as the brain of the printer, processing com- mands and controlling the stepper motors and other components.

Ramps 1.4 Controller: It is used to control the Ar- duino Atmrga 2560 REV3+ 4PCS A4988 Drivers.

Stepper motor Drivers A4988:

Stepper Motor Drivers: Control the current and volt- age supplied to the stepper motors, allowing precise control of movement. Drivers included in this project is A4988.

200V Power Supply: Power Supply: Provides the necessary power to all electronic components. A 200V DC power supply is used for consistent perfor- mance and safety.

Safety Equipments: Safety Features: Include fuses, thermal protection, and proper grounding to ensure safe operation of the printer.

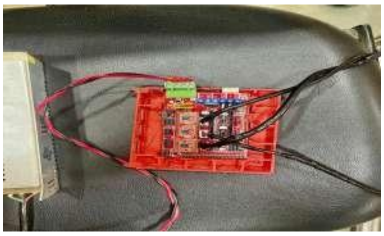


Figure 18: Arduino and Stepper Driver wiring

Software Setup

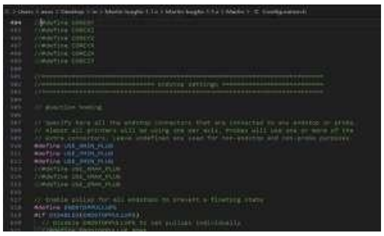


Figure 19: Marlin Firmware

The software setup for operating a civil concrete 3D printer involves a combination of firmware, host software, and slicing software, each playing a cru- cial role in ensuring precise and efficient printing.The firmware, Marlin, is a popular open-source option that runs on the printer's control board, managing the mo- tion of the printer and the extrusion process. Marlin is highly customizable, allowing it to be adapted for the specific needs of concrete printing, such as adjusting for the unique flow characteristics of concrete and en- suring stable layer deposition. Pronterface serves as

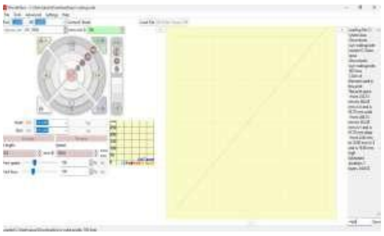


Figure 20: Pronterface

the host software, providing a user-friendly interface for controlling the printer. It allows operators to man- ually move the printer, adjust settings in real-time, and monitor the printing process. Pronterface's com- patibility with Marlin makes it an ideal choice for real-time printer management and troubleshooting. The slicing software, Slic3r, converts 3D models into G-code, which the printer can interpret. Slic3r's ad- vanced slicing algorithms and customizable settings enable the creation of optimal toolpaths for concrete extrusion, ensuring uniform layer heights and precise geometry. Together, these software components form an integrated system that enhances the control, accu- racy, and reliability of the concrete 3D printing pro- cess.

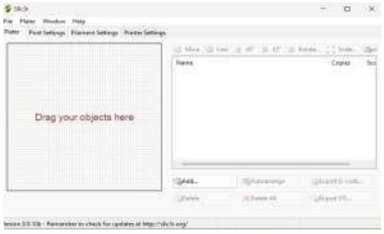
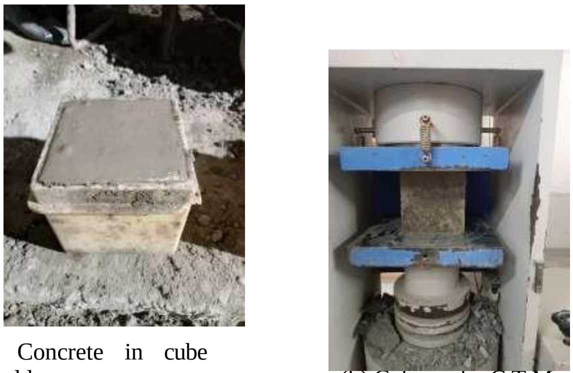


Figure 21: Slic3r

Concrete Mix Design



(a) Concrete in cube Mould

(b) Cube under C.T.M.

Figure 22: Concrete mix design testing

The design of the concrete mix is essential for the successful implementation of 3D concrete printing. It must meet several critical requirements to ensure the mix is suitable for extrusion and layer-by-layer con- struction.Concrete mix design is a process of select- ing suitable ingredients of concrete and determining their relative quantities with the objective of produc- ing a concrete of the required strength, durability, and workability as economically as possible.

Materials	**Quantity (kg)**	**Proportions**
Cement	663.0	3.315
Flyash	165.7	0.8285
Water	265.2	1.326
Quartz powder (25µm)	497.2	2.486
Quartz sand (1 mm)	372.9	1.864
Quartz sand (2 mm)	372.9	1.864
Synthetic fibres	1.8	9 grams
Admixtures	0.83	4 grams

Table 1: Material Quantities and Proportions for 3D Concrete Design Mix

Flow Values (mm)	Time Duration (min.)
590 × 600	0
560 × 580	60
550 × 550	120
540 × 545	180

Table 2: Fresh Concrete Test Values

Compressive Strength (MPa)	Days
12	1
48	3
78	7
108	14
118.8	28

Table 3: Hardened Concrete Compressive Strength Test Values

Methodology

(a) Extruder wiring (b) Printer

Figure 23: All 3 nozzle configurations

The methodology of 3D concrete printing be- gins with the manufacturing of a specialized printer that includes a robust frame to support the con- crete extrusion process. The hardware setup involves an Arduino Mega microcontroller integrated with a RAMPS (RepRap Arduino Mega Pololu Shield) board, which serves as the main control board for managing the printer's operations. Stepper motors are employed to control the precise movements along the X, Y, and Z axes, facilitated by motor drivers that modulate the current and voltage to these motors. The software infrastructure includes Marlin firmware, which is uploaded to the Arduino Mega to handle the printer's motion and extrusion controls.

Pronterface is used as the interface for controlling the printer, allowing users to load G-code files gen- erated from Slic3r. Slic3r is a slicing software that converts 3D models into G-code instructions by lay- ering the model into horizontal sections and defining the path for the extruder. The extruder mechanism is specifically designed for concrete, involving a pump system that pushes the concrete mix through a noz- zle. During the printing process, the extruder follows the G-code paths, layer by layer, to build the structure from the bottom up.This coordinated effort between hardware and software ensures the precise deposition of concrete, resulting in the final printed structure.

Figure 24: 3D printed cube

Testing and Results

Initial Calibration Hardware Calibration

Figure 25: compressive strength test of 3d printed cube

Frame Alignment: Ensure the printer's frame is perfectly aligned and level. This can be done using precision tools like spirit levels and laser levels. Any misalignment can cause issues with the accuracy of the prints. • Axis Calibration: Calibrate the X, Y, and Z axes to ensure accurate movement. This involves checking the stepper motor steps per unit and adjust- ing if necessary. Use calibration objects and measure the printed dimensions to verify accuracy. • Nozzle Calibration: Ensure the nozzle is properly aligned and the correct distance from the print bed. This is critical for achieving consistent extrusion. Perform a series of test extrusions to verify the nozzle's position

Software Calibration

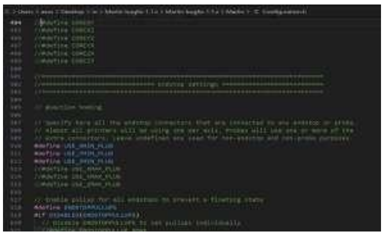


Figure 26: marlin snip

- Firmware Configuration: Verify that the firmware settings match the printer's hardware specifica- tions. This includes setting the correct steps per unit for each axis, maximum feed rates, and accel- eration values.
- Bed Leveling: Use the printer's bed leveling proce- dure to ensure the print bed is flat and level. This

can involve manual adjustment screws or automatic bed leveling sensors.

- Extrusion Calibration: Calibrate the extrusion sys- tem by determining the exact steps per millimeter for the extruder motor. This can be done by extrud- ing a set amount of material and measuring the ac- tual output, then adjusting the firmware settings ac- cordingly.

Printed concrete cubes tests

Density = W

Figure 27: weight of cubes

Ensure the concrete cubes are prepared properly, considering:

- **Mix design:** The proportion of cement, aggregates, water, and any additives.
- **Printing process:** Ensure consistent layer deposi- tion and minimal defects.
- **Curing:** Maintain appropriate curing conditions (temperature, humidity) for the required period, typically 28 days.

Testing Procedures The primary tests conducted on concrete cubes include:

Figure 28: 3d printed concrete structure

Compressive Strength Test

- **Apparatus:** Compression testing machine.
- **Procedure:**

1. Place the cube on the testing machine with the smooth sides facing up.
2. Apply load gradually at a constant rate until the cube fails.
3. Record the maximum load applied.

- **Calculation:**

$$\text{Compressive Strength} = \frac{\text{Maximum Load}}{\text{Cross-sectional Area}}$$

Given the cross-sectional area is $100\,\text{mm} \times 100\,\text{mm} = 10000\,\text{mm}^2$.

Density Test

- **Apparatus:** Scale, Vernier caliper.
- **Procedure:**

1. Measure the weight of the cube.
2. Calculate the volume (since it's a perfect cube, $V = 100\,\text{mm} \times 100\,\text{mm} \times 100\,\text{mm} = 1000000\,\text{mm}^3$).
3. Compute the density.

- **Calculation:**

Volume

Interpreting Results

- **Compressive Strength:** Compare the measured compressive strength against the expected values or standards for the specific mix design and appli- cation. Typical values for ordinary concrete range from 20 MPa to 40 MPa for standard mixes.
- **Density:** Concrete density typically ranges from 2200 kg/m³ to 2500 kg/m³ for conventional con- crete. Lightweight concrete has a density of about 1800 kg/m³ or lower.

Example Calculation

Let's assume we conducted the tests and obtained the following data:

- **Maximum Load:** 250 kN
- **Weight of Cube:** 2.4 kg

Compressive Strength Calculation

- Cross-sectional Area $A = 100\,\text{mm} \times 100\,\text{mm} = 10000\,\text{mm}^2$.
- Maximum Load $F = 250\,\text{kN} = 250000\,\text{N}$.

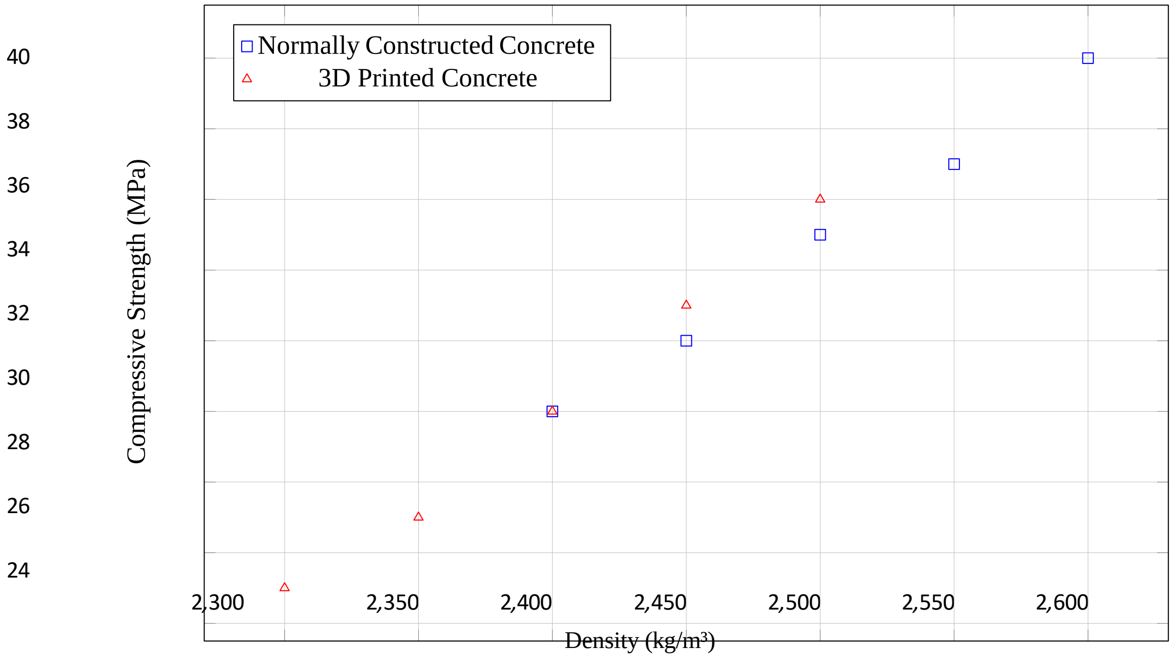
$$\text{Compressive Strength} = \frac{250000\,\text{N}}{10000\,\text{mm}^2} = 25\,\text{MPa}$$

Density Calculation

- Weight $W = 2.4\,\text{kg} = 2390\,\text{g}$.
- Volume $V = 1000000\,\text{mm}^3 = 1000\,\text{cm}^3 = 1\,\text{L}$.

$$\text{Density} = \frac{2390\,\text{g}}{1\,\text{L}} = 2390\,\text{kg/m}^3$$

comaprison between



(a) Comparison of Compressive Strength and Density between Normally Constructed and 3D Printed Concrete Cubes

Conclusion

Based on the results:

- The compressive strength of 25 MPa suggests it is suitable for standard structural applications.
- The density of 2400 kg/m³ is within the typical range for conventional concrete, indicating proper material properties and mix design.

Ensure all tests follow relevant standards (such as ASTM or EN) for accurate and reliable results.

Conclusions from Testing and Results

Strengths

Print Quality: High-quality prints with accurate dimensions and smooth surface finish. • Structural Performance: Printed structures with adequate strength and durability for the intended application. • Process Reliability: Consistent and reliable printing process with minimal interruptions or issues.

Areas for Improvement

Figure 30: 3d printed extruders

- Extrusion System: Enhancements to the extrusion system to improve flow consistency and reduce block- ages. • Mix Design: Optimization of the concrete mix design to achieve better workability and buildability. • Calibration Procedures: Refinement of the calibration procedures to improve accuracy and reduce the need for adjustments.

Benefits of 3D Concrete Printing

- **Design Flexibility**: 3D concrete printing allows for complex geometries and intricate designs that are difficult to achieve with traditional construction methods.
- **Cost Efficiency**: Reduces labor costs and material waste due to the precise deposition of concrete only where needed.
- **Speed**: Significantly faster construction times com- pared to conventional methods, allowing for rapid prototyping and production.
- **Sustainability**: Minimizes material usage and waste, and can incorporate recycled materials into the concrete mix.
- **Customization**: Enables easy customization and adaptation of designs to meet specific requirements and preferences without additional cost.
- **Safety**: Reduces the need for human labor in poten- tially hazardous environments, thereby enhancing worker safety.
- **Resource Efficiency**: Optimizes the use of raw ma- terials and reduces the environmental impact asso- ciated with construction.
- **Reduced Error**: Enhances accuracy and reduces

human error through automated and precise layer- by-layer construction.

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