OPTIMISATION OF MIX DESIGN FOR 3D PRINTABLE CONCRETE AND DEVELOPMENT OF AUTOMATED CONTINUOUS SUPPLY MECHANISM OF RAW MATERIALS

FINAL YEAR PROJECT

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This thesis is dedicated to our parents.

For their love, support, and prayers throughout our lives.

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ABSTRACT

This thesis focuses on the mix design optimization in 3D printable concrete and the development of an automated continuous supply mechanism for the enhancement of current state-of-the-art technology in 3D concrete printing. The addition of supplementary cementitious materials like fly ash and sugarcane bagasse ash lends strength to the sustainability and mechanical performance of 3DPC with reduced cement content. The study has introduced an automated supply system, which enables continuous material flow during printing for improved efficiency and print quality. Results from experiments proved that mix designs and supply mechanisms that were optimized reduce labor significantly, with lower environmental impact and enhanced reliability in 3D printing. This indicates that such innovations could be critical to solving housing shortages in disaster-prone regions and making the construction solution fast and sustainable. This paper contributes immense amounts of insight into the field of 3DCP and suggests pathways forward for future development and commercialization.

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CHAPTER 1

INTRODUCTION

1.1 Background

The three-dimensional concrete printing (3DCP) is a revolutionary technology and has received attention for research. It is a novel and emerging technology that is envisioned to produce a third industrial revolution. It offers advantages across various industries. One of its primary uses in construction is allowing for the rapid and cost-effective creation of complex architectural designs. (Batikha et al., 2022) Automation and digitalization can significantly contribute to upgrading construction methods, creating new jobs, increasing productivity, and compensating unskilled laborers. The process involves layer-by-layer extrusion of concrete material based on digital models, providing greater precision and minimizing the wastage of materials. (Baduge et al., 2021) It allows the construction of very complex and complicated structures which would be nearly impossible with traditional methods of construction. It also provides room for enhanced customization, enabling the addition of special features and functions per the project's requirements. Generally, concrete casting is done using formworks which accounts for 50% of the total project cost. This technology does not require molds or formwork to shape the concrete, one of the aspects researchers have been working on in the past decade. It, therefore, reduces the cost of labor and formwork as well as construction time. (Jipa & Dillenburger, 2022) This method has boosted construction works by 50-80% and reduced material consumption by 30-60% since less material is wasted. The increased productivity and efficiency of this technology have enabled work time to be reduced from months to days to hours. In addition to this, 3D printing promotes sustainability by utilizing environment-friendly materials. (Paritala et al., 2023) The process works on the principle of extrusion whereby a cementitious mixture is pumped to a height and extruded through a nozzle at a speed of 50-500mm/s. The 3DCP is still expanding and has gaps to be addressed. In the past decade, much research has been focused on evaluating material. The mixture usually contains fine aggregate or small-sized coarse aggregate to allow extrusion through the nozzle.

This technology is currently employed in various parts of the world, and several groundbreaking projects have been undertaken. Popular 3DCP applications include affordable, accessible housing, natural disaster relief, and emergency shelter construction. The basic use is in the construction of houses and buildings. It is expected to address the housing shortage problems around the globe and one such project is ongoing in Nigeria. In 2019, Apis-Cor constructed a two-story building in Dubai, which is claimed to be the largest 3DPC in the world. Walls at Loughborough University have been successfully printed, and Gosselin et al., have optimized multifunctional 3DP walls for thermal insulation. The first 3D-printed concrete bridge was developed in the Netherlands. The United Arab Emirates has printed concrete bus stops and is utilizing this technology in the Future Dubai Office to achieve its smart city goals. 3D concrete printing extends to producing various infrastructure components, including walls, columns, and facades.

1.2 Research Significance

Pakistan recently witnessed massive floods in 2022. According to research conducted by the real estate portal Zameen, there is a shortage of 10 million houses in Pakistan which is expected to increase to 13 million by 2025. Therefore, there was a need for immediate and cheap housing in the country. Traditional construction methods face limitations regarding efficiency, customization, and sustainability. In addition to this, it is more expensive and time-consuming. 3D printing technology has emerged as a promising solution, but challenges persist, particularly in optimizing the mix design of printable concrete and ensuring a seamless supply of raw materials. The lack of standardized mix designs and inefficient material supply mechanisms hinder the widespread adoption of 3D printable concrete in construction projects.

Despite such potentials over the regular construction practices, 3D concrete requires a high amount of cement. This can eventually lead to more greenhouse gas emissions, affecting the climate, and increasing cost as well. The research, therefore, has shifted towards the use of Supplementary Cementitious Materials (SCMs) in the 3D printed concrete. This study aims to address the effect of Sugarcane Bagasse Ash, combined with fly ash, as an SCM on the rheological properties, mechanical properties, and bond strength of printed layers. The use of SCMs has proved to have critical effects on various parameters of 3D-printed concrete. Important parameters to consider are the printability and durability of concrete. Printability is defined as the capability of the material and nozzle to generate a composed filament. (Prabhakar et al., 2021; Wangler et al., 2019) However, Printability is a collective term incorporating Pumpability, Extrudability, and Buildability all at once. To meet all these properties, the rheological characteristic of 3DPC must be different from conventional concrete properties. (Wangler et al., 2019) Printability is affected by these parameters and hence, termed the rheological properties of concrete. (Dilawar Riaz et al., 2023) Durability, on the other hand, is how long and well the structure can sustain loads. (Khan et al., 2023)

In Pakistan, the first printer prototype was developed in 2023. Having a frame of 1x1x1.5m and a printable area of 0.8x0.8x1m, it could print up to 15kg of concrete as per its extruder capacity. This meant that a rigorous labor force was required to print a house or even a prototype. This called for the need for a continuous supply mechanism to ensure that concrete was available as per the requirements of the project.

1.3 Problem Statement

Pakistan has been a victim of multiple natural disasters such as floods and earthquakes. Millions of people are affected and left homeless. The current construction methods require extensive expenses, time, and labor. A much more efficient technique to provide low-cost, rapid housing is using 3D printing technology.

However, the current prototype lacks continuous supply resulting in minimal reduction in labor and consequently, cost. This also leads to interruptions in printing as consequent layers have a time-lapse required to fill the extruder again, reducing interlayer bonding. The setting times of different layers are also distinct due to the formerly mentioned reason. In addition to this, there is limited availability of specialized 3D printable mix as there is limited research done on the topic. The conventional mix has excess cement, this along with other concrete ingredients has adverse environmental impacts. Cement production alone generates 2.5 billion tonnes of carbon dioxide (CO2) per year, accounting for 4-8% of the world's CO2 production. It also emits large amounts of toxic substances, such as sulfur dioxide and carbon monoxide, into the air which can worsen air quality and cause respiratory diseases. These emissions can lead to environmental changes.

This study aims to optimize the mix design of 3D printable concrete with reduced cement, using locally available materials. In addition to this, it aims to develop an automated continuous supply system of raw materials. It takes its inspiration from a real-life batching plant and is designed such that it can reduce labor and improve time.

1.4 Objectives

There are two main objectives of this study, which are further divided into two sub-objectives:

1.4.1 Development of Continuous Supply:

a) **Mechanical assembly:**
   - Design and implement an automated system for monitoring and controlling the supply of raw materials
   - Integrate smart sensors and IoT technologies to ensure real-time data monitoring
   - Establish a mechanism for predictive maintenance to minimize downtime

b) **Extruder upgradation:**
   - Design a suitable shape that allows easy extrusion without being clogged
   - Figure out suitable dimensions compatible with the auger blade

1.4.2 Optimization of Mix Design:

a) **Material Selection:**
   - Investigate locally available materials and their pozzolanic activities, and explore sustainable additives to enhance the environmental profile of the concrete
   - Investigate the properties and suitability of bagasse ash and fly ash as alternatives to traditional cement

b) Trial mixing:

- Conduct comprehensive research on the properties of printable concrete
- Develop a standardized mix design that balances printability, strength, and durability while considering the environmental effects

1.5 Scope of Work

The research aims to develop a usable prototype of a 3D printer that is automated, autonomous and can help address problems of housing shortages. The continuous supply system will be similar to that of a concrete batching plant. The research also aims to develop a sustainable mix design with fly ash and sugarcane bagasse ash as SCMs. The feasibility of this mix will be validated through non-standardized testing of 3D printable concrete.

CHAPTER 2

Literature Review

2.1 Introduction to 3D Printable Concrete

Three-dimensional concrete printing is a transformative technology that is bound to radically change the face of construction. It enables fast, cost-efficient, and sustainable construction of complex architectural designs. This is a process wherein a cementitious mixture is extruded layer by layer according to a digital model, offering the ability for precision and customization without traditional molds or formwork. This greatly helps reduce labor costs, construction time, and less waste of material; hence, it proves effective toward the general efficiency and sustainability of construction processes (Bos et al., 2016).

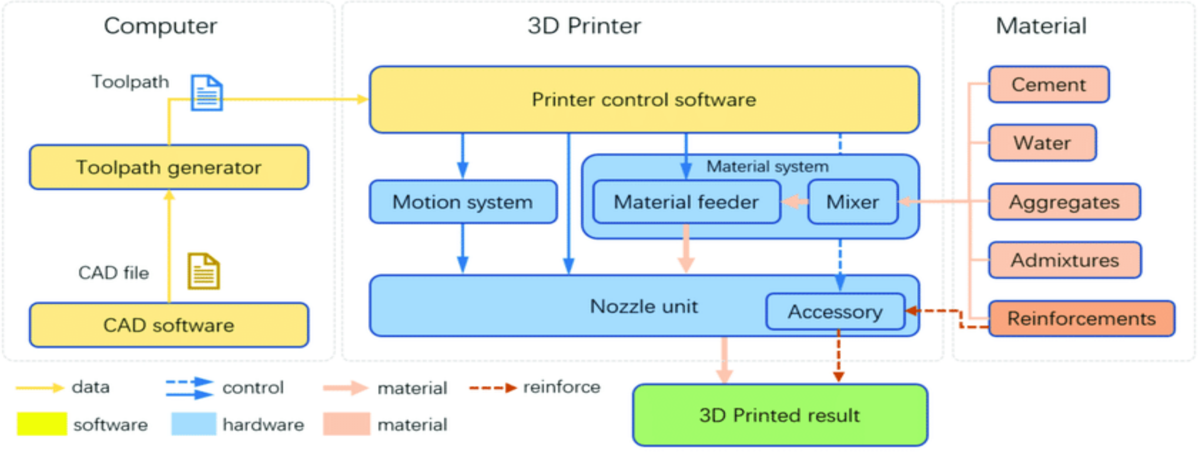


Figure 2-1: 3d Concrete Printing System (Xiangpeng Cao, 2022)

Figure 2-2: 3d concrete printer (Apis Cor, 2019)

2.2 Technological Advances in 3D Concrete Printing

2.2.1 Rheological Properties and Printability

It is generally realized that the printability of 3D concrete will be based on its rheological properties, focusing mainly on pumpability, extrudability, and buildability, which shall be attained for the successful completion of the process of 3D printing:

- **Pumpability:**
  This is the extent to which concrete mix can be easily pumped through a delivery system. A mix with good pumpability steadily flows through the pipeline, not causing blockages or segregation.

- **Extrudability:**
  It is the ability of the mix to be extruded through the nozzle without segregation. Ensures the material holds its shape and consistency throughout the process of extrusion.

- **Buildability:**
  It is the extent to which the layers extruded will hold the next layers without deforming. A mixture with brilliant buildability would maintain its original shape and structural integrity upon the addition of layers (Le et al., 2012).

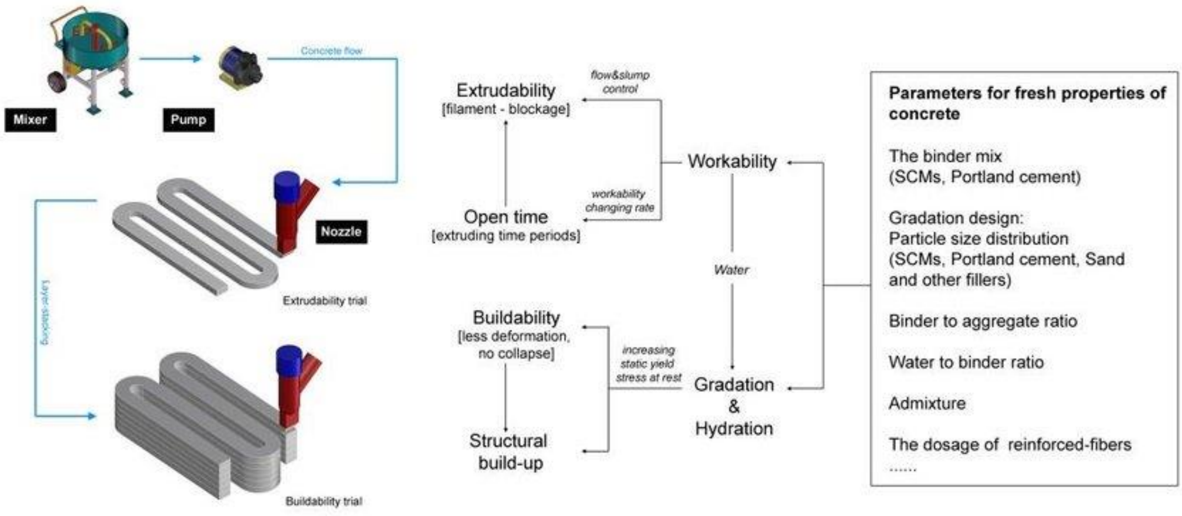


Figure 2-3: Fresh properties of 3D printable concrete and dominant parameters (Yu Chen, 2019)

Therefore, the major challenge in 3D concrete printing remains the optimum balance among these very diverse properties. The water-to-cement ratio, particle size distribution, addition of superplasticizers, and viscosity-modifying agents all come in very handy in controlling these properties (Panda et al., 2018).

The role of superplasticizers has been at great lengths investigated to improve the printability of concrete mixes. Those chemical admixtures that raise the workability or flow characteristics of concrete without increasing the water content are known as superplasticizers. They act on cement particles to disperse them, thus reducing water demand and improving flow characteristics. Critical to ensure the mix can be easily extruded without segregation and its capacity to maintain shape after deposition (Sika, 2016).

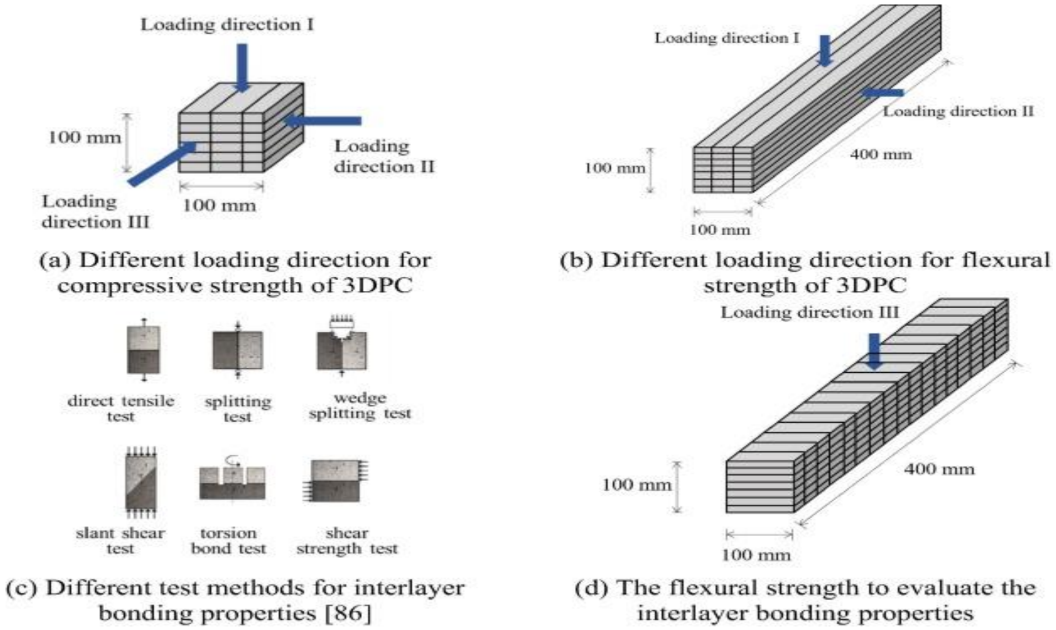
Studies by Le et al. (2012) claimed that adjustment in water-to-cement ratio and addition of viscosity-modifying agents to a lot can enhance rheology in 3D printable concrete, thus ensuring necessary pump ability, extrudability, and buildability for successful 3D printing.

2.2.2 Mechanical Performance and Anisotropy

One of the associated challenges of 3D concrete printing is anisotropy in mechanical properties due to the layer-by-layer construction method. Anisotropy simply means that the strengths of the structure printed vary in different directions. This is mainly caused by differences in bonding between layers vis-à-vis the monolithic nature of traditionally cast concrete.

These include path optimization and material reinforcement. The former involves varying the printing path so that deposition and bonding are uniform, while the latter adds fiber or other material that provides mechanical strength to the structure being printed (Khoshnevis, 2004).

Kazemian et al. (2017) investigated fibers in 3D-printed concrete to enhance improved mechanical properties. This study found that the inclusion of steel fibers, polypropylene fibers, and glass fibers would raise the tensile strength and flexural of the printed concrete enormously. These fibers bridge cracks and can enhance the ductility of the material; hence, anisotropy would be solved, and structural integrity enhanced for the 3D printed concrete.



(a) Different loading direction for compressive strength of 3DPC

(b) Different loading direction for flexural strength of 3DPC

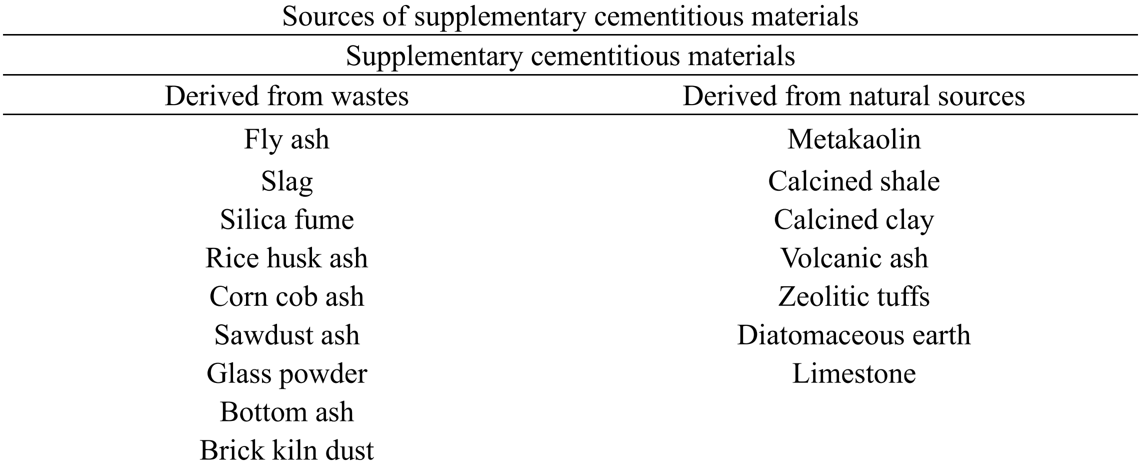
(c) Different test methods for interlayer bonding properties [86]

(d) The flexural strength to evaluate the interlayer bonding properties

Figure 2-4: Test methods for anisotropic mechanical properties of 3DPC (Shaodan Hou, 2020)

2.3 Sustainability and Supplementary Cementitious Materials (SCMs)

Sustainability is the major factor of construction practices today, and the same is the case for 3D concrete printing. Extra sustainability for 3D printed concrete can be made available by adding SCMs into the mix through the inclusion of fly ash and sugarcane bagasse ash.



Sources of supplementary cementitious materials

Supplementary cementitious materials	
Derived from wastes	Derived from natural sources
Fly ash	Metakaolin
Slag	Calcined shale
Silica fume	Calcined clay
Rice husk ash	Volcanic ash
Corn cob ash	Zeolitic tuffs
Sawdust ash	Diatomaceous earth
Glass powder	Limestone
Bottom ash	
Brick kiln dust	

Figure 2-5: Sources of Supplementary Cementitious Materials (Adeyemi Adesina, 2020)

- **Fly Ash:**
  Fly ash is a by-product of coal combustion in a thermal power plant. The pozzolanic properties of fly ash enhance the durability and strength of concrete in the long run. It reacts with calcium

hydroxide to form extra calcium silicate hydrate, raising the mechanical properties of concrete (ACI Committee 232, 2004).

Fly ash has been significantly used as a partial replacement of cement in concrete mixes. In that regard, it enhances the workability of concrete, reduces the heat of hydration, and enhances the long-term strength and durability of concrete. Besides, the use of fly ash reduces the carbon footprint of concrete due to the reuse of industrial wastes (Thomas, 2007).

Figure 2-6: Fly Ash (Sagar, 2020)

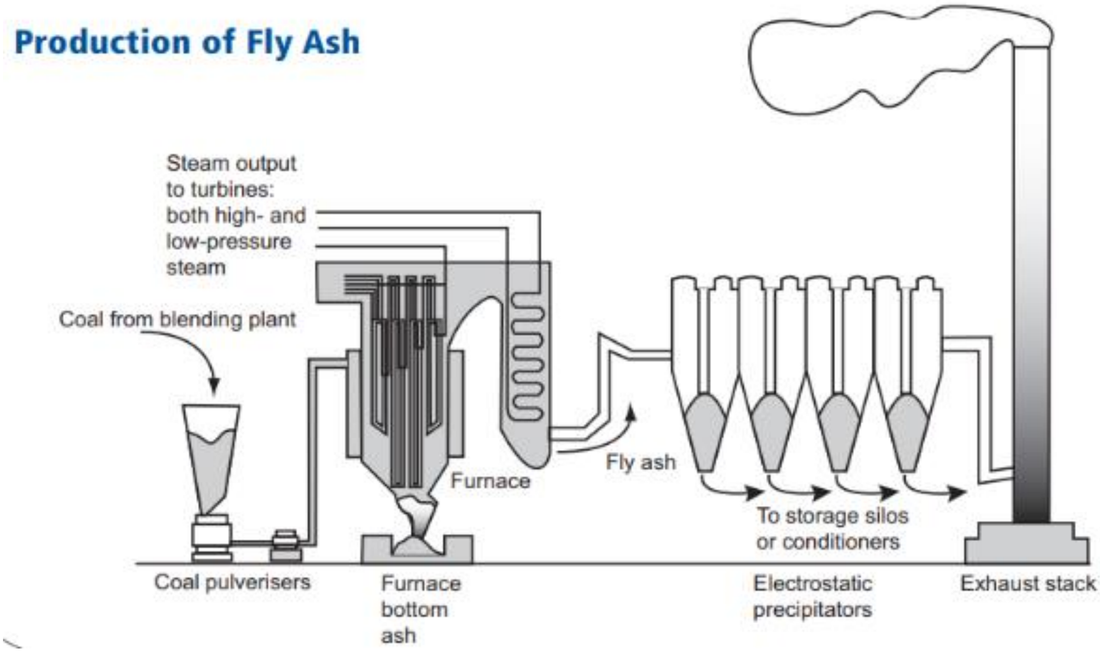


Figure 2-7: Production of Fly Ash (Michael Thomas, 2007)

- **Sugarcane Bagasse Ash (ScBA):**
  ScBA is obtained from the agricultural waste of sugarcane processing. The high amount of silica it contains makes it a very good pozzolan. On increasing the content of ScBA in concrete, there is an increase in its compressive and tensile strength and a decrease in the environmental impact involved in cement production. Studies have shown that ScBA can maximize the compressive and tensile strength of concrete and allow for applications in 3D printing (Cordeiro et al., 2009).

  Performance improvement in 3D printed concrete by supplementary cementitious materials (SCMs) applies industrial and agricultural by-products/wastes and thus gives the pathway to reduce the carbon footprint of the construction industry. For instance, Priya et al. (2016) and Li et al. (2022) have demonstrated the advantages of using ScBA for improving the mechanical properties of concrete while enhancing its sustainability.

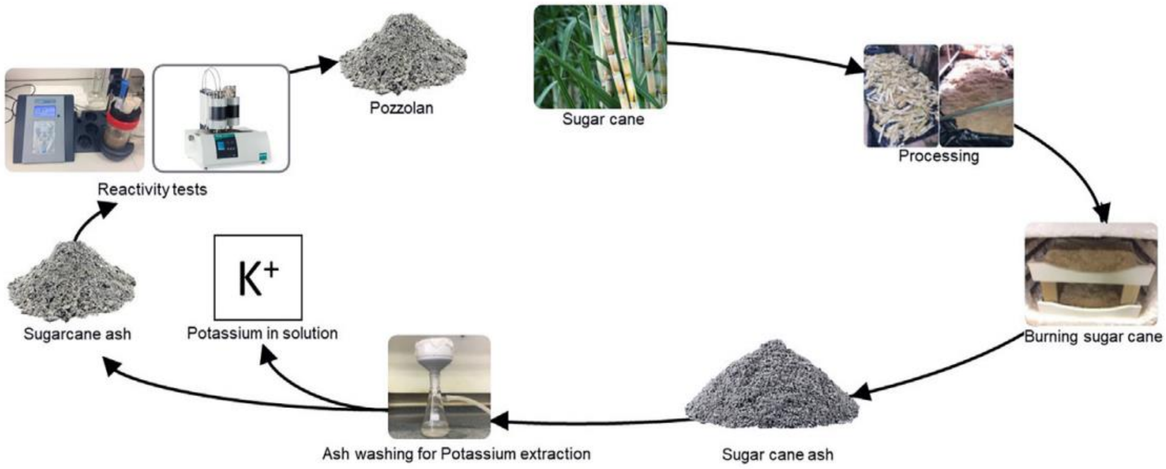


Figure 2-8: Production of Bagasse Ash (Gabriela, 2020)

2.3 Optimization of Mix Design for 3D Printable Concrete

2.3.1 Material Selection

Material selection in 3D printable concrete is very critical to achieving the desired properties of the mix. The usual materials used in this are ordinary Portland cement, fine aggregates, fly ash, ScBA, and superplasticizers. All these materials have a certain role in improving the rheological and mechanical properties of the concrete mix. They are:

a) Ordinary Portland Cement (OPC):

OPC is the primary binder in the mix; it should be selected for its well-documented properties, availability, and compatibility with SCMs. OPC should be available in any structure carrying loads, due to its high early strength and durability (Mindess et al., 2003).

Availability in Pakistan: OPC is immensely available in Pakistan because of the numerous cement manufacturing plants. Key manufacturers, such as Lucky Cement, D.G. Khan Cement, and Maple Leaf Cement, ensure OPC supplies throughout the country. The production capacity of cement in Pakistan annually is roughly 45 million tons; out of this, OPC is produced in the maximum quantity.

OPC constitutes the largest proportion of the binder content by weight in most 3D printable concrete mixes at about 50-60%. Major construction projects would need several tons per day, depending on the size and extent of the work.

b) Sand:

Fine aggregates, mainly in the form of sand, contribute to easy extrusion of the mix through the nozzle of the 3-D printer. The particle size distribution of the sand is carefully selected to have good buildability and flowability for the mix. The skeleton structure given to the mix by the sand therefore generally contributes to the strength and stability of the printed layers (Neville, 2011).

Availability in Pakistan: Sand is amply available in Pakistan, contributed by riverbeds, deserts, and coastal areas. River sand is supplied considerately by the Indus River and its tributaries and is used extensively for construction.

Sand normally occupies from 60 to 70% of the mix volume in printable concrete. If the project is huge in scale, then consumption can run to the tune of a few cubic meters to several dozen cubic meters per day.

c) Fly Ash:

Fly ash is a by-product resulting from coal combustion in thermal power plants. It has pozzolanic properties to improve the durability and the long-term strength of concrete. Fly ash shall be added to the mix for purposes of improving workability and reducing water demand, generally improving performance (ACI Committee 232, 2004).

Availability in Pakistan: Fly ash is easily available in Pakistan due to the presence of coal-run powerhouses, such as Jamshoro Power Plant and Sahiwal Power Plant. They generate huge amounts of fly ash as byproducts that could be utilized for concrete production.

The fly ash content in most 3D printable concrete mixes comes in the range of 15-25% of the binder. It is, also, widely available in huge amounts, further confirming its feasibility for use as a supplementary material in construction projects.

d) Sugarcane Bagasse Ash (ScBA):

ScBA is derived from the agricultural waste of the sugarcane processing industry. Being rich in silica, it becomes a very sound pozzolan. Additional ScBA in concrete improves its compressive and tensile strengths, reducing environmental impacts from cement production (Cordeiro et al., 2009).

Availability in Pakistan: Pakistan produces around 80 million tons of sugarcane annually, thereby being one of the largest producers of the crop. Huge amounts of bagasse are burnt to produce the energy needed for running the sugar mills, from which huge amounts of ScBA are generated through controlled burning processes. Major sugar mills in Punjab and Sindh contribute bagasse ash.

In concrete mixes, ScBA can replace cement by 10-30%. Considering that the quantities of sugarcane and hence bagasse produced worldwide are very high, there is huge potential for ScBA utilization in building operations.

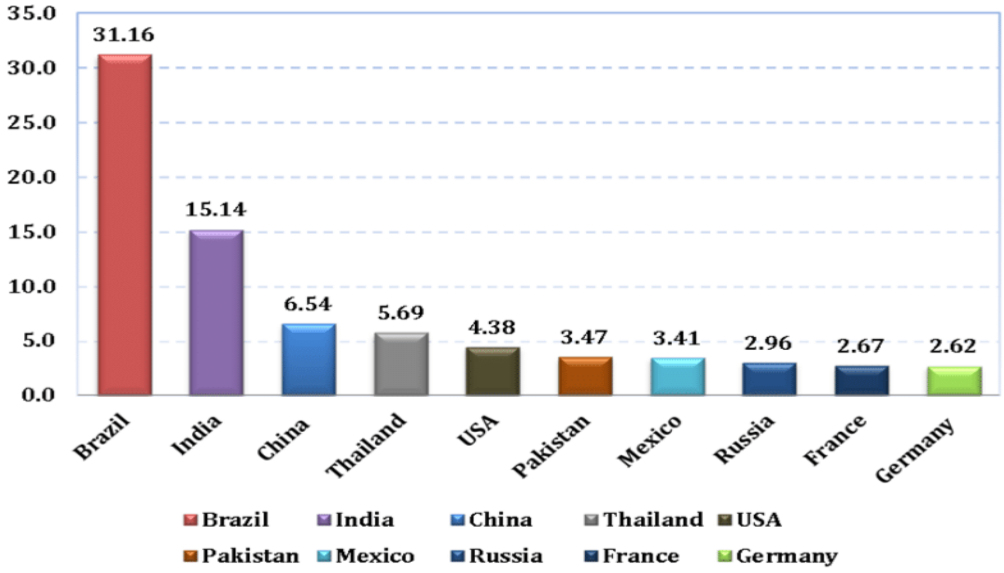


Figure 2-9: World production of sugarcane bagasse (thousand metric tons) in 2020 (Ashraf, 2020)

e) Superplasticizers:
These chemical admixtures improve mix workability without increasing water content. According to Sika, superplasticizers disperse cement particles and reduce water demand, improving the flow characteristics of the mix required for extrusion and printability (Sika, 2016).

Availability in Pakistan: Superplasticizers are readily available in Pakistan, due to the existence of manufacturers and local suppliers to the needs of the construction industry. Firms such as Sika Pakistan and BASF Pakistan offer different kinds of superplasticizers for special fields of application in concrete.

Superplasticizers are added in small quantities of about 0.5 to 2% by weight of binder content. Though added in small proportions they have a very dominant effect on the workability of the mix and properties of concrete.

2.3.2 Initial Mix Proportions (Based on Le et al., 2012)

The optimized mix design for 3-D printable concrete can be developed through an iterative process of trials and adjustments to balance workability, buildability, and mechanical strength. Initial trials are conducted to find an optimal proportion among cement, fly ash, and ScBA. Trials results will show what adjustments are required to further refine this mix design.

Table 2-1: Initial Mix Proportions

Material	Proportion (%)
Cement (OPC)	60
Fly Ash	20
ScBA	20
Sand	100 (by volume)
Superplasticizer	1 (by weight)

Initial mix proportions are designed to come up with a mix that is at least printable and buildable. Further trials would be carried out by varying these proportions to improve certain properties.

2.3.3 Testing and Evaluation

These tests are conducted to ensure that the optimized mix design satisfies all the performance criteria. These tests would further furnish very valuable data to aid in further fine-tuning of the mix design.

1) Fresh State Property Tests:
a) Rheological Test:

The slump flow test gives a very vital indication of the flowability and consistency of freshly mixed concrete. Higher values of slump flow denote increased workability, a property central to conventional applications in concrete use and new technologies like 3-D concrete printing.

Different researchers have put in an extensive effort to find out the effect of adding fly ash to concrete mixes on its workability. Since fly ash comprises fine particles, mostly spherical, it reduces the water demand in concrete mixes, hence increasing their flowability. This will make the mix hold up its consistency and workability more easily. This is vital for traditional construction techniques as well as advanced ones (Thomas, 2007).

Bagasse ash has also been investigated as a supplementary cementitious material in conventional concrete. According to some studies, bagasse ash can improve the workability class of conventional concrete due to an increase in the slump flow caused by its pozzolanic nature, providing a smoother mix; however, the effect is generally lower compared with fly ash. It is observed that bagasse ash causes a moderate increase in slump flow, sufficient to produce a workable mix with the right consistency for conventional construction procedures (Cordeiro et al., 2009).

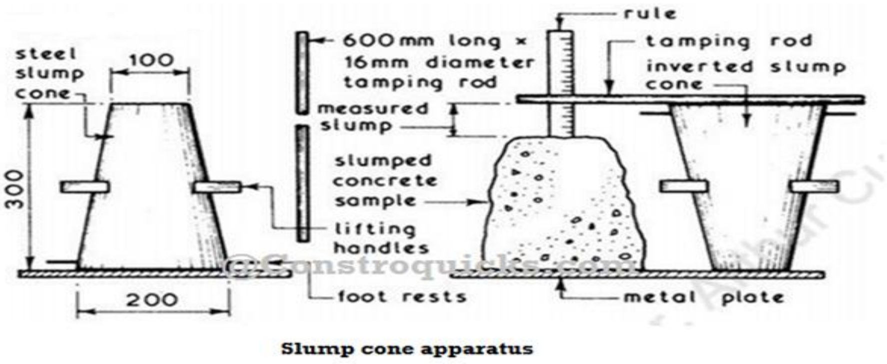


Figure 2-10: Slump Cone Apparatus (Certified Material Testing Products, 2024)

b) Flow Table Test:

Flow table test: This test shall be used to determine the plasticity and spreadability, two of the very important properties of concrete mixes, which would establish that the mix has the potential to be easily placed and consolidated. This test gives the diameter of the spread of concrete on being subjected to a given number of jolts and hence is an indicator of its flow characteristics.

The enhancement of the flow properties in concrete by fly ash has received a lot of coverage in the literature. Fine, spherical particles of the material can enhance mix workability via internal friction reduction, resulting in easier spread during the flow table test. Improved flowability brings out the extraordinary ability of a mix to fill molds or formwork uniformly; this is very important for producing a quality finish for normal and 3D-printed concrete (Thomas, 2007).

The inclusion of bagasse ash has also been seen to positively affect the flow characteristics in conventional concrete. It has been observed that the addition of bagasse ash to concrete results in a modest increase in flow diameter, thus depicting improved workability. This can be attributed to the fine nature of bagasse ash, similar to fly ash, which helps reduce water demand and generally improves the fluidity of the mix (Cordeiro et al., 2009).

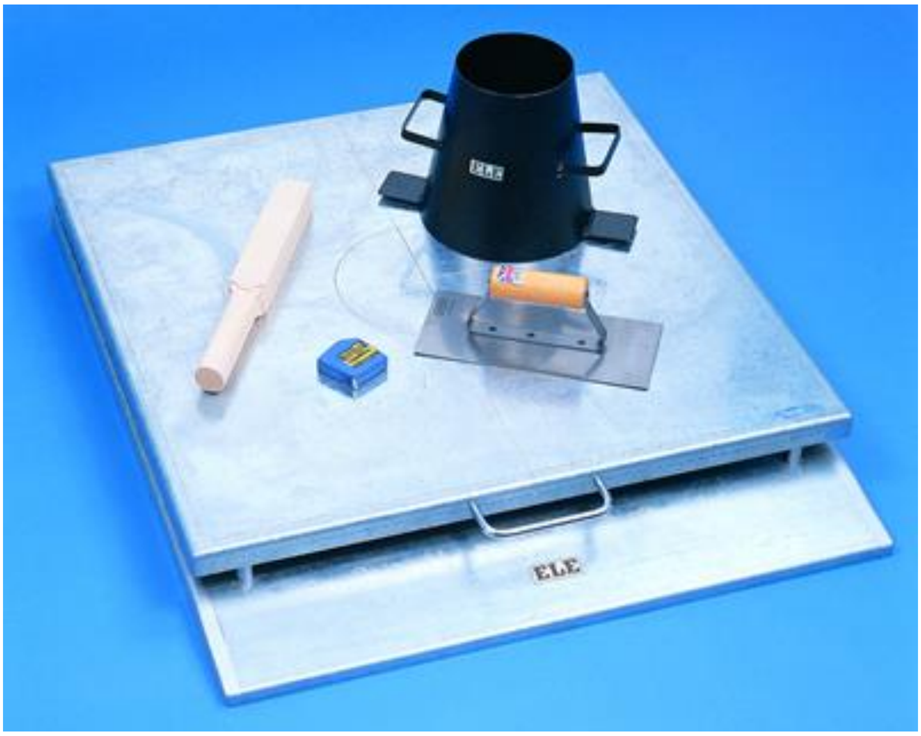


Figure 2-11: Flow table apparatus (ELE International, 2024)

c) Extrudability Test:

Fly ash is thus considered a critical component for enhancing the extrudability of 3DP concrete. Its fine particles increase the cohesiveness of the mix, which will consequently reduce the likelihood of segregation during the process of extrusion. This is thus in support of less friction offered by its spherical-shaped particles within the mix during smooth flow through the nozzle. This feature is thus of absolute necessity in the attainment of a uniform and continuous extrusion process, hence paramount for the successful layering of 3D printed structures (Le et al., 2012).

According to research, mixes with fly ash showed better extrudability and hence required less extrusion pressure to produce a good quality printed layer. The inclusion of fly ash will ensure that the concrete can be efficiently extruded and also aid in getting the proper shape and consistency of the material being printed. This makes fly ash, hence, an invaluable component in mix design optimization for 3D concrete printing, in which the balance between flowability and buildability predominates (Kazemian et al., 2017).

d) Thixotropy Test:

Thixotropy can be defined as the ability of a material to regain its viscosity after subjecting it to shear stress. It is crucial in 3D concrete printing because it keeps the printed layers in shape and supports the following layers. In the context of printable concrete in 3D, it allows the concrete to flow during the extrusion method and afterward quickly stiffen to retain the shape.

Fly ash is known to improve the thixotropic behavior of concrete mixes. The harder and weakly viscous matrix allows rapid reformation of the viscosity after extrusion. Such characteristics are very critical for avoiding the tendency to scrunch up the printed layers, which is said to ensure that each layer will stiffen and cure in its desired shape and position when later layers are printed on top of it (Le et al., 2012).

Studies have shown that fly ash attributes lead to concretes with an advanced thixotropy, with better shape retention after extrusion. Much precise and stable construction is thus possible with this property which is quintessential for the 3D printing of vertical structures. Therefore, according to Roussel (2018), one property function of fly ash is balancing the fluidity requirements for extrusion with structural rigidness immediately after the deposition (Roussel, 2018).

e) Buildability Test:

Buildability is improved by low deformation and a greater number of layers printed above each other. It is evaluated by the deformation of a certain layer (W. Long et al. 2019, V. Mechtcherine et al. 2019, B. Panda et al. 2019) or the maximum number of layers printed before collapsing. (M. Papachristoforou et al. 2019, Y. Zhang et al. 2018) Uniaxial compressive stress-stress response of fresh state 3D printed concrete is used to derive the proposed failure prediction model. A. Tripathi et al. illustrated a typical compressive stress-strain response of fresh mortar under a slow loading rate of 1%/min. The pre-peak response consists of the elastic and initial plastic regime whose slopes determine the elastic and plastic modulus respectively. The initial elastic response is during extrusion where the filament withstands some load and undergoes small deflection but eventually goes back to its original state like that of other soft materials. (M. Dennison et al. 2016, Y. Tanigawa et al. 1989) When more layers are printed onto one another, the stress in one or more bottom layers exceeds the elastic yield stress and the material undergoes further deformation that cannot be reversed: this is the plastic response of the material. The time-dependent strength and stiffness evolution can be determined by characterizing the stress-strain response at regular intervals of time. (R. Jayathilakage et al. 2020, R.J.M Wolfs et al. 2018) These graphs show that there is a bi-linear stress-strain relationship with growth in each layer of the 3D-printed material. A. Tripathi et al. also deduced a conceptual representation of stress growth in different layers during printing. The resulting graph is a staircase model with the horizontal distance indicating the time between the subsequent layer and the rise denoting an increase in stress upon deposition of the next layer. This relationship also demonstrates the buildability of 3D-printed elements as it shows the maximum layers that can be printed before they collapse, which is the basis of buildability analysis. (Panda et al. 2018) Based on this stress-strain relationship, researchers have formulated various equations that deduce the maximum heights of different failure methods. For example, L. Casagrande et al. derived the equation to determine the print height at which stresses on the bottom layer exceed elastic yield stress:

$$h_e = \sigma e / \rho g \quad (1)$$

where h_e is the elastic height limit, and σe is the elastic yield stress.

Moreover, another failure method is the buckling of slender elements. A.G. Greenhill [88] formulated the equation to find the height at which elastic buckling due to self-weight occurs. This is as follows:

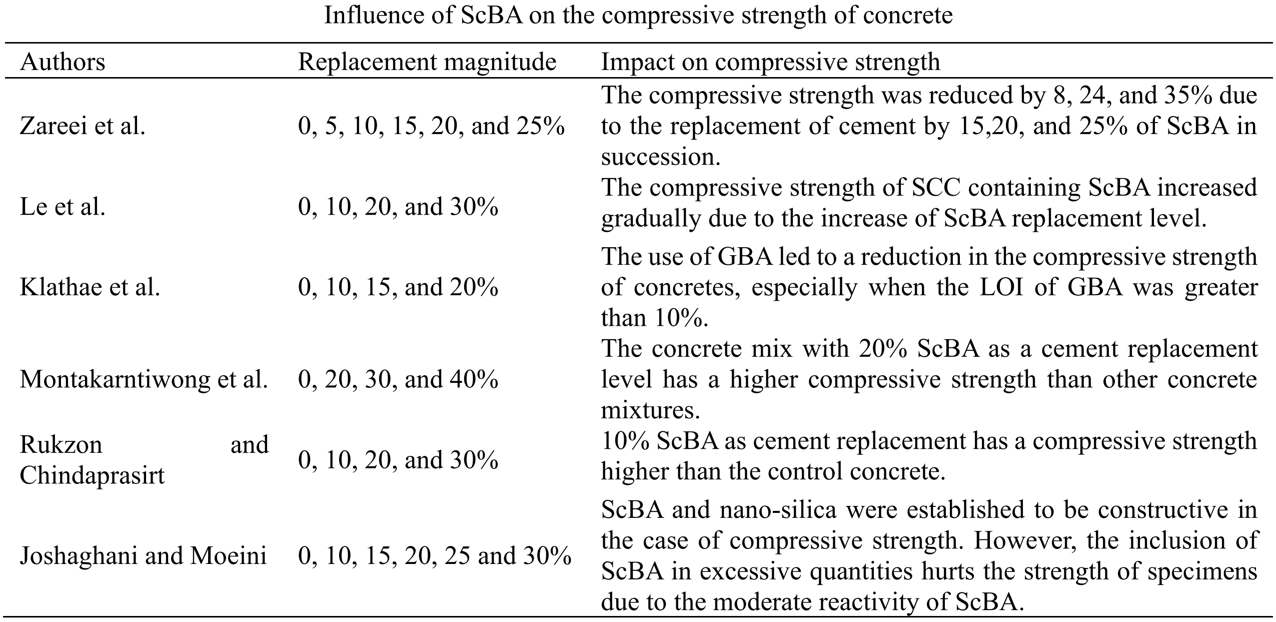
$$h_{b,el} = [\ 7.8373\ E_e I / \rho g A]^{1/3} \quad (2)$$

where E_e is the elastic modulus, and I is the second moment of inertia. Note that this failure can occur only if the condition $h_{b,el} < h_e$ is satisfied.

2) Mechanical Property Tests:

a) Compressive Strength Test:

Compressive strength is one of the critical parameters which quantify the load-carrying capacity of concrete. It has been established that in conventional concrete, the addition of fly ash improves long-term compressive strength. This increase occurs through the pozzolanic reaction of fly ash to form more C-S-H, leading to increased density and strength with time. This makes fly ash a valuable component not only in conventional concrete but also in 3D printable concrete, where structural integrity is highly important to be maintained (Thomas, 2007).



Influence of ScBA on the compressive strength of concrete

Authors	Replacement magnitude	Impact on compressive strength
Zareei et al.	0, 5, 10, 15, 20, and 25%	The compressive strength was reduced by 8, 24, and 35% due to the replacement of cement by 15,20, and 25% of ScBA in succession.
Le et al.	0, 10, 20, and 30%	The compressive strength of SCC containing ScBA increased gradually due to the increase of ScBA replacement level.
Klathae et al.	0, 10, 15, and 20%	The use of GBA led to a reduction in the compressive strength of concretes, especially when the LOI of GBA was greater than 10%.
Montakarntiwong et al.	0, 20, 30, and 40%	The concrete mix with 20% ScBA as a cement replacement level has a higher compressive strength than other concrete mixtures.
Rukzon and Chindaprasirt	0, 10, 20, and 30%	10% ScBA as cement replacement has a compressive strength higher than the control concrete.
Joshaghani and Moeini	0, 10, 15, 20, 25 and 30%	ScBA and nano-silica were established to be constructive in the case of compressive strength. However, the inclusion of ScBA in excessive quantities hurts the strength of specimens due to the moderate reactivity of ScBA.

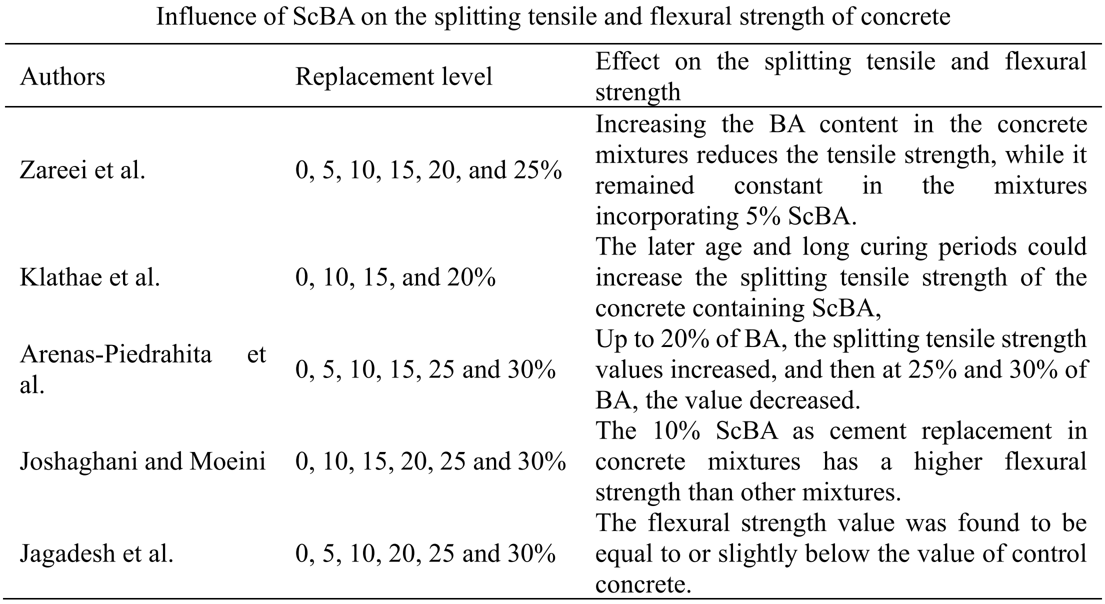
Figure 2-12: Influence of SCBA on the Compressive Strength of Concrete (B.S. Thomas, 2021)

The influence of bagasse ash on compressive strength has been investigated in ordinary concrete (Le et al., 2012). Bagasse ash is an ash that behaves similarly to fly ash (i.e., a pozzolanic material); therefore, it contributes to the formation of C-S-H and increases the compressive strength. However, the increase tends to be more moderate compared to fly ash. Accordingly, the use of bagasse ash in 3D printable concrete remains relatively unexplored, leading to huge potential for innovation (Cordeiro et al., 2009).

b) Tensile Strength Test:

For instance, tensile strength, which quantifies the ability of concrete to resist tension and the bond strength between layers, is very relevant in 3D printing. Fly ash has been shown to enhance the tensile strength of both conventional and 3D printable concrete due to the enhanced bonding at the interfacial transition zone. That means stronger and more cohesive layers for increased structure durability overall (Le et al., 2012).

It is found that bagasse ash improves the tensile strength of conventional concrete, albeit at levels less than fly ash. Its pozzolanic reaction provides improved particle packing and bonding, enhancing the tensile properties of concrete (Cordeiro et al., 2009).



Influence of ScBA on the splitting tensile and flexural strength of concrete

Authors	Replacement level	Effect on the splitting tensile and flexural strength
Zareei et al.	0, 5, 10, 15, 20, and 25%	Increasing the BA content in the concrete mixtures reduces the tensile strength, while it remained constant in the mixtures incorporating 5% ScBA.
Klathae et al.	0, 10, 15, and 20%	The later age and long curing periods could increase the splitting tensile strength of the concrete containing ScBA,
Arenas-Piedrahita et al.	0, 5, 10, 15, 25 and 30%	Up to 20% of BA, the splitting tensile strength values increased, and then at 25% and 30% of BA, the value decreased.
Joshaghani and Moeini	0, 10, 15, 20, 25 and 30%	The 10% ScBA as cement replacement in concrete mixtures has a higher flexural strength than other mixtures.
Jagadesh et al.	0, 5, 10, 20, 25 and 30%	The flexural strength value was found to be equal to or slightly below the value of control concrete.

Figure 2-13: Influence of ScBA on the splitting tensile and flexural strength of concrete

c) Flexural Strength Test:

It is described that the flexural strength of a mix is a very good property for resisting bending stresses in a concrete mix. More specifically, this applies to beams and slabs, key components in the structure of building construction. Research findings have proved that the incorporation of fly ash into concrete significantly improved its flexural strength. This improvement in flexural strength can be attributed to the increased toughness and better dispersion of stress imparted by fly ash throughout the concrete matrix. This rise in flexural strength for 3D printable concrete becomes very critical because it ensures class conformity of the printed element to bear the required loads without cracking or bending under stress (Le et al., 2012).

In contrast, the use of bagasse ash in conventional concrete decreases flexural strength. Bagasse ash is finer with pozzolanic properties, and hence helps improve the cohesion and integrity of the concrete matrix as a whole; however, these gains in flexural strength are not quite so prominent.

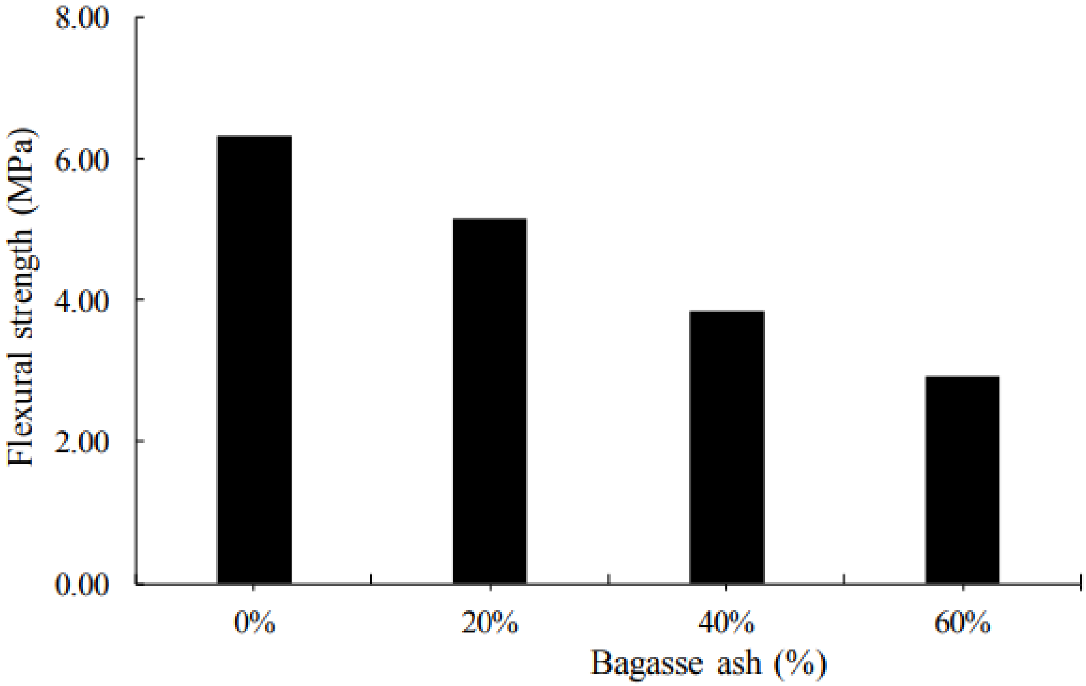


Figure 2-13: Flexural strength of pavement concrete containing bagasse ash at 28 days (Chindaprasirt, 2010)

2.4. Development of Automated Continuous Supply Mechanism

2.4.1 Design and Fabrication

This mechanism of continuous supply will continuously feed the input raw material to the 3D printer and drastically cut short interruptions during printing. The main components of the system would include hoppers, gate systems, mixers, and pumps. This entire proposed system shall have to integrate with smart sensors and IoT technologies for real-time monitoring and control to run smoothly and efficiently.

In 3D concrete printing, an ideal continuous supply mechanism is very vital. In different instances, many authors have mentioned that the supply system should be well-designed to sustain both the materials' flow and quality consistently (Roussel, 2018; Weng et al., 2018).

2.4.2 Fabrication and Assembly

The manufacturing and assembly of the Continuous Supply System includes several steps to provide a high degree of accuracy and preciseness to the design. This comprises:

a) Component Design:

The components alone are designed on the CAD software by considering the capacity and functionality required. Roussel (2018) showed that simulation tools could be used to optimize the design of each component so that it would work better.

b) Fabrication:

Appropriate materials and processes like machining, welding, and assembly are then used in the fabrication of components. According to Weng et al. (2018), high-quality materials will ensure durability and reliability.

c) Integration:

The fabricated components are then integrated into a coherent system with smart sensors and IoT technologies that can support the implementation of real-time monitoring and control. Roussel (2018) emphasized the importance of integrating sensors to provide continuous feedback and ensure optimal operation.

2.4.3 Performance Evaluation and Optimization

Evaluation will be based on the print quality, material usage, and construction time of the continuous supply system, as well as its reliability. All the feedback from this evaluation will be put into refining the system's efficiency and reliability when applied in practice.

The performance of the Continuous supply system shall be tested under various tests and the same shall be analyzed to identify the potential issues or scope improvement in the same (Roussel, 2018; Weng et al., 2018).

a) Print Quality Assessment:
Evaluates the consistency and accuracy of the printed layers. Roussel (2018) has suggested high-resolution cameras and image processing software check quality in real-time.

b) Material Usage Analysis:
It helps to determine the excess usage of materials during the printing process. Weng et al. (2018) stated that this excess of materials was what increased the cost and had impacts on the environment.

c) Construction Time Measurement:
This is the time taken to complete the printing process. Roussel (2018) introduced the use of automated scheduling tools to schedule the printing process and, in turn, optimize and reduce construction time.

d) System Reliability Testing:
The system's reliability or robustness against various working conditions must be verified. Weng et al. (2018) proposed conducting the stress test to determine the system performance under high load conditions.

The results of such tests will further optimize the continuous supply system concerning its efficiency and reliability in actual applications.

2.6 Case Studies and Applications

2.6.1 International Examples

Several breakthrough projects all over the world prove that 3D concrete printing technology has potential:

a) Apis Cor's Two-Story Building in Dubai:

In the year 2019, Apis Cor realized a two-story building in Dubai that has been called the largest 3D-printed structure globally. That only proved the scaling possibility and efficiency of 3D concrete printing for large constructions (Gosselin et al., 2016).

b) 3D-Printed Concrete Bridge in the Netherlands:

The first 3D-printed concrete bridge was developed in the Netherlands, hence proving the ability of 3D concrete printing in infrastructure development. The project showed how 3D printing can be used in the production of complex and strong structures (Bos et al., 2018).

Figure 2-14: Municipality of Nijmegen, Michiel van der Kley (summum.engineering, 2021)

c) Dubai's Smart City Initiatives:

The UAE has applied 3-D concrete printing in various projects at the heart of its smart city goals, ranging from bus stops to the Future Dubai Office. This showcases how 3D printing can contribute toward the goals of sustainable development (Apis Cor, 2019).

Figure 2-15: Dubai Future Foundation Office (Sheridanuae, 2023)

2.6.2 National Context

A prototype of a 3D printer was developed in Pakistan in the year 2023, and this has been a milestone concerning the adoption of 3DCP technology. This prototype has developed a frame size of 1x1x1.5m and a printable area of 0.8x0.8x1m, underlining the necessity of a continuous supply mechanism to ensure efficient and uninterrupted printing.

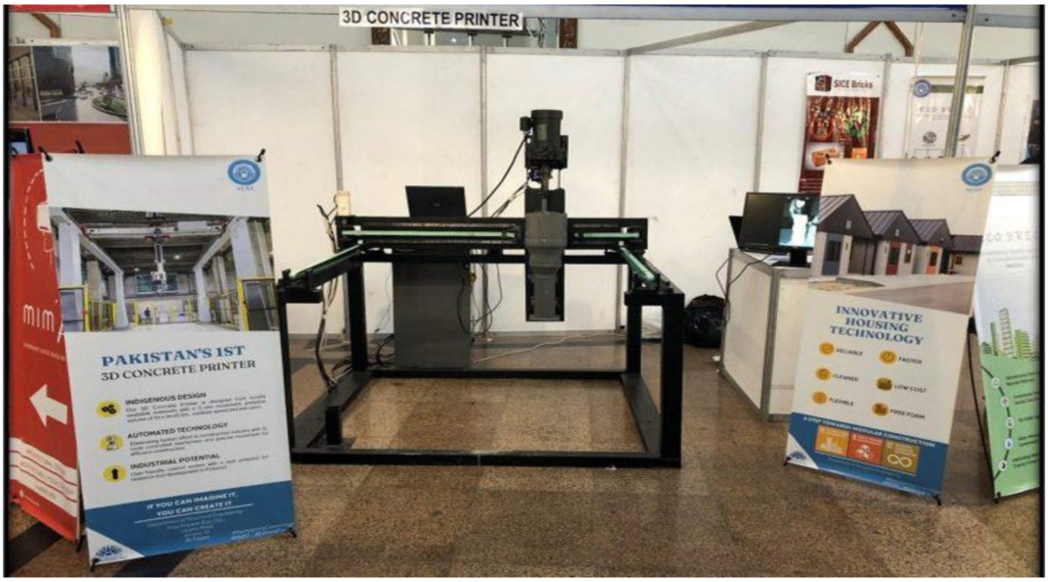


Figure 2-16: 3D Concrete Printer Prototype (mmnews, 2023)

A prototype developed at present shows that 3D printing could resolve crises of housing shortages and sustainable construction in Pakistan (Ahmed et al., 2023)

Chapter 3

Methodology

3.1 Overview

This chapter deals with the general research methodology that would achieve the dual objectives of mix design optimization of the 3D printable concrete and developing an automated continuous supply mechanism for raw materials. The research methodology is therefore outlined to follow spelt-out stages: literature review, materials selection, experimental procedures, data analyses, and validation of the system. In every phase, the methodology will also directly reflect specific research questions and targets in an effective, logical, and decisive way in its results.

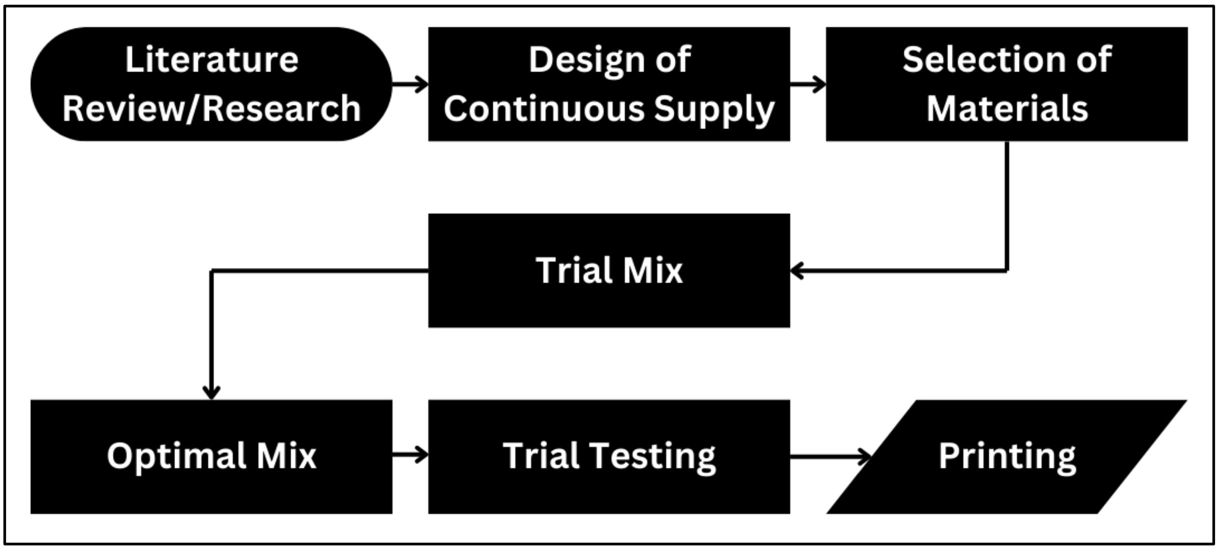


Figure 3.1: Methodology Flowchart

3.2 Research Design

The research design adopted in the project is divided into two primary phases:

1. Optimization of Mix Design for 3D Printable Concrete

2. Development of Automated Continuous Supply Mechanism

The two phases have been further divided into steps ranging from literature research to material selection, experiment design, data collection, and analysis. It is a systematic approach to probing the research problem comprehensively and efficiently.

3.3 Optimization of Mix Design

3.3.1 Literature Review

More than anything else, it is within the past decade that 3DCP technology made its quantum jump in development because of the need to find more efficient, cost-effective, and sustainable methods of construction. Its procedure formulates structure based on a digital model and concreting, which enables layer-to-layer deposition of concrete—thereby doing without the formwork usually adopted in building methods and thus allowing greater design flexibility (Bos et al., 2016). All the key existing studies have been oriented to defining the rheological properties of materials about 3DCP, considering the basic problems of workability, buildability, and extrudability that have to be assured for a quality print.

For instance, printability is the ease by which concrete can be smoothly extruded from the nozzle, holding a profile without collapsing (Le et al., 2012). Known factors for influencing fresh concrete printability are the water-to-cement ratio, particle size distribution, and additions of superplasticizer and viscosity-modifying agent. Buildability refers to the ability of the extruded layers to support the built-upon layers without minimum detriment. All of these properties should be balanced together in an optimized way for the success to be achieved in 3DCP.

Besides the rheological properties, a lot of research is focused on mechanical performance. Research has shown that layer-by-layer construction introduces anisotropy in mechanical properties, such that the strengths of the printed structure are different in different directions (Khoshnevis, 2004). Several approaches are being investigated at present for this remedy: affect path optimization and material reinforcement.

The sustainability, as well as the performance of concrete, has been attempted to be improved through supplementary cementing by secondary cementitious materials (SCMs) such as fly ash and sugarcane bagasse ash (ScBA) in several studies. Fly ash is usually obtained as an auxiliary by-product resulting from the burning of pulverized coal. However, in its primary nature, it has pozzolanic properties that significantly can contribute to enhancing the long-term durability and strength of concrete (ACI Committee 232, 2004). ScBA, which is derived from the agricultural wastes produced during the processing of sugarcane, is considered a material that has been in the limelight due to the high content of silica and reduces the impact of the production of concrete on the environment (Cordeiro et al., 2009).

3.3.2 Material Selection

a) Cement

Ordinary Portland Cement (OPC) is the primary binder used in the mix. The main reasons behind the choice are well-documented properties, availability, and better compatibility with the SCMs defined. OPC has high early strength and durability and is therefore recommended for use in structural construction. The chemical reaction of cement with water is referred to as the hydration process and leads to the development of both calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) within the concrete, which results in strength development (Mindess et al., 2003).

b) Fly Ash

Fly ash is a finely divided residue coming from the combustion of pulverized coal in thermal power plants; it is widely used as a partial replacement for cement in concrete mixes. Some benefits come from improvements in workability; the heat of hydration decrease; and the increase in strength and durability of concrete over a long time of its functioning. Fly ash reacts with the calcium hydroxide produced from the cement hydration to yield additional C-S-H, which increases the strength and durability of the concrete (ACI Committee 232, 2004). Besides upgrading the 3D printable concrete, fly ash used in the mixture also minimizes the environmental footprint by recycling industrial wastes.

c) Sugarcane Bagasse Ash

Sugarcane Bagasse Ash (ScBA) is a byproduct of the sugar industry obtained by burning the raw material, sugarcane bagasse. ScBA contains good amounts of silica, which makes them strong pozzolans. They further contribute to the strength and durability of concrete by reacting with calcium hydroxide and forming additional C-S-H. The application of ScBA in concrete has numerous benefits on its mechanical properties and leads to the sustainability of the concrete by reusing agricultural waste (Cordeiro et al., 2009). According to studies, the addition of ScBA in concrete maximizes its compressive and tensile strength, making it a potential material for 3-D printable concrete.

d) Sand

Fine aggregates, particularly sand, are used for the mix to be able to extrude easily through the nozzle of the 3D printer without clogging or segregating. The particle size distribution of the sand shows careful selection to increase the buildability and flowability of the mix. Sand envelopes provide a skeletal structure to the mix and, hence, contribute to the overall strength and stability of the printed layers. The selection of sand is critical, as the particle size and shape can significantly influence the rheological properties of the mix (Neville, 2011).

e) Superplasticizers

Superplasticizers, otherwise known as high-range water reducers, are chemical admixtures that improve the workability or flow characteristics of concrete without increasing the water content of the mix. By acting on the cement particles, these admixtures disperse them to reduce the demand for water while enhancing the flow characteristics of the mix (Sika, 2016). The addition of superplasticizers in 3D printable concrete is done to achieve the required rheological properties so that the mix can be easily extruded without segregation and maintain its shape after deposition.

3.3.3 Mix Proportioning

Mix design is the determination of the quantities and proportions of the constituent materials that are required to be made into concrete of specified properties for 3D printing. The process is iterative and comprises several trials for optimal adjustment of constituents to balance workability, buildability, and mechanical strength.

a) Initial Trials

The fly ash is set as fixed to its minimum required percent for printability, while different percentages of ScBA are tried to find an optimum mix that would balance buildability and extrudability. Initial trials were carried out in the search for a mix easily extrudable, retaining form, and hitting the intended mechanical properties.

b) Optimized Mix Development

The mix proportion is further modified to have optimum properties for this 3D printable concrete. The optimization will balance the workability, buildability, and mechanical strength of the mix. The optimization refines the proportion of cement and SCMs with sand and superplasticizers.

c) Mix Design Evaluation

A suite of tests such as slump, flowability, compressive strength, shear strength, interlayer bonding, deformation, printer setup, and buildability tests assess the fresh and hardened properties of the optimized mix design. This assessment process will serve the needed information about the performance of the mixes, which will further develop it towards the refinement of the optimum properties to be achieved for 3D printing.

3.4 Development of Continuous Supply Mechanism

3.4.1 Design of Continuous Supply System

The continuous supply system is designed to ensure a steady and automated flow of raw materials to the 3D printer. This system comprises several key components, including hoppers, gate systems, mixers, and pumps.

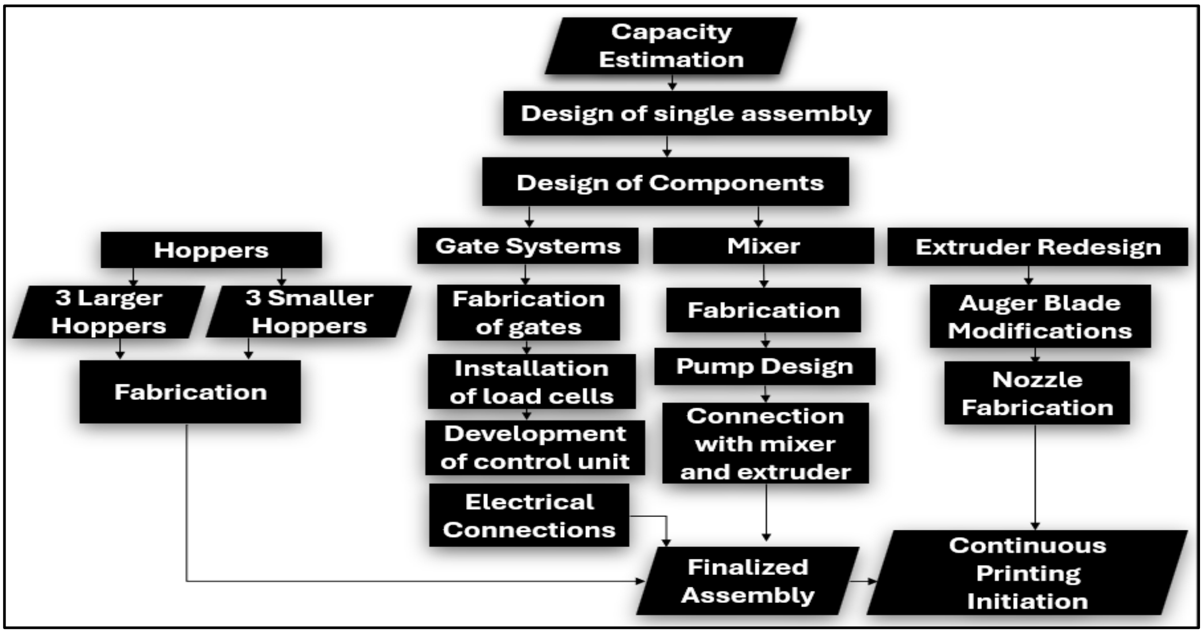


Figure 3.2: Methodology for the development of Continuous Supply Mechanism

a) Hoppers

These raw materials will be stored and discharged through six hoppers. Out of the six, three can be used for the main constituents, that is, cement, sand, and SCMs, and three for supplementary materials. The design of the hopper has to take care of the problems associated with storage capacity, material flow characteristics, and cleaning and maintenance features.

b) Gate System

It controls the material dispensed out of every hopper by its gate system, which is controlled and operated by load cells, allowing for very tight control over mix proportions. Because the gate system is designed to eliminate losses of material and hold flow rates constant, load cells have real-time responsiveness to the levels of materials put into the hoppers. This raises the need for automation to make the required adjustments to maintain the proportions in the mix as already set.

c) Mixer

The removable mixer mixes the raw materials, and afterward, it is attached to a pump at the outlet, which is used to send the mixed concrete into the extruder. The mixer configuration allows for uniform mixing to avoid the separation of the concrete, and through homogeneity, the quality obtainable from the printed concrete is improved. Moreover, the mixer is endowed with sensing devices for the monitoring and control of the mixing process in real time.

d) Pump and Extruder

There is also an adjustable extrusion speed that guarantees a continuous supply of mix to the extruder, laying down the concrete successively in layers following a digital design. The pump design and the extruder design themselves truly form the basis of quality prints. This would naturally mean that the pump has to deliver material without any pulsation, and it needs to have a continuous flow to the extruder, and the extruder, in turn, is to have firm control over each deposition of the layer. In-built nozzles of different layer thicknesses and print resolutions are in place.

3.4.2 Fabrication and Assembly

a) Component Design

With the CAD design software, each component that needs to make up the continuous supply system is designed as a way of ensuring precision and accuracy in the design. Taking into consideration the capacity and functionality that will be required, the design of each component is affected.

b) Fabrication

The correct material is chosen, and machining with proper processes of fabrication is done to get a high performance, and long durable components. Fabrication includes machining, welding, and assemblies of parts.

c) Integration

The fabricated elements are joined together to form a coherent system. The smart sensors and IoT are integrated with the system to regulate and supervise the data in real-time.

3.5 Experimental Testing

3.5.1 Slump Test

The slump test is conducted to measure the workability and consistency of the concrete mix. The concrete is poured into a standard slump cone in three layers and compacted using a tamping rod. The cone is then lifted, and the concrete is allowed to slump under its weight. The difference in height between the cone and the slumped concrete is measured and gives the slump value, which describes the flowability of the mix. This is repeated over different time intervals to monitor any change in workability with time, which is important to ensure that the mix remains suitable to be 3D printed during the project.

3.5.2 Deformation Test

The mix's buildability, based on its ability to hold its original shape under load, is reflected in the deformation test. A cylindrical sample is deformed at the center with a 1000 g weight under different time frames. This test will help in understanding the mix's ability to sustain its self-weight and extra loads without large deformations, which is very important for maintaining the integrity of 3D-printed structures. What is required is to create a fine balance between buildability and extrudability, where mixes can be printed in layers without collapsing or deforming excessively.

3.5.3 Extrudability Test

Extrudability testing involves the testing of concrete regarding its continuous extrusion capacity from the 3D printer's nozzle head. The test will be done by changing the speed of extrusion measured in RPM to get an optimum flow rate, which creates a minimum settlement while holding its shape as intended. The width and height of the extruded material are measured as an aspect ratio, acting as an independent variable that helps in the determination of the optimum speed of extrusion. Correct extrudability has to be achieved to ensure the mix can be printed in continuous layers without disruption or faults.

3.5.4 Buildability Test

Buildability is checked through two main tests. The first test is that of unconfined compression, UCS, where the mix is loaded vertically to determine the mixture's ability to hold itself up without collapse. Another test measures deforming under a 1000g applied load for a change in shape by noticing variations in height and width. These tests will establish the mix's ability to support the subsequent layers with minimal deformation so that the printed structure remains stable and retains its designed geometry.

3.5.5 Shear Test

The shear strength of the mix is tested with the Vicat apparatus, where a plunger is inserted into the mix, and resistance to penetration is measured. The shear strength is calculated through the formula:

$$\sigma = 2/\pi dh3 \tag{3}$$

where d is the plunger diameter and h is the depth of penetration.

This test also determines the initial and final setting times of the mix, which is valuable in establishing how quickly the mix starts to gain strength and is viable for the next layer to be workable in the printing process.

3.5.6 Compressive Test

Compressive strength test shall be conducted on 50mm cubic samples following ASTM C-109. This test is carried out to determine the compressive strength of concrete; as such, it is very important to establish that the structural integrity of printed elements remains intact. The test is carried out in three directions (X, Y, Z) and on cast samples, while the strength is measured at 28 days. The results of this study can therefore indicate anisotropy in the printed concrete and the effects of printing processes on the mechanical properties of the material.

3.5.7 Interlayer Test

Tensile testing measures the interlayer bonding strength by applying a load at 0.25 MPa/s over 130 mm in length of the printed layers. This test measures the maximum strength developed between two layers, defining the quality of bonding and the possibility of delamination under stress. This will thus turn into an important test associated with the structural continuity and integrity of a 3D printed component, since if the interlayer bonding is weak, it may mean failure in service.

It is explained in detail in these test methodologies how each test was conducted, thus able to provide an integral overview of the understanding of the suitability of concrete mix for 3D printing applications.

3.6 Data Recording

All results of tests are recorded in structured data sheets. Measurement data reaches from fresh state tests to mechanical property tests, also process observations of the extrusion process are involved. Data recording is done very carefully for trustworthy analysis and optimization of mix design and continuous supply system.

3.6.1 Statistical Analysis

Statistical tools are used to analyze the obtained data. Descriptive statistics and regression analysis were employed to determine tendencies and various mix proportions that showed significant effects on the properties of concrete. In descriptive statistics, data may be summarized to include mean, median, standard deviation, and range. Regression analysis models the relationship amongst the mix proportions in their effects on concrete properties so that prediction and optimization may be made. ANOVA is used to test whether there are lots of differences in the mean of different groups.

3.6.2 Optimization

Mix design optimization will enhance the mix design and continuous supply system, realizing improvement because of the analysis, which will enable iteration of further tests to adjust the combination to achieve an optimum balance between workability, buildability, and mechanical strengths. The process of optimization will be guided by the view from the result of the statistical analysis and, in the end, result in a mixed design and supply system that assures the predefined performance criteria indicated in a performance-based way.

3.7 Validation

3.7.1 Prototype Testing

A prototype of the continuous supply system is tested with the optimized concrete mix-in. The testing is to be carried out with actual 3D printing of the structural element to check upon its feasibility within the system. The prototype shall help provide valuable information relating to functionality and reliability for the continuous supply system and further improvement and enhancement.

3.7.2 Performance Evaluation

Several evaluation criteria are considered, basically about the print quality, material usage, construction time, and system reliability. Feedback from all tests into consideration is used for further refinements. The performance evaluation shall ensure that the continuous supply system satisfies requirements for 3D printing and creates high-quality printed structures efficiently and reliably.

3.8 Summary

The chapter provides a detailed methodology for the optimization of concrete to be 3D printable and the development of its associated continuous supply mechanism. In this context, it presents the iterative procedure of mix proportioning, evaluation, and optimization, followed by the continuous supply system design and fabrication. Experimental testing in the fresh and hardened state properties was incorporated to ensure satisfaction with the performance of the optimized mix. In correspondence, the development of a continuous supply system and its validation are very important in striving to achieve reliable and efficient processes in 3D printing.

CHAPTER 4

RESULTS

4.1 Continuous Supply Mechanism

The continuous supply mechanism was designed to fully automate the process of 3D concrete printing. The initial prototype was based on extrusion only. The added assembly aided in the weighing and mixing process of the printer, thus reducing time and effort. The components included 6 hoppers, a gate system, a mixer, and a cavity pump. The designs were drawn on AutoCAD for 2D visuals and dimensions.

4.2 Concrete Mix Design

After rigorous testing and literature review, an optimized mixed design of printable concrete was made. Table 4-1 shows the final mix design composition, consisting of fly ash and sugarcane bagasse ash as supplementary cementitious materials. Figure 4.2 shows each constituent's mass in 1 cubic meter of volume. The density of the optimized mix design is 2124kg/m^3.

Table 4-1: Optimized Mix Design by Proportion

Material	**Proportion (%)**	**Weight**
Cement (OPC)	27.6	586.4
Fly Ash	10	219.9
ScBA	7	146.6
Sand	34.5	732.9
Superplasticizer	1 (by weight)	19
Water	20.7	438.3
S/B	0.79	0.79
W/B	0.46	0.46

4.2.1 Test Results

To validate the optimized mix design, non-standardized testing was done on the printed mix. As illustrated in the methodology, these tests focused on properties such as compressive strength, interlayer bonding, shear strength, buildability, etc.

a) Slump Test

The mix design was optimized in terms of flow through the slump test. The test was carried out at different times (minutes). The results showed the printable range. Table 4-2 and Figure 4.3 represent these results. The percentages of ScBA and Fly Ash are calculated concerning cement replaced.

Table 4-2: Results of Slump Test

Mix ID	**ScBA (%)**	**Fly Ash (%)**	**Slump (mm)/Time(mins)**					
			10	**15**	**20**	**30**	**35**	**40**
M1	10	25	210	205	174	147	126	109
M2	20	25	203	191	171	134	118	96
M3	25	25	192	176	162	138	125	99
M4	30	25	176	159	140	127	109	95
M5	35	25	165	158	136	118	109	92

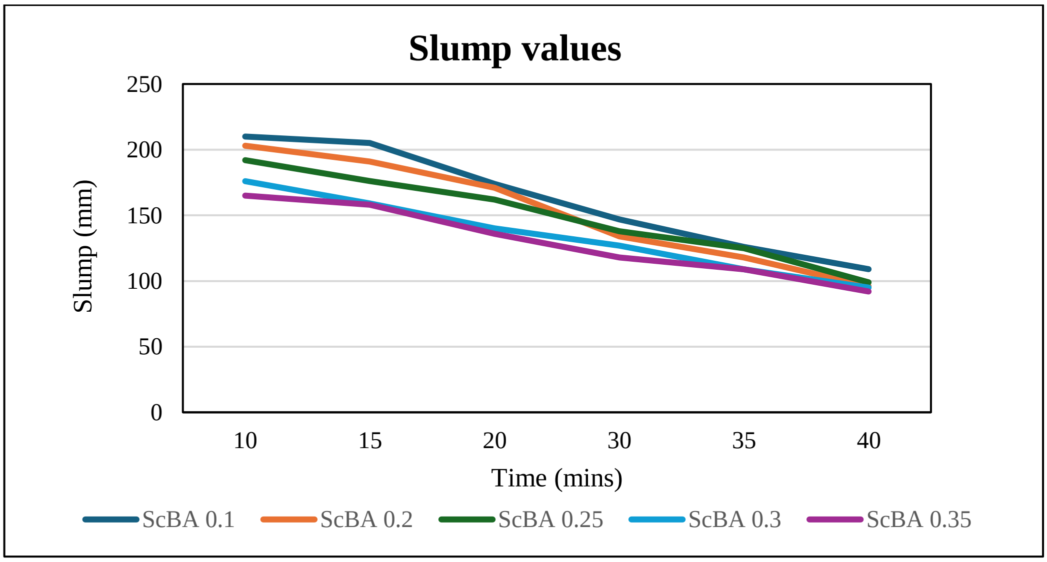


Figure 4.1: Graph showing the Results of Slump Test

b) Deformation Test

The deformation test was carried out to achieve a balance between buildability and extrudability. Deformation was seen under a load of 1000g. Figure 4.4 shows the results of the test concerning time.

Table 4-3: Results of Deformation

Mix ID	**ScBA (%)**	**Fly Ash (%)**	**Deformation (mm)/Time(mins)**						
			10	**15**	**20**	**25**	**30**	**35**	**40**
M1	10	25	12	10	7	6	4	3	2
M2	20	25	10	10	8	7	6	5	3
M3	25	25	15	12	10	8	7	7	6
M4	30	25	10	9	9	7	6	5	4
M5	35	25	160	10	8	8	7	6	6

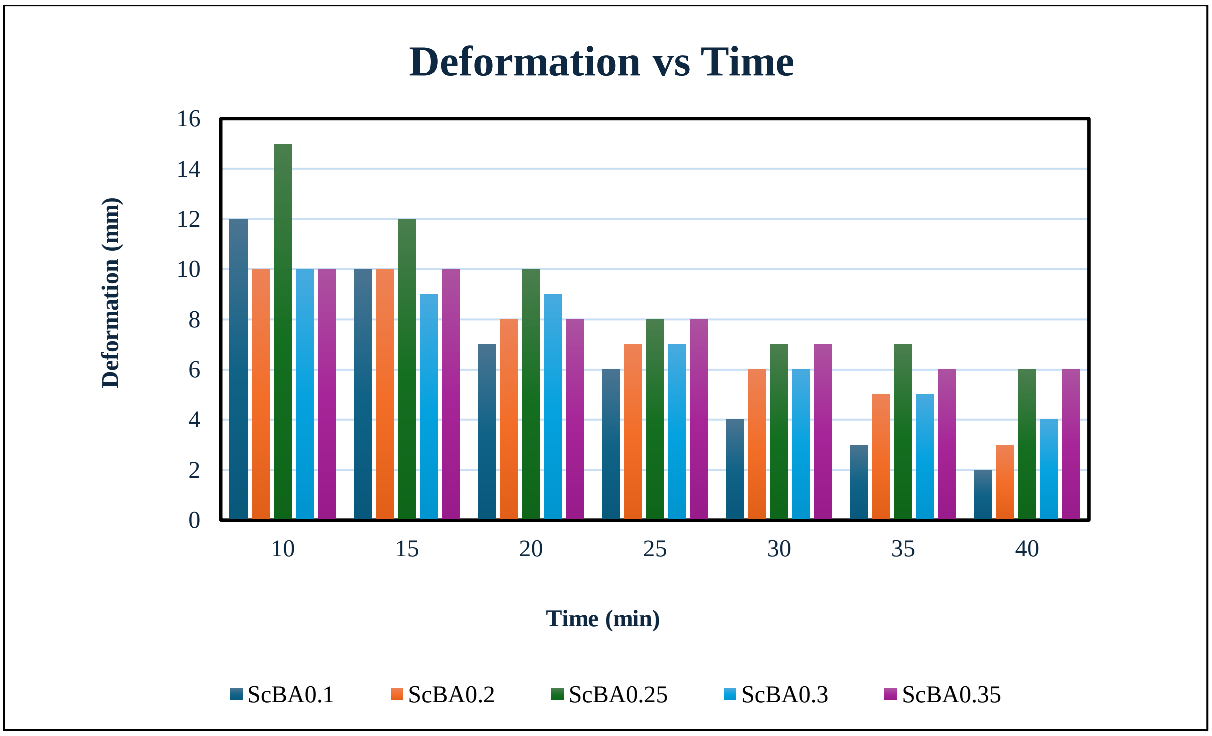
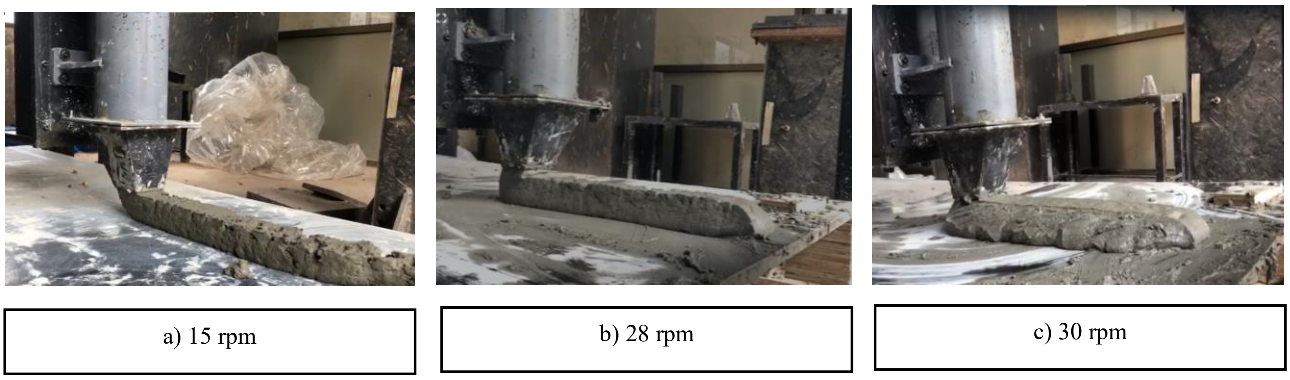


Figure 4.2: Graph showing the Results of Deformation

c) Extrudability Test

Extrudability was tested using the test for printer setup. To ensure printability, the optimum linear speed had to be found out. Extrusion was based on rpms and had to be fixed for minimum settlement. A balance between extrudable and linear speed was achieved. The aspect ratio of width and height after extrusion was calculated as an independent variable. Figure 4.5 illustrates the results. Figure 4.6 shows the extruded materials at different extrusion speeds.


a) 15 rpm

b) 28 rpm

c) 30 rpm

Figure 4.3: Printed mix at different extrusion speeds as follows: a) 15 rpm, b) 28rpm, c) 30 rpm

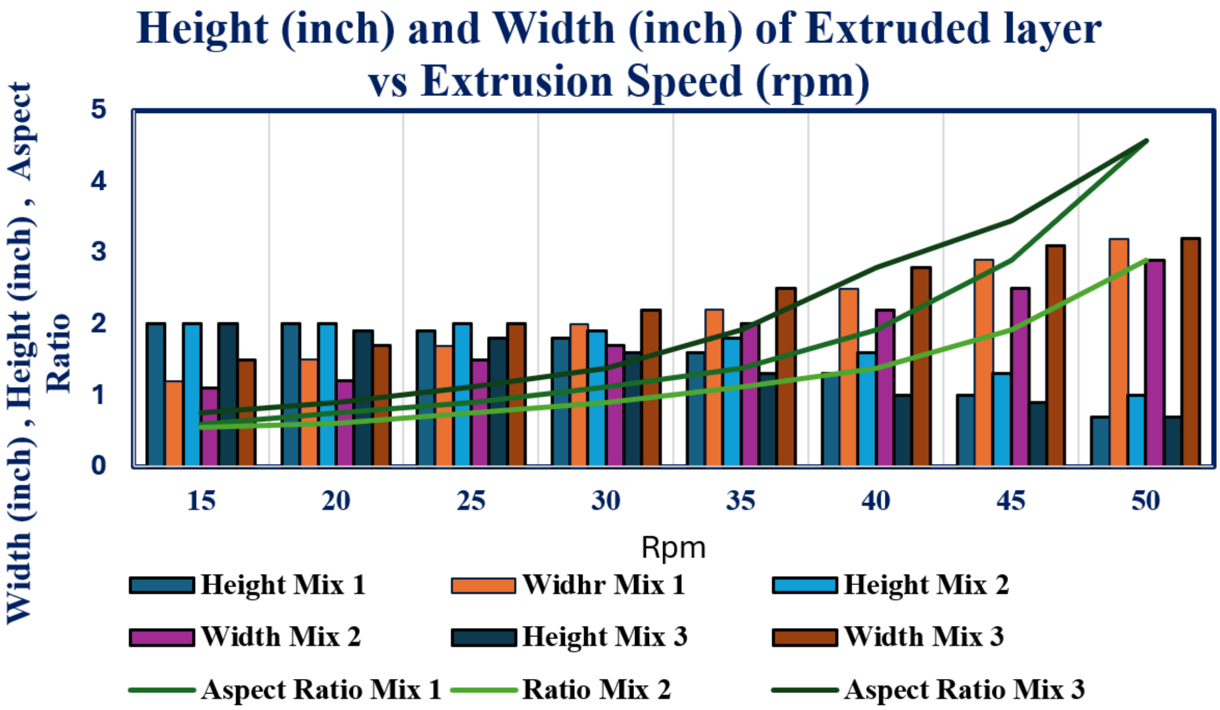


Figure 4.4: Relation between Aspect Ratio and Extrusion speed (rpm) (Raja Dilawar Riaz et al., 2023)

d) Buildability Tests

Buildability was assessed through two tests. The first was a fresh state evaluation using the unconfined compression (UCS) test. Minimum settlement was to be achieved. Figure 4.7 shows the results of different cylinders after taking up the strain of 3 different mixes.

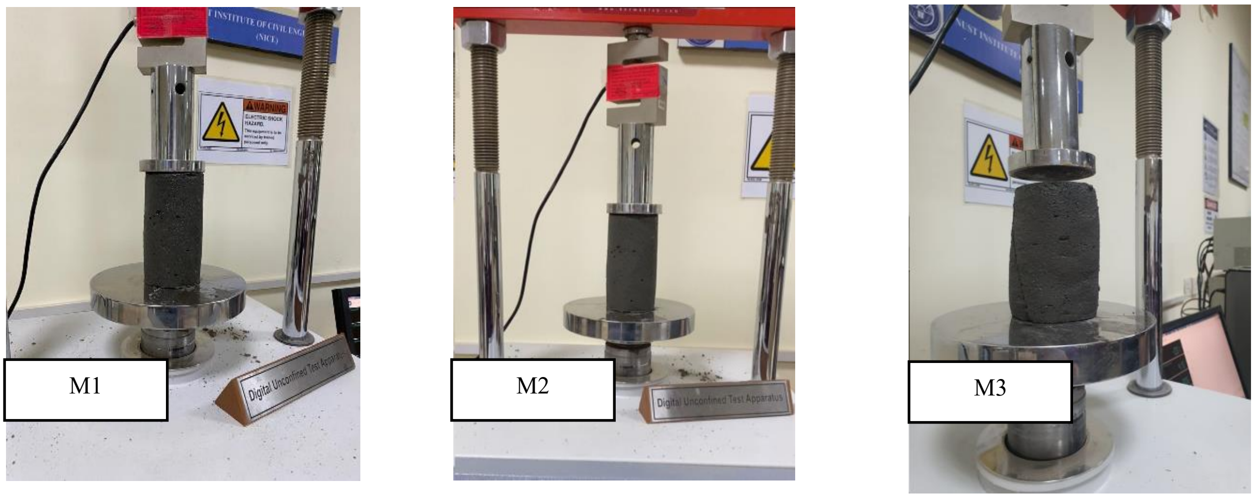


Figure 4.5: Buildability Results using UCS

The second test was to observe the change in shape when a load of 1000g was applied. Variations in height and width were observed as shown in figure 4.8. The acceptable range was 8-13mm while the optimized mix design had a value of 10mm.

Figure 4.6: Change in shape after 1000g loading

e) Shear Strength

Literature has used the Vicat apparatus to test the shear strength of the optimized mix using plunger dia and depth of penetration. The formula used was $\sigma = \frac{3}{2\pi(d)(h)}$ where h is the depth of penetration and d is the diameter of the plunger i.e. 10mm. The same apparatus was used to find the initial setting time of the concrete mixes as well. Table 4-4 shows these values and Figures 4.9 and figure 4.10 show their graphical representation.

Table 4-4: Vicat Apparatus results

Mix ID	ScBA (%)	Fly Ash (%)	Initial Setting Time (mins)	Final Setting Time (mins)	Vicat Depth(mm)	H(mm)	Shear Stress (MPa)
M1	10	25	137	323	37	3	0.0159
M2	20	25	145	342	35	5	0.0095
M3	25	25	151	345	27	13	0.0037
M4	30	25	156	357	20	20	0.0024
M5	35	25	160	364	10	30	0.0016

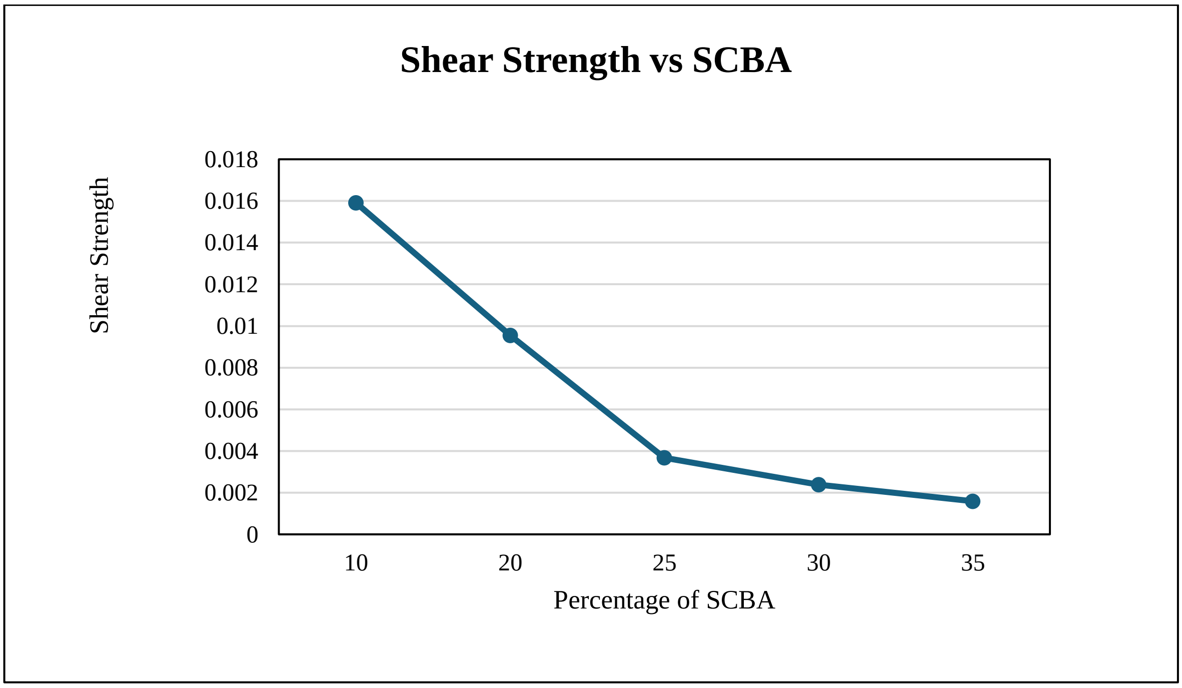


Figure 4.7: Shear Strength Results

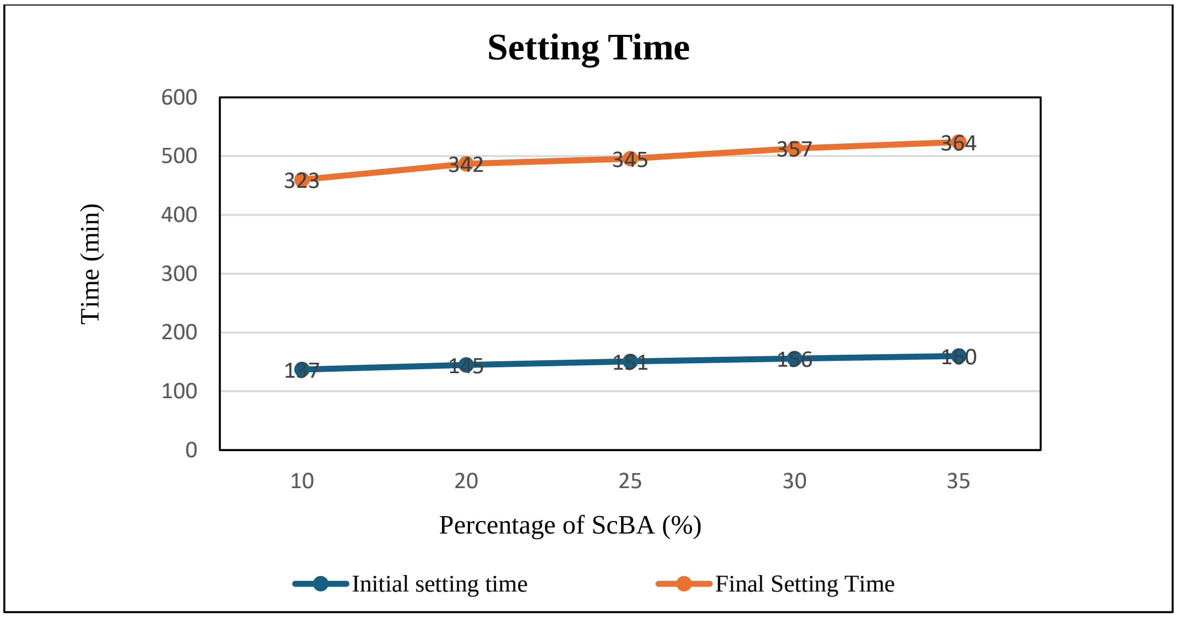


Figure 4.8: Initial Setting Time

f) Compressive Strength

Compressive Strength tests were carried out on a cubic sample of 50mm length as per ASTM C-109. The strengths were compared in all three directions of printed elements as well as cast compressive strength. Table 4-5 shows the results of the loading rate of 0.25mm/s. The tabulated strengths are measured at 28 days. Figure 4.11 shows the graph of strength with a change in the sugarcane bagasse ash constant. Figure 4.12 shows the change in strength with an increase in sugarcane bagasse ash percentage.

Table 4-5: 28-day strength of concrete mix design in different directions

Mix ID	**ScBA (%)**	**Fly Ash (%)**	**28-Day Strength (MPa)/Direction**			
			X	**Y**	**Z**	**Casted**
M1	10	25	35.2	32.3	29.7	35.2
M2	20	25	28.6	24.7	21.6	28.6
M3	25	25	25.1	19.7	21.2	25.1
M4	30	25	17.8	14.2	14.1	17.8
M5	35	25	12.5	8.4	9.8	12.5

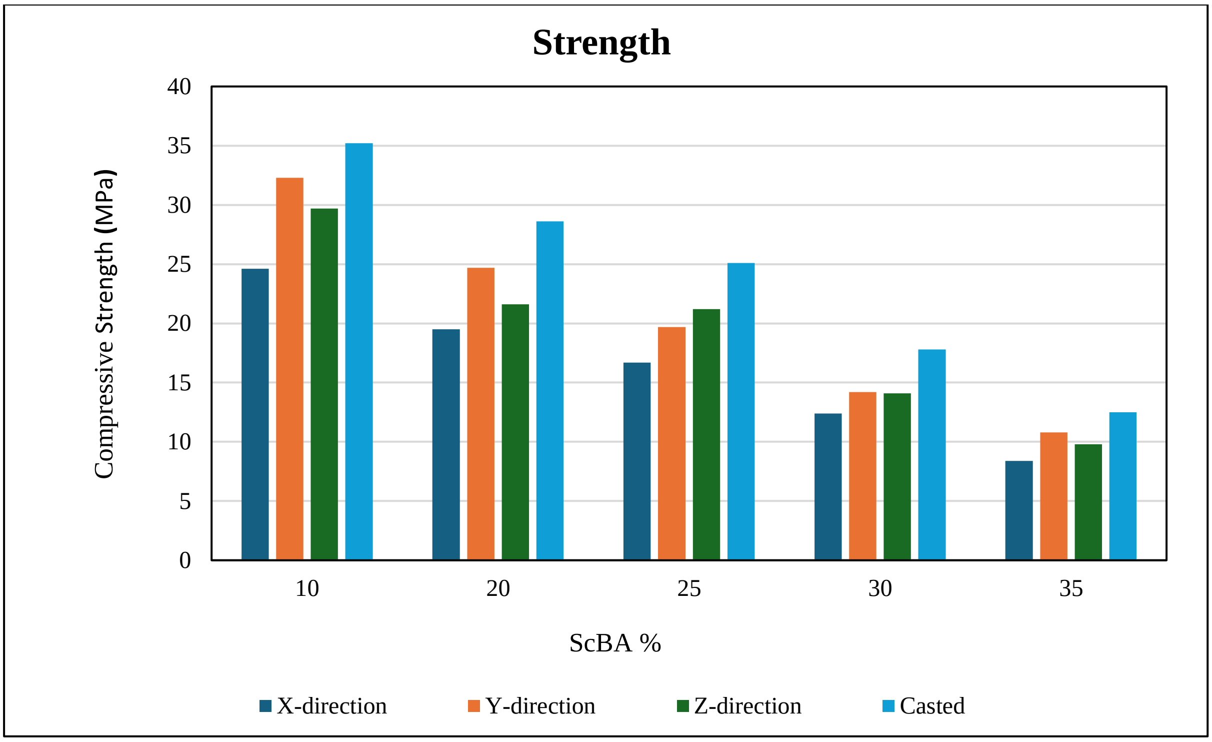


Figure 4.9: Compressive Strength in all direction with varying ScBA percentages

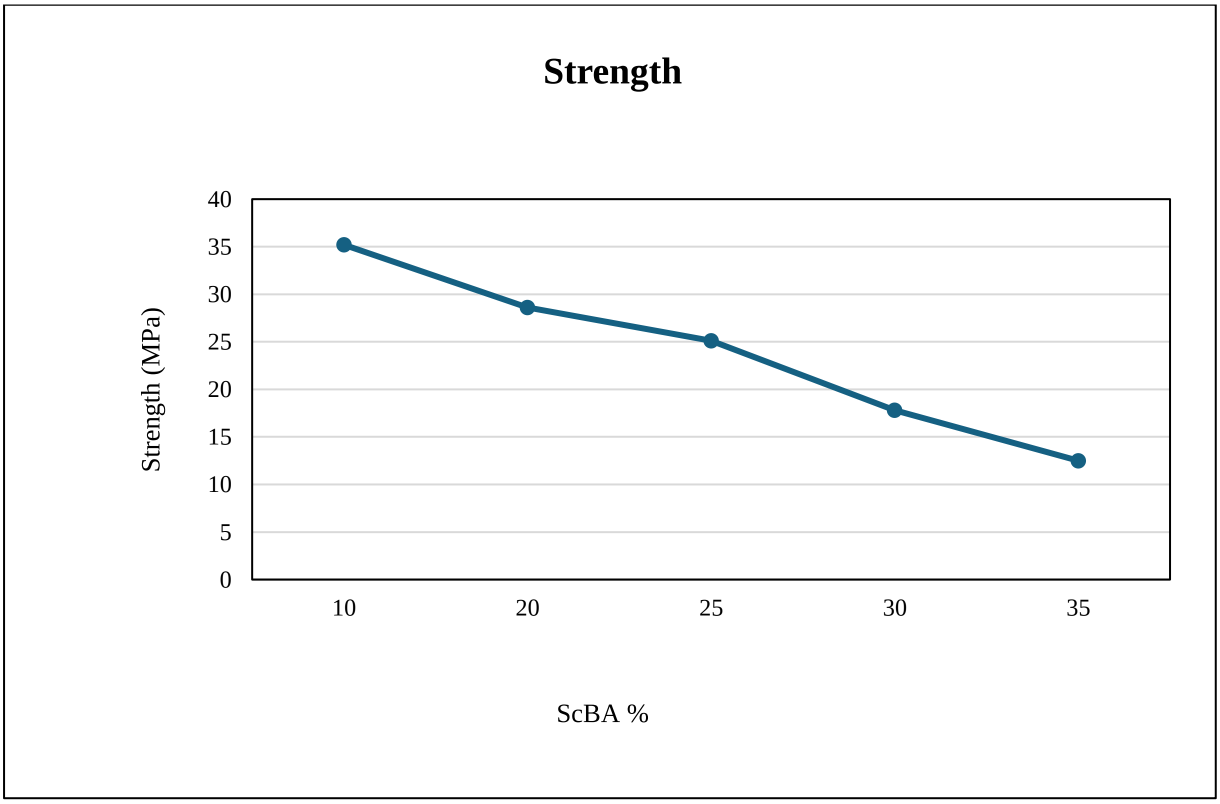


Figure 4.10: Change in strength with change in ScBA content

g) Interlayer Bonding

Tensile testing may be used to assess interlayer bonding. The assembly bears a load of 0.25MPa/s on a length of 130mm. The maximum strength achieved between two layers is 2.1 MPa which passes the requirement. Figure 4.13 shows the resulting crack after the interlayer bonding test has been performed.

Figure 4.11: Interlayer Bonding Specimen

4.3 Validation

The validation of the results of our concrete mix design through the tests using a 3D printer. By printing layers of the designed mix, we were able to closely observe and measure the performance and consistency of the material under real-world conditions. Each printed layer was examined for strength, and uniformity, ensuring that the mix met the required specifications. The process allowed us to identify and address any potential issues with the mix, ultimately confirming its suitability for 3D printing applications. This practical validation demonstrated that our concrete mix design is strong and dependable for use in advanced construction technologies.

CHAPTER 5

CONCLUSION

Mix design optimization for 3D printable concrete and development of an automated continuous supply mechanism of raw materials is vigorously vigorous and, at the same time full of learning processes. This study had the objective of improving the efficiency, sustainability, and cost-effectiveness of the modern construction method. This research using locally available materials like Sugarcane Bagasse Ash and Fly Ash has helped a lot in the field of 3D Concrete Printing.

The objective of the research was the development of a sustainable optimized mix design for 3D printable concrete that optimizes printability, strength and durability while purposefully minimizing environmental impact and costs. To provide a comprehensive solution, the material selected included Ordinary Portland Cement (OPC) as the primary binder, with Fly Ash (FA) and Sugarcane Bagasse Ash (ScBA) added to reduce the cement content and maximize sustainability. Experiment in lots with different percentages of OPC, FA, and ScBA were conducted to come up with the best mixture. A well-proportioned mix could be 27.6% OPC, 10% FA, 7% ScBA, and 34.5% sand, leaving the rest 20.7% as water and 1% by weight superplasticizer. Admixtures of superplasticizers were added to improve the mixture's flowability and pumpability with less water. Mix design that incorporated ScBA and FA as SCMs was optimized. Besides reducing the impact on the environment by the use of industrial and agricultural wastes, the materials improved the various properties of the concrete mix. Workability, buildability, and mechanical strength mix design were optimized. The addition of ScBA into the mix significantly improves the buildability class of the concrete, whereas FA improves the extrudability class and printability. Mechanical property tests, including compressive, tensile, and flexural strength, showed that the performance of the optimized mix design was superior to that of conventional concrete mixes. The compressive strengths reached up to 39 MPa, the tensile strengths up to 3.9 MPa, and the flexural strengths up to 5.4 MPa at 28 days.

The research was centered around sustainability Measures that focused on cement reduction by using an increased proportion of SCMs like FA and ScBA. This reduced the CO2 emissions from the cement production process as well as utilized wastes from industries and agriculture towards reducing the negative environmental impacts. Other SCMs may be considered, for further research, including silica fume and metakaolin in order to enhance the performance and sustainability of the mix.

Upon optimization in the laboratory, pilot projects must then be conducted to test the optimized mix design under real conditions of construction of low-cost housing or emergency shelters, among others. Data of performance in different conditions are thus used to refine the mix design to be generally applicable.

The research established the viability and advantages of mix design optimization for 3D printable concrete using locally available SCMs and an automated continuous supply mechanism. Clearly, the results proved the potential for technology to change construction practices in general through 3DCP since it is far more effective, sustainable, and cost-effective. The present study deals with the urgent challenges and new solutions for further progress in the development of 3D concrete printing and its wide application in construction practice.

5.1 Future Recommendations:

These will have far-reaching impacts on the construction industry generally but especially in regions that have housing shortages or are prone to natural disasters. It makes this research possible to quickly build low-cost sustainable housing using 3DCP technology and thus resolves critical house needs and, on top of that, provides help during disaster relief.

Future work on this project should be on the following issues:

- Standardization of testing methods: It is proposed to develop standardized testing protocols for evaluating these different properties of 3D printable concrete, which would help bring consistency and reliability to the results.
- Mix design further optimization: Other locally available SCMs would be tried, and their effects on the properties of 3D printable concrete would be studied for further performance and sustainability.

- Scaling up of the Technology: Study how the mechanism of continuous supply and 3DCP technology could be scaled to cover larger construction projects of multi-story buildings and infrastructure components.
- Environmental Impact Assessment: The impact on the environment from 3DCP technology will be estimated through life cycle analysis and carbon footprint evaluation.

REFERENCES:

- ACI Committee 232. (2004). "Use of Fly Ash in Concrete." American Concrete Institute.
- Ahmed, G. H., Nasih, H., Askandar, G. B. (2022). "A review of large-scale 3DCP: Material characteristics, mix design, printing process, and reinforcement strategies." Structures, 43, 129-142.
- Apis Cor. (2019). "Apis Cor builds the world's largest 3D printed building in Dubai." Retrieved from https://www.apis-cor.com/en/about/news/apis-cor-builds-the-worlds-largest-3d-printed-building-in-dubai
- Bos, F., Wolfs, R., Ahmed, Z., Salet, T. (2016). "Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing." Virtual and Physical Prototyping, 11(3), 209-225.
- Bos, F., Ahmed, Z., Salet, T. (2018). "Structural integrity of 3D printed concrete: Experimental testing and numerical modeling." Cement and Concrete Research, 109, 64-75.
- Cordeiro, G. C., Toledo Filho, R. D., Tavares, L. M., Fairbairn, E. M. R. (2009). "Pozzolanic activity and filler effect of sugar cane bagasse ash in Portland cement and lime mortars." Cement and Concrete Composites, 31(4), 275-283.
- Gosselin, C., Duballet, R., Roux, P., Gaudillière, N., Dirrenberger, J., Morel, P. (2016). "Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders." Materials & Design, 100, 102-109.
- Khoshnevis, B. (2004). "Automated construction by contour crafting—related robotics and information technologies." Automation in Construction, 13(1), 5-19.
- Kazemian, A., Yuan, X., Cochran, E., Khoshnevis, B. (2017). "Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture." Construction and Building Materials, 145, 639-647.
- Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Gibb, A. G. F., Thorpe, T. (2012). "Mix design and fresh properties for high-performance printing concrete." Materials and Structures, 45, 1221-1232.
- Li, Y., Xu, Q., Nair, S. O. A., Neithalath, N. (2022). "Utilization of sugarcane bagasse ash (SCBA) in construction technology: A state-of-the-art review." Journal of Building Engineering, 56, 104774.

- Mindess, S., Young, J. F., Darwin, D. (2003). "Concrete." Prentice Hall.
- Neville, A. M. (2011). "Properties of Concrete." Pearson Education.
- Panda, B., Unluer, C., Tan, M. J. (2018). "Investigation of the rheology and strength of geopolymer mixtures for extrusion-based 3D printing." Cement and Concrete Composites, 94, 307-314.
- Priya, K. L., Ragupathy, R. (2016). "Effect of sugarcane bagasse ash on strength properties of concrete." International Journal of Research in Engineering and Technology, 5(4), 159-164.
- Rekhi, J., Stern, A. (2022). "3D Concrete Printed Construction: Building the Future of Housing Layer-by-Layer." Cityscape, 24(2), 221-230.
- Roussel, N. (2018). "Rheological requirements for printable concrete." Cement and Concrete Research, 112, 76-85.
- Sika. (2016). "Superplasticizers." Retrieved from https://usa.sika.com/en/solutions_products/construction/01a023/01a023sa01.html
- Thomas, M. (2007). "Optimizing the Use of Fly Ash in Concrete." Portland Cement Association.
- Weng, Y., Li, M., Ruan, S., Wong, T. N., Tan, M. J., & Qian, S. (2018). "Anisotropic mechanical behavior of 3D printed fiber-reinforced cementitious composites." Cement and Concrete Research, 121, 23-30.
- Zhang, Y., Shi, C., Zhang, H., Li, N. (2019). "Rheological and hardened properties of high-thixotropy 3D printing concrete." Construction and Building Materials, 201, 278-285.
- ACI Committee 232 (2004). "Use of Fly Ash in Concrete". ACI Materials Journal, 101(5), pp. 382-399.
- Bos, F.P., Wolfs, R.J.M., Ahmed, Z.Y., Salet, T.A.M. (2016). "Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing". Virtual and Physical Prototyping, 11(3), pp. 209-225.
- Cordeiro, G.C., Toledo Filho, R.D., Tavares, L.M., Fairbairn, E.M.R. (2009). "Ultrafine grinding of sugar cane bagasse ash for application as a pozzolanic admixture in concrete". Cement and Concrete Research, 39(2), pp. 110-115.

- Khoshnevis, B. (2004). "Automated construction by contour crafting—related robotics and information technologies". Automation in Construction, 13(1), pp. 5-19.
- Le, T.T., Austin, S.A., Lim, S., Buswell, R.A., Gibb, A.G.F., Thorpe, T. (2012). "Mix design and fresh properties for high-performance printing concrete". Materials and Structures, 45(8), pp. 1221-1232.
- Mindess, S., Young, J.F., Darwin, D. (2003). "Concrete". 2nd ed. Upper Saddle River, NJ: Prentice Hall.
- Neville, A.M. (2011). "Properties of Concrete". 5th ed. Harlow: Pearson Education Limited.
- Sika (2016). "Concrete Admixtures: Superplasticizers"
- Batikha M, Jotangia R, Baaj M, Mousleh (2022). “3D concrete printing for sustainable and economical construction: A comparative study.” Automation in Construction, 104087, 134
- Baduge S, Navaratnam S, Abu-Zidan Y, McCormack T, Nguyen K, Mendis P, Zhang G, Aye L (2021). “Improving the performance of additively manufactured (3D printed) concrete: A review on material mix design, processing, interlayer bonding, and reinforcing methods.” Structures, 1597-1609
- Jipa A, Dillenburger B (2022). “3D printed formwork for concrete: state-of-the-art, opportunities, challenges, and applications.” 3D Printing and Additive Manufacturing, 84-107, 9(2).
- Paritala S, Singaram K, Bathina I, Khan M, Jyosyula S (2023). “Rheology and pumpability of mix suitable for extrusion-based concrete 3D printing–A review.” Construction and Building Materials, 132962, 402.
- Prabhakar M, Saravanan A, Lenin A, Mayandi K, Ramalingam P (2021). “A short review on 3D printing methods, process parameters, and materials.” Materials Today: Proceedings, 6108-6114, 45
- Wangler T, Roussel N, Bos F, Salet T, Flatt R (2019). “Digital Concrete: A review.” Cement and Concrete Research, 105780, 123.

- Dilawar Riaz R, Usman M, Ali A, Majid U, Faizan M, Jalil Malik U (2023). “Inclusive characterization of 3D printed concrete (3DPC) in additive manufacturing: A detailed review.” Construction and Building Materials, 394.
- Khan S, Ilcan H, Aminipour E, Sahin I, Al Rashid A, Shamaran M, Koc M (2023). “Buildability analysis on the effect of structural design in 3D concrete printing (3DCP): An experimental and numerical study.” Case Studies in Construction Materials, e02295, 19.
- Raja Dilawar Riaz, Usama Majid, Ammar Ali, Muhammad Faizan (2023). “To develop a 3D Concrete printer (CNC router Machine based) Capable of moving in 3 D Degrees of Freedom” [Undergraduate thesis, National University of Sciences and Technology].
- https://www.ele.com/product/apparatus-for-determining-flow-in-concrete-flow-table-
- https://blog.certifiedmtp.com/concrete-slump-test-guide/
- https://www.summum.engineering/portfolio/3dcp-bridge/
- https://www.sheridanuae.com/the-rise-of-smart-cities-in-the-uae-and-its-impact-on-the-construction-industry/
- https://mmnews.tv/nust-develops-pakistans-first-3d-concrete-printer/