



# 3D Concrete Printing of Structures: Mix Design with Partial Replacement of Sand with Raw Sewage Sludge

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**Abstract.** This research work explores the application of a novel, cutting edge additive manufacturing technology known as 3D printing within the construction sector. Concrete 3D printing creates highly precise, geometrically detailed, and intricate structures. Parameters such as workability, extrudability, buildability, and rheological characteristics of the concrete mixture heavily influence its success and efficiency. In addition to these technical requirements, attention is also directed toward sustainability considerations, which are becoming increasingly critical in modern construction practices. In this study, particular prominence is placed on examining the incorporation of raw sewage sludge as a partial substitution for sand in the design mix, exploring its feasibility and potential benefits in sustainable construction practices. The research not only addresses material performance but also discusses the benefits of utilizing waste resources to reduce environmental burden and conserve natural aggregates. It combines innovative and sustainable materials with cutting-edge manufacturing, thereby contributing to more ecologically sustainable construction in a way that does not diminish structural quality or efficiency.

**Keywords:** 3D printing, Additive manufacturing, Concrete mix.

## 1 Introduction

Considering worldwide interest in diminishing CO<sub>2</sub> outflow, there is a requirement for inventive development advancements to not just prepare towards an eventual fate of sustainable construction, but also to lessen construction and management costs while giving strategic advantage. Accordingly, this fosters a deeper thought of 3D printing manufacturing and that's why it is used in the building construction industry [1].

3D substantial printing is an inventive development strategy that was introduced to the building construction business and it has proven to be an innovative strategy in terms of reducing development time, costs, and design constraints, as well as in decreasing errors and being harmless to the ecosystem [2]. It includes creating a predesigned fabricating component in two-dimensional layers put on top of one another, the repetition of which yields a three-dimensional model. The substance, is spilled from a printing type of nozzle that doesn't require any formwork [3].

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While 3D printing developed in the 1980s, it wasn't familiarized to the field of building construction industry until the 1990s by researchers at the University of Southern California [4]. The researchers have published detailed material on innovative fabrication, specifically detailing the progress of several trial machines. This includes an XYZ gantry system, a three-component of assembly of nozzle, and a six-axis coordinate motion control network [4]. Advances in this domain remained largely consistent until around 2012, when several researchers began researching various methodologies and innovations related to 3D manufacturing. The Loughborough University has introduced pioneering work in substantial printing [5]. Additionally, the Chinese organization WinSun demonstrated its 3D printing manufacturing process by printing 10 houses in about 24 hours, with each house costing a mere \$5000. Advancing the technology added, WinSun effectively printed a five-story building, currently recognized as the world's most prominent 3D-printed structure [4][6]. Indian Institute of Technology, Madras and Bombay, have approached fostering 3D printing in development with a few prototypes with various plan blends. They have effectively developed a single-story house [7]. As international adoption of additive manufacturing accelerates, a wide array of 3D-printing projects are transitioning from the planning stages to active implementation.

Developing a suitable ink is perhaps the greatest obstacle in large-scale 3D concrete printing. The primary goal line is to engineer a mixture that balances seamless printer compatibility with the rigorous structural difficulties of the finished build. Developing real printable concrete means meeting strict values for flow, layering, and setting time. Researchers are capitalizing heavily on testing new materials to push the limitations of concrete performance in additive manufacturing.[8]. Khoshnevis [9] enhanced the topographical precision and aesthetic quality of 3D-printed manufactured concrete components by using mortar and clay-like material. Le [10] Conversely, this study examined how the presence of superplasticizers, retarders, and accelerators affects rheological workability, compressive strength, and setting duration. Similarly, because present-day research often focuses on different material characteristics, a comprehensive investigative framework remains essential for this field. The present study talks about the application of 3D concrete printing technology with a focus on its implications across multiple engineering aspects. Primarily, it emphasizes the materials perspective by developing a suitable concrete mix tailored for 3D printing requirements [4] [10] [15] [23]. The formulation of the optimal mix is achieved through a series of experimental investigations designed to assess its fresh and hardened state properties [16] [17] [21]. In parallel, the study also explores the design considerations of the printing system, proposing an appropriate machine setup after analysing the specific procedural demands of the printing process [6] [8] [23]. To validate the feasibility of the adopted approach, an initial prototype element is first printed, serving as proof of approach for the method. This integrated methodology highlights the dual importance of material development and process design in advancing 3D printing applications within the construction industry [2] [11] [19].

The highlights of 3D manufactured concrete printing are reflected in its ability to enhance understanding of advanced construction technologies and extend their applications to real-life projects. This technique contributes significantly to the expanding collection of scientific knowledge by demonstrating its role in advancing automation within structural engineering practices. It further emphasizes improvements

in resource management, productivity, and cost-effectiveness, while offering a modern construction approach that ensures reduced project durations. By integrating precision, efficiency, and sustainability, 3D concrete printing stands out as a high-level construction method capable of transforming conventional practices into more streamlined and economical solutions [11].

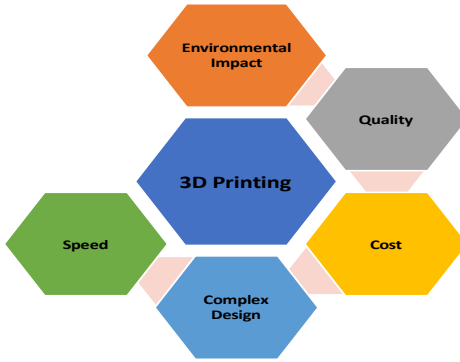


Figure 1. Five key benefits of 3D printing

The challenge of managing the surging volume of sewage sludge from municipal and industrial plants is becoming progressively acute. This trend is driven by the growth of modern sewer networks, the adoption of more severe action standards, and the construction of advanced processing facilities. To address this, current innovations focus on viewing sludge not as a burden, but as a valuable raw substrate for recovery. One of the most promising avenues for this repurposing is the construction industry, where treated surplus can be integrated into building materials [12]. Mixing sewage sludge into construction supplies bypasses several costly, high-energy dispensation phases, typically yielding a hard-wearing and secure end product. This consistency is backed by data regarding physical integrity, moisture repulsion, and freeze-thaw resilience. Also, studies specify that heavy metal leaching remains minimal, particularly when the sludge content within the composite is kept at a moderate ratio. The usage of sewage sludge in 3D printing may yield uncertain outcomes, as the concrete utilized in 3D printing differs from ordinary concrete [13][14].

## 2 Methodology

### 2.1 Design Mix Goals

In order to produce a concrete that can be 3D printed, it is necessary to follow the necessities set forth by the particular printing technique. An ideal mixture must meet multiple competing performance metrics, as shown in Figure 2. The main difficulty is striking a balance between these challenging goals. For example, while increasing compressive strength is significant, which calls for a lower water-to-cement ratio, enough moisture must be kept in order to guarantee that the material is still workable

enough for extrusion. Likewise, the blend ought to be able to flow through the framework, but it should be buildable after pouring and each layer ought to have the option to hold itself. At long last, when poured, the blend ought to set as quickly as could be expected, however, slow sufficient to guarantee appropriate bonding with the resulting layer.



## Mix Design

- Maximize the flowability in the system
- Maximize the buildability upon pouring
- Maximize the speed of concrete setting
- Maintain appropriate setting rate and bonding

Figure 2. Mix design goals

We establish strong, measurable design mix guidelines to attain these goals. The blend's extrudability, fluidity, buildability, compression strength and open time are the five most important characteristics that are analyzed. Since the objective is to attain a continuous, straightforward streaming paste, extrudability and flowability are related with the manufactured concrete expulsion, stream and workability.

**BUILDABILITY** describes property of the printed layer of being self-supportive, and shape-holding also it talks about the capacity of the bedding layers to hold the following layers on top of them without breaking up or deforming. As 3D printing is formwork-free, there is an essential need for it to be self-supporting. The concrete should be strong enough to hold the shape of the structure and not fall on either side due to gravitational forces. Buildability can be better by increasing the aggregates and using additive materials and admixtures [15][16].

**EXTRUDABILITY** is performing a significant role in the 3D manufactured printing of concrete. This technique explains how the paste can be repeatedly moved from the print head nozzle and stocked at the head of nozzle. By itself, extrusion guarantees consistency in the building's construction and printing. The extrusion is determined by the aggregate's size in relation to the nozzle's size. Extrusion is made enabled by the proportion of aggregate particle size to nozzle size. If the aggregate is too small, it will be difficult to wrap the surface area, and if it is very large, the nozzle will be blocked. This will cause the concrete to split easily [15][17].

**PUMPABILITY** parameters should be designed to make the 3D manufactured printing concrete a success. The distance by which the concrete has to be pumped is usually ignored and is a governing factor for pumpability. The concrete pumping

distance is more in the site construction than the 3D printing prefabricated in factories or labs [15][17].

## 2.2 Materials For Design Mix

One of the most widely used types of cement, is Standard Portland cement. After being mixed in a ratio of about two parts of calcareous materials to one part of argillaceous materials, the ingredients are crushed and processed in ball mills in a dry condition or blended in a wet state. The dry powder or wet slurry is next burnt in a rotary kiln at a temperature between 1400 and 1500 degrees Celsius. After being cooled, the clinker from the kiln is sent to ball mills where gypsum is added and it is ground to the necessary fineness for the product class. It consists of lime (CaO) (60 to 67%), Silica (SiO<sub>2</sub>) (17 to 25%), Alumina (Al<sub>2</sub>O<sub>3</sub>) (3 to 8%), Iron oxide (Fe<sub>2</sub>O<sub>3</sub>) (0.5 to 6%), Magnesia (MgO) (0.1 to 4%), and sulfur trioxide (SO<sub>3</sub>) (1 to 3%), Soda and/or Potash (Na<sub>2</sub>O+K<sub>2</sub>O) (0.5 to 3%) [18].

A byproduct of producing electricity in coal-fired power plants is fly ash. It has pozzolanic qualities and is composed of silica and aluminium. When combined with calcium oxide and water, it produces a material that resembles cement. In general, fly ash can be separated into two classes. Because Class F fly ash particles are coated in a material that resembles melted glass, they are less susceptible to expansion caused by sulphate. Class C is more mainstream, has a higher CaO proportion, and is also resistant to the expansion [19]. Silica fume is a waste product from making silicon metal or ferrosilicon alloys. Silica fume is very useful in concrete. It is an extremely reactive pozzolan because of its chemical and physical qualities. Concrete that has silica fume in it can be highly strong and last a long time. Silica fume is mostly made up of silicon dioxide (SiO<sub>2</sub>) that is not in a crystal form. The separate particles are very small, around 1/100th the size of a typical cement particle.

Table 1. Main constitution of binding materials

Cementitious Material	CaO (%)	SiO <sub>2</sub> (%)	Al <sub>2</sub> O <sub>3</sub> (%)	Fe <sub>2</sub> O <sub>3</sub> (%)	Blaine fineness (m <sup>2</sup> /g)	Specific gravity (g/cm <sup>3</sup> )	Loss on ignition (%)
Portland Cement	62.3–62.7	20.2–21.9	4.7–5.3	3.68–4.04	0.33–0.38	3.15	1.90–3.02
Fly Ash	2.8–4.2	53.3–56.2	20.1–27.6	6.04–6.69	0.29–0.38	2.08–2.25	1.78–3.46
Silica Fumes	0.45	90.3–92.3	0.71	1.31	10-13	2.22–2.33	1.80–2.5

The majority of fine aggregates are naturally occurring grains of sand that are extracted from the earth. Fine aggregate is made up of organic sand or any pieces of broken stone smaller than 4.75 mm. Fine aggregates are the structural filler that takes up most of the space in concrete mix formulations. You can have a big effect on the production by changing the composition, shape, size and other aspects of fine aggregate. The fine aggregate utilized in the study is characterized by a size that has been filtered through a 4.75mm sieve and retained on a 2.36mm sieve [21]. Sewage sludge is the leftover, semi-solid material that is made when industrial or municipal wastewater is treated. It

has viruses, micro-pollutants, heavy metals, and other dangerous chemicals in it. The disposal method isn't very good because the only options we have right now are landfill removal and burning, which pollute the air and land [12]. Recent research has looked at how the amounts of heavy metals and nutrients in sludges from different sewage treatment plants change. Establishing quality control is difficult since the chemical makeup of sewage sludge is different in different places. The sewage sludge in India typically had total nitrogen levels of 15400–1920 mg Kg<sup>-1</sup>, available levels of nitrogen 4600–6 $\mu$  mg Kg<sup>-1</sup>, available levels of phosphorus 44–60 mg Kg<sup>-1</sup>, and available levels of potassium 290–410 mg Kg<sup>-1</sup>. In addition to these elevated concentrations of other heavy metals, including arsenic (8-23 mg Kg<sup>-1</sup>), cadmium (2-9 mg Kg<sup>-1</sup>), chromium (66-1098 mg Kg<sup>-1</sup>), mercury (7-32 mg Kg<sup>-1</sup>), nickel (12-596 mg Kg<sup>-1</sup>), and lead (26-154 mg Kg<sup>-1</sup>) [12].

People usually mix primary, secondary, and tertiary sludges. The combination, which has 1 to 4% solids, is called sewage sludge in "raw form". Raw sewage sludge could be bad for your health and the environment since it has pathogens in it, is unstable, and can break down. However, there are now numerous treatment procedures that can stabilize sewage sludge, lower its levels of pathogen, and raise its content of solids [14].

1. **Thickening:** The sludge is thickened by concentrating its solids in one of two ways: either by making them float by adding air to the sludge or by letting them settle at the bottom. The sludge is still a liquid, but the number of solids has gone up to 6%.
2. **Dewatering:** There are several ways to do this, such as drying of air on sand beds, centrifugation, and pressing of belt (filter). It raises the content of the solids to 15 to 30, air drying kills microorganisms and centrifugation, filtering cause certain nutrients to be lost [12] [13] [14].
3. **Anaerobic digestion:** One of the most common ways to treat sludge is to keep it in a vacuum at 20 to 55 °C for up to two months. Anaerobic microorganisms devour the sludge and make carbon dioxide and methane. Some treatment plants collect and use the methane to keep the temperature of the treatment process [6] [8] [11].
4. **Aerobic digestion:** This is the reverse of anaerobic digestion. Instead of keeping sludge in a vacuum, air with a lot of oxygen is constantly added to it at a temperature of 15 to 20°C for up to two months. Aerobic bacteria eat through the sludge and make carbon dioxide [12] [18].
5. **Composting:** The sludge is dried out until it has about 20% solids, and then it is mixed with a natural material that is high in carbon, such as sawdust. The blend is treated with high-impact circumstances on the soil for a few days at temperatures of at least 55°C during the fertilizing the soil contact.

The sludge utilized in this study has been dried for 28 days in the sun and at natural temperature. After that, it has been crushed using a rammer tool and sieved as per the IS: 2386 (Part I) – 1963[25]. The sieve analysis shows that the most that can be kept is 300  $\mu$

## 2.3 Chemical Additives

**Superplasticizers (SPs)** are also known sometimes referred to as high-range water reducers, are additives used in high-strength concrete manufacturing. Plasticisers are chemicals that help cement form with around 15% less water. Superplasticizers allow water content to drop by at least 30% [6]. A few weight percent of these additional materials are used. Cement curing is slowed down by plasticisers and superplasticizers.

The superplasticizer used in this study is Sika Plastiment – 2001 NS, which improves the flowability of concrete when added to it. The proportion is varied from 0.5% to 2.0% by weight. Higher percentages can also be considered in special circumstances. After 50-70% of the mixing water has been added, it can be added straight to the concrete mixer or mixed with water [9].

Accelerators are combinations that speed up the rate at which cement hydrates, which shortens the time it takes to set and builds strength quickly. Accelerators have other benefits, including

- Cut down on the time needed for curing
- Allow for the earlier removal of formwork
- Move up the time when a building can be used
- Partially pay them back for slowing down the effects of low temperatures during construction in the winter.

Some examples of accelerators are sulphates (except calcium sulphate), alkali carbonate of aluminate and silicates, aluminium chloride, calcium chloride, sodium chloride, sodium and potassium hydroxides, calcium formate, formaldehyde, and paraformaldehyde [20]. Accelerators should be added to concrete in a certain limited otherwise it will act as a retarder and increase the setting time. For example, 2% of  $\text{CaCl}_2$  by weight of cement is added; it will work as an accelerator, but when it is increased, it will react as a retarder and increase the setting time [22].

## 3 Methods

To guarantee that accomplished mix is the ideal one, a few tests must be performed considering the objective boundaries to be accomplished. Five boundaries (extrudability, flowability, buildability, compressive strength, and open time) together add to the overall progress of the printing system.

### 3.1 Mix Proportion

Seven numbers of design mix are designed with partial substitution of fine sand with sewage sludge. And two mixes are prepared without any partial substitution of sand. The constitution of the design mix is described in Table 2.

Table 2. Concrete mix constitution

Mix	Cement	Sand	W/C Ratio	Fly Ash	Silica Fumes	Sp	Sewage Sludge
M0	6030	1076	0.32	0	0	0	0
M1	630	1098	0.32	160	90	1.40	122
M2	630	1122.5	0.32	160	90	1.40	97.5
M3	630	1160	0.32	160	90	1.40	60
M4	660	1160	0.32	130	90	1.40	60
M5	660	1160	0.32	160	60	1.40	60
M6	660	1160	0.32	145	75	1.40	60

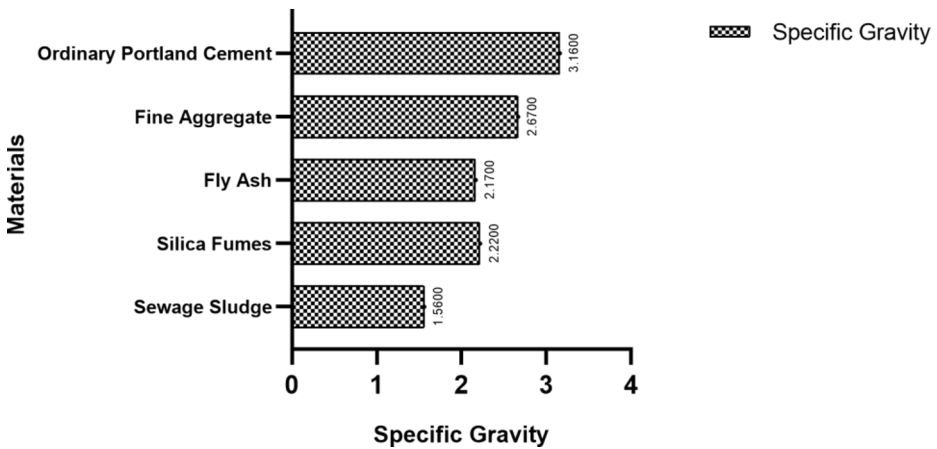


Figure 3. Specific gravity of different materials used in concrete mix

Seven designs mixed with various sand to binders’ proportion were planned. The sand content was increased in 2% additions from 53 to 57% by weight of dry mixture combination in Mix 0 to Mix 6, while the cement content was kept constant. The binder in all mixes 1 to 5 involves around 70% cement, 20% fly ash, and 10% silica fume. A water-cement proportion of 0.32 was chosen for accomplishing a strength of 35-40 MPa based on past investigations of high-strength concrete. The printing mix was made better to be more fit to testimony through the 40 mm x 20 mm width nozzle. The measurements of superplasticizer were kept constant at 0.5%, and sewage sludge was changed from 10% to 2% to get ideal mix design extents for printing. Fine aggregate used has been sieved, in which the aggregate has been passed through 4.75mm and retained at 2.36mm. The accelerators and retarders can be used in accordance with need and should be added as per IS9103[24]. The specific gravity of different materials which is used in the above mix designs is shown in Figure 3.

**Specimen Preparation:** Concrete specimens of size 70.6 mm were taken for the present study to evaluate their compressive strength. Also, beams of 100 x 100 x 700 mm were made to find out how strong they were when bent. The ingredients were all put into the right moulds. The compaction wasn't done because it doesn't work with 3D printing concrete. In real life, there is no vibration procedure or compaction for concrete that has been extruded

### 3.2 Testing Methods Of Specimens

The specimens were tested using established methods found in the Indian Codes. We used a slump cone that was 300 mm tall, 200 mm wide at bellow, and 100 mm wide on the top to find the slump of all the concrete mixes. We poured the mixtures into the cone just after mixing.

- V Funnel Test: The V-funnel test is utilized to check how thick fresh concrete is and how easily it can flow through tight spaces by measuring how long it takes for the V-funnel to fill up. The funnel of V-shaped is poured with new concrete for this test. The V-funnel flow time ( $V_t$ ) is the time it takes for the funnel to empty after opening the bottom outlet. Viscosity, interparticle friction, or flow obstruction are all related to the value of  $V_t$ . The concrete for 3D printing should work smoothly and not separate or jam too much when it goes through the little orifice.
- L-Box Test – The test of L-Box is utilized to see how well concrete mixtures flow and, more specifically, how well they pass. The test's findings can be used to determine how well concrete flows through the printing systems tiny pipes and tiny gaps made by the deposition head.
- The Vicat needle test is a common way to tell how cement mortars are setting and hardening. The IS: 4031 (Part 5) says how long it takes for fresh combinations to build up and finish. A Vicat mold that is 40 mm high is used to hold the mortar. A 1 mm<sup>2</sup> cross-section needle is attached to a 300 g movable rod. The needle is made to fall under the force of gravity and goes through the sample. The height of penetration is measured as a function of time. This technique is repeated at set intervals until the cement mix is fully hardened.
- In Concrete Lab, we used a CTM machine with a bending load of 2000 kN and a rate of 0.6 kN/Sec to find the compression strength at 7 and 28 days after curing.

## 4 Results And Discussion

### 4.1 Initial And Final Setting Time

The setting time initially of the mixes was achieved in the range of 26 to 30 minutes, which can then even be shortened by the addition of accelerators in a controlled proportion. The use of admixtures can make a big difference, even with the slightest change in the admixtures. The same trend goes for the final setting of the mixes.

Table 3. Initial and Final setting time(IST &amp; FST)

Property	IST (min)	FST (min)
M0	28	189
M1	32	205
M2	32	205
M3	30	190
M4	28	188
M5	30	192
M6	30	192

#### 4.2 Slump Test

The slump values of the tested specimens of the concrete are expressed in Table 4.

Table 4. Slump value of Design Mixes

Property	Slump Values(mm)
M0	18
M1	20
M2	16
M3	15
M4	12
M5	10
M6	10

The first goal for the mixes designed was to get the real slump, which was reached in all of the mix designs between 10 and 20 mm. The slump values went up a little bit as the amount of sludge of sewage used as fractional replacement for fine aggregate went up. Mix 6 had the lowest slump value, which was 10 mm, while mix 1 had the highest, which was 20 mm. This increase in workability may be because the plastic is hydrophobic, which means it doesn't hold water well. There was no separation of the mixes during the test because the water-binder ratio was set according to the design mix.

### 4.3 Compressive Strength

The capacity of the material to withstand the direct pressure of applied compressive force, therefore making it the most important rheological property. The instrumental setup of CTM testing machine is shown in Figure 4, and the outcomes of 7-day and 28-day compression sresistance are shown in Figure 5.



Figure 4. Laboratory testing of concrete moulds

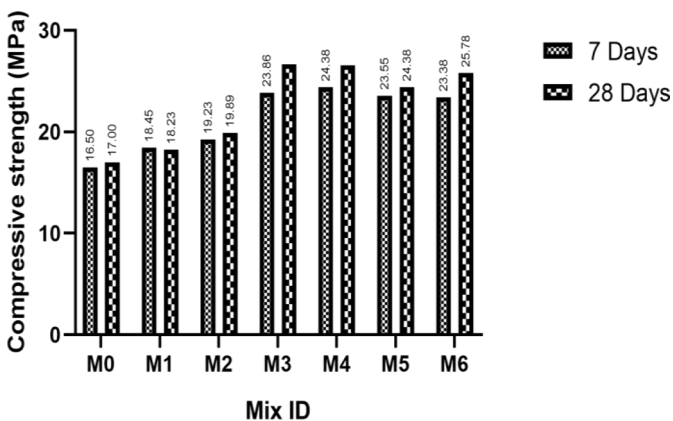


Figure 5. Compressive strength of various concrete mix ID

### 4.4 Flexural Strength

Flexural strength, or the modulus of rupture, serves as a critical metric for evaluating capacity of material to withstand distortion under load along its longitudinal axis. It exactly quantifies the maximum tensile stress concrete can endure in a bending test

before structural failure occurs. While compressive strength is the standard industry benchmark, flexural strength delivers a more accurate assessment for components primarily subjected to bending moments, such as pavements, slabs, and beams [4], [10]. Because concrete is inherently quasi-brittle and weak in tension, failure typically initiates at the extreme tension fibers at the bottom surface of the element, where stress concentrations lead to crack propagation. [5, 25]. The flexural strength of regular concrete is usually between 10% and 20% of its compression strength. The flexural performance of concrete is affected by various elements, including mix percentage, water-cement ratio, aggregate type, curing process, and testing age [20], [19], [2]. Researchers have demonstrated that including mineral admixtures such as sewage sludge ash can enhance flexural strength by increasing the density of the concrete and mitigating micro-cracks [12, 13, 14, 21].

In the novel time, along with the development of 3D manufactured concrete printing, flexural strength has become even more critical. This is due to the layer-by-layer process of printing creates weak joints between layers, which reduces the bending resistance of printed elements if the bond is poor [9], [8]. To overcome this, the mix design, rheology, and printing parameters must be carefully controlled so that the material has both good printability and adequate flexural strength [15], [16], [23]. Overall, flexural strength remains an essential measure of quality in both conventional concrete and 3D printed structures, ensuring safety, durability, and serviceability under real loading conditions [1], [6], [11].

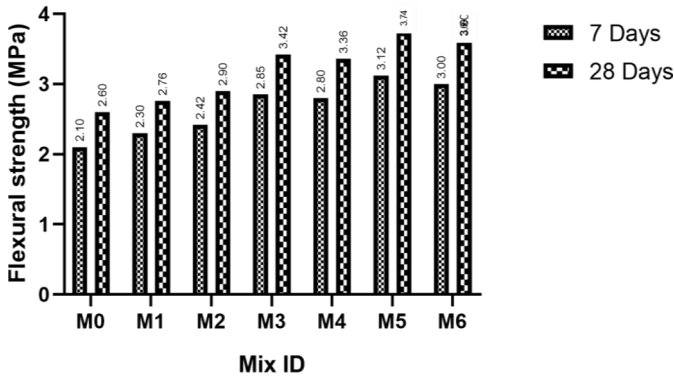


Figure 6. Flexural strength of various concrete mixes

## 5 Conclusion

From this study of some of the mechanical characteristics of fresh and hardened concrete with sludge of sewage as sand replacement, the following conclusion can be extracted.

1. The slump value was in the range 10 – 20 mm. Out of which, Mix 6 has

- achieved the minimum slump value.
2. The V funnel and L-Box test become irrelevant as the concrete mix M0 to M6 does not fall under the gravitational pull in both tests. So, it has become clear that in actual condition the interlocking of layers of the extruded concrete will be good enough to hold the concrete in place under gravitational pull and self-weight.
  3. The IST was in the range of 28 to 32 minutes, while the FST was recorded in the range of 188-205 minutes, which is far less than the conventional construction concrete. Moreover, the setting time can be modified even less by using the accelerators in a verified proportion.
  4. Since the building process of 3D concrete printing is really quick, the compressive strength should be achieved after extrusion. Therefore, on the 3rd day, the compressive strength was found to be in the range of 8.45 to 11.74 N/mm<sup>2</sup>. The 3rd day compression strength was not good. Therefore, the 7th day compressive strength has been taken, which we get maximum in mix 4, i.e., 26.56 N/mm<sup>2</sup>. The compressive strength has not increased from the 7th day to the 14th and 28th day. The strength has barely increased.
  5. The flexural strength has been determined at 7 & 28 days. The maximum flexural strength attained is by mix 5. The flexural strength has been tested at 7 th day it was found to be maximum in Mix 5, which is 3.12 N/mm<sup>2</sup>.

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