3D printed concrete using Portland pozzolana cement - fly ash based.

Mohamed Ibrahim A1, Senthil Kumar N1

1School of Civil Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India.

Abstract. This project investigates the feasibility and properties of 3D printed concrete using Portland Pozzolana Cement (PPC). The increasing demand for construction materials, particularly ordinary Portland cement (OPC), has led to a surge in its usage. Consequently, Portland Pozzolana Cement (PPC) has gained popularity as an alternative due to its advantageous properties. PPC, characterized by its enhanced durability and sustainability, has become a preferred choice in the construction industry, offering versatility and reliability in various construction applications. The main focus of the project is economical printing of concrete structures through 3D printing technology. With sustainability and cost-effectiveness as paramount considerations, the study delves into refining the mix proportions ideal for 3D printing applications. By harnessing the potential of Portland Pozzolana Cement (PPC) with a 35% fly ash content, the aim is to strike a balance between structural integrity, workability, and affordability. It examines various key properties essential for successful 3D printing, such as extrudability, printability, flowability, buildability, setting time and thixotropic open time. Furthermore, the project examines the strength of 3D printed concrete mixes. Through testing and studying these properties, the research aims to contribute to the advancement of eco-friendly and efficient construction practices by using 3D printing and innovative cementitious materials. The findings from this study provide valuable insights to enhance the efficiency of 3D printing and the strength of printed concrete structures, including beams, walls, and other structural elements. By implementing these ideas, potential advancements in construction methodologies could be realized, facilitating more robust and cost-effective building practices. This research aims to contribute to the ongoing evolution of 3D printing technology in construction, ultimately fostering innovation and sustainability in the built environment.

Keywords. 3D Printing, Flyash, pozzolana cement, 3D modelling, Extrusion

1 Introduction

In the past few years, the demand for new and eco-friendly materials and methods in the construction industry has increased tremendously. One promising way to change how we make things is by using 3D printing. This technology allows for greater flexibility, efficiency and creativity in design. Concrete is still important in construction, and 3D printing is
changing the way we use it. Some examples are the creation of eco-friendly 3D printed concrete structures and introducing the Minimass beam, a novel 3D printed concrete structural element optimized for load-bearing purposes [1-3]. But conventional cement known as Ordinary Portland Cement (OPC) is causing environmental concern as it generates a lot of carbon emissions and requires a lot of energy to produce. To overcome these problems, other types of cement such as Portland Pozzolana Cement (PPC) have become more popular. PPC which contains fly ash, which help make the concrete more eco-friendly and better in quality. Fly ash and silica fume are materials that can be mixed into 3D concrete mixes, adding versatility to the composition of the concrete used in 3D printing [4]. The project focuses on making construction environmentally friendly by using a PPC, which has a high ash content. Since PPC is better for the environment than regular cement, the project wants to find a better way to mix it for 3D printing. The goal is to create concrete mixes that work well with 3D printing and are better for the environment. The main goal of this project is to find the correct mix for making 3D printed concrete using PPC cement with 35% fly ash. By using PPC with fly ash together, the project aims to develop concrete mixes strong enough for construction. The coarse aggregate also used in 3D concrete mixes. The effects of coarse aggregate on both printability and mechanical characteristics, providing valuable insights into the performance of concrete [5-6]. This study looks at how well the 3D printed concrete mix works when it is in fresh condition. It carefully examines things like how easy it is to push out (extrudability), how well it can be printed (printability), how smoothly it flows (flowability), how long it takes to harden (setting time) and how it behaves over time before hardening (thixotropy open time). Buildability is defined as the ability of fresh printable concrete to exist in the form of bonded layers that bear the load of the newly printed concrete without collapsing the existing layer [7]. This helps ensure that the printing process works well and that the concrete is of good quality. Understanding these new properties is very important because it ensures that the printing parameters are accurate, leading to the creation of strong concrete structures without any problems. The microstructure, mechanical and flexure behavior can be examined by various tests [8-9]. The glass fibres and steel fibres are used to enhance the strength of concrete. By using these fibres, we can produce 3D printed ultra high performance concrete [10-11]. The success of the 3D-printable concrete lies in its fresh concrete and rheological properties [12-16]. The flow table test measures how easily a 3DPC mix can flow, indicating its workability and ease of placement during printing. Compression and flexural tests assess the strength and durability of the cured 3DPC, helping engineers understand how well it can bear loads and resist bending forces in practical applications [17-23]. Also, the project expands its focus to evaluate the compressive strength of 3D printed concrete mix. Compressive strength serves as an important indicator of structural performance and durability, thereby influencing the suitability of printed components for real-world applications. In short, the project is a major initiative to use new technology in eco-friendly materials and construction. By using PPC with fly ash in 3D printed concrete, the research aims to help make building more environmentally friendly and efficient.

2 Experimental Program

2.1 Materials

2.1.1 Portland pozzolana cement
Portland pozzolana cement (PPC) combines Portland clinker with 35% fly ash content. This mixture undergoes a pozzolanic reaction with calcium hydroxide in the presence of water to form an additional calcium silicate hydrate (C-S-H) gel. As a result, PPC containing fly ash improves the workability, strength and durability of concrete, while reducing its carbon footprint. This blend offers improved long-term performance, resistance to alkali-silica reaction, and environmental sustainability compared to conventional Portland cement, making it an ideal choice for a variety of construction applications, including 3D printing. In India, the Bureau of Indian Standards (BIS) provides the specifications and guidelines for various construction materials, including cement. The Indian Standard (IS) code for Portland Pozzolana Cement (PPC) with fly ash is IS 1489 (Part 1): 2015.

2.1.2 Sand

Sand used in mortar mix plays an important role in masonry construction, contributing to mortar workability, strength and durability. Generally, mortar sand is selected for its ability to fill the voids between larger aggregate particles, which promotes better adhesion and cohesion in the mortar mix, compared to concrete sand that is finer in particle size. To ensure uniformity, stability and optimum performance in building applications including brickwork, stone masonry and plastering, proper quality and compatibility with the cement binder are essential when selecting sand for mortar mix. The sand used for this project is sieved through a 2.36 mm (about 0.09 inch) sieve.

2.1.3 Super plasticizer

Superplasticizers are high quality water-reducing admixtures used in concrete to improve its workability and fluidity without compromising strength. These chemicals disperse the cement particles more effectively and reduce the water-cement ratio required for a given consistency. This results in improved flow, reduced viscosity and increased slump retention, allowing easier placement and compaction of concrete, particularly in congested reinforcement areas or complex shapes. Superplasticizers play an important role in achieving high-performance concrete with improved durability, reduced permeability and improved finish, making them essential additives in modern construction practices. In this project, the application of two different types of superplasticizers is aimed at evaluating their performance and suitability for the concrete mix under investigation. By comparing the performance of polycarbolic ether superplasticizer (SP-PCE) and Conplast SP430 superplasticizer (SP430), this study determines which admixture gives optimal results in terms of workability, slump retention and overall performance of the concrete mix. The findings of this comparative analysis will provide valuable insights for selecting the most suitable superplasticizer for future concrete production, ensuring improved workability, durability, enhanced flow properties and structural integrity in construction application.

2.1.4 Viscosity modifying agent

A viscosity modifying agent (VMA) is an additive used in concrete mixes to change the chemical properties of the cement paste, thereby influencing the flow, workability and stability of the concrete. Unlike superplasticizers, which primarily reduce water content and increase fluidity, VMAs work by modifying the viscosity of the concrete mix, improving its cohesion, and preventing segregation and bleeding. VMAs are particularly useful in self-
consolidating concrete (SCC), high-performance concrete (HPC) applications, and 3D printing concrete, where maintaining a consistent and consistent mix is important. Common types of viscosity modifiers include cellulose ethers, synthetic polymers, and clay-based materials. By using VMAs into concrete mixes, construction professionals can achieve improved pumpability, reduced formwork stress and improved surface finish, ultimately contributing to the efficiency and quality of construction projects.

2.2 Mix proportion

Currently, there is no universally recognized or standardized code designed for composite design in 3D printed concrete (3DPC). Traditional concrete mix design codes do not fully address the unique needs and considerations of 3DPC due to its innovative and evolving nature. There is no standardized guidelines for 3DPC mix design poses challenges for practitioners and researchers. However, efforts are underway to develop guidelines, protocols and standards to improve material formulations and printing parameters. Empirical studies, experiments and computational modeling are used to address these challenges and ensure stability, reliability and performance in printed structures. In the absence of standardized codes, practitioners rely on available literature, research articles, and industry best practices to inform the collaborative design process. Working with experts in materials science, construction engineering and additive manufacturing provides valuable insight and guidance. Customized mix designs tailored to the needs of 3D printing technology are developed through interdisciplinary collaboration and ongoing research efforts. As the 3D printed concrete industry develops, it is expected that standardized guidelines and codes for mix design will emerge. These guidelines reflect the growing understanding and acceptance of 3D printing technology in construction. Interdisciplinary collaboration and research efforts will shape the future of 3DPC mix design practices. Despite the current lack of standardized codes, ongoing research and collaboration efforts are paving the way for optimized mix designs in 3D printed concrete. As the field continues to evolve, standardized guidelines will play an important role in ensuring consistency, reliability, and performance in 3DPC construction projects. For this project, numerous trials were conducted to develop the optimal design mix for 3D Printed Concrete (3DPC) using Portland Pozzolana Cement (PPC). Through iterative testing and analysis, we aim to optimize mix ratios to achieve printability, flowability, and structural integrity required for successful 3D printing applications (Refer with: Table 1).

2.3 Printer specification

The Extrusion-Based Concrete Printer is designed for versatile material use, accommodating concrete, clay, viscous pastes, and more. Equipped with precise motion control including X, Y, Z rotation axis, hopper extrusion and accelerator mixing, it ensures accurate and consistent printing. Weighing 1.2 tonnes and with a generous build size of 1100 x 1100 x 600mm, this printer offers efficient operating speeds across all axes including X, Y, Z, rotation, hopper discharge and accelerator combination (refer with: Fig.1).
An extrusion-based concrete printer offers a wide range of capabilities to meet a variety of printing needs. With nozzle sizes ranging from 10mm to 40mm and options including round, square and rectangular variations, it offers flexibility in design choices. It supports a layer height of 3 mm for non-bulk composite and 20 mm for bulk composite, ensuring accuracy in printing various structures. Running at impressive speeds, the maximum print speed is 11 kg/min, 100 mm/s non-gross compound and 35 mm/s gross compound, facilitating efficient and timely printing processes.

3 Results and discussion

3.1 3D Printing parameters check

3.1.1 Flowability

Flowability in fresh concrete refers to its ability to move smoothly and smoothly from the 3D printer's extrusion nozzle. This is an important property that ensures the concrete is accurately deposited and shaped layer by layer during the printing process. Optimum flow enables concrete to maintain its desired shape and dimensions, enabling the creation of complex and precise structures without compromising structural integrity. Achieving the right flow is essential to ensure efficient and effective 3D printing operations, ultimately creating high-quality finished products with consistent performance and aesthetics.
A flowability test is performed using a flow table tool, and the flow value is noted (Refer with: Table1). It involves placing a sample of mortar mix on a flat, circular table and spreading it uniformly (refer with: Fig.2). Then, the table is rapidly dropped from a fixed height and the spread of the mortar mixture is measured. This test helps determine the consistency and ability of mortar to flow and spread. The flow table test for concrete is standardized under ASTM C1437. In 6 types of mortar mixes, the 3b mix is suitable for the 3D printed concrete because of its good flowability. The required flow value is 180-230 mm (Refer with: Fig.2, Table1).

<table>
<thead>
<tr>
<th>Mix design</th>
<th>Cement (g)</th>
<th>Sand (g)</th>
<th>SP-PCE 0.5% (ml)</th>
<th>SP-430 0.5-0.6% (ml)</th>
<th>VMA 0.1% (ml)</th>
<th>W/C</th>
<th>Flow (mm)</th>
<th>Flow(limit in literature) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>300</td>
<td>450</td>
<td>1.5</td>
<td>-</td>
<td>-</td>
<td>0.3</td>
<td>0.38</td>
<td>130</td>
</tr>
<tr>
<td>1b</td>
<td>300</td>
<td>450</td>
<td>1.5</td>
<td>-</td>
<td>1.5</td>
<td>0.3</td>
<td>0.40</td>
<td>142</td>
</tr>
<tr>
<td>2a</td>
<td>300</td>
<td>450</td>
<td>-</td>
<td>1.5</td>
<td>-</td>
<td>0.3</td>
<td>0.38</td>
<td>170</td>
</tr>
<tr>
<td>2b</td>
<td>300</td>
<td>450</td>
<td>-</td>
<td>1.5</td>
<td>0.3</td>
<td>0.3</td>
<td>0.40</td>
<td>180</td>
</tr>
<tr>
<td>3a</td>
<td>300</td>
<td>450</td>
<td>-</td>
<td>1.8</td>
<td>0.3</td>
<td>0.3</td>
<td>0.38</td>
<td>195</td>
</tr>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>-</td>
<td>1.8</td>
<td>0.3</td>
<td>0.4</td>
<td>0.40</td>
<td>210</td>
</tr>
</tbody>
</table>

**3.1.2 Thixotropy open time (TOT)**

Thixotropy open time (TOT) in 3D printing concrete refers to the time the concrete maintains its thixotropic properties when extruded through the printing nozzle. Thixotropy is a rheological property of some materials, including concrete, where viscosity decreases under shear stress and gradually recovers over time when the stress is removed.

<table>
<thead>
<tr>
<th>Mix design</th>
<th>Cement (g)</th>
<th>Sand (g)</th>
<th>SP-430 0.6% (ml)</th>
<th>VMA 0.1% (ml)</th>
<th>W/C</th>
<th>Time (min)</th>
<th>Flow (mm)</th>
<th>Flow(limit in literature) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8</td>
<td>0.3</td>
<td>0.4</td>
<td>0</td>
<td>210</td>
<td>180-230</td>
</tr>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8</td>
<td>0.3</td>
<td>0.4</td>
<td>10</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8</td>
<td>0.3</td>
<td>0.4</td>
<td>20</td>
<td>192</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8</td>
<td>0.3</td>
<td>0.4</td>
<td>30</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8</td>
<td>0.3</td>
<td>0.4</td>
<td>40</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8</td>
<td>0.3</td>
<td>0.4</td>
<td>50</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8</td>
<td>0.3</td>
<td>0.4</td>
<td>60</td>
<td>115</td>
<td></td>
</tr>
</tbody>
</table>

In 3D printing, TOT is an important parameter affecting the extrusion and printability of concrete mixtures. This determines the time window in which the concrete maintains its desired flow and shape-holding ability, allowing for precise deposition and layering in the printing process. Monitoring and optimization of TOT is essential to achieve sustainable and
high-quality 3D printed concrete structures. It is indirectly dependent on the setting time of concrete. During the flow test, measurements are taken every 10 minutes up to 60 minutes, with the flow value showing a decrease after 30 minutes (Refer with :Table 2). To rectify this, 0.1% of a SP is introduced at the 30-minute mark (Refer with: Table 3). Subsequently, the flow value is observed to improve, indicating successful correction of the flow characteristics of the material (Refer with : Fig.3).

Table 3. Flow value for 0- 60 mins (adding 0.1%SP at 30 mins)

<table>
<thead>
<tr>
<th>Mix design</th>
<th>Cement (g)</th>
<th>Sand (g)</th>
<th>SP-430 0.6% (ml)</th>
<th>VMA 0.1% (ml)</th>
<th>W/C</th>
<th>Time (min)</th>
<th>Flow (mm)</th>
<th>Flow (limit in literature) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8</td>
<td>0.3</td>
<td>0.40</td>
<td>0</td>
<td>210</td>
<td>180-230</td>
</tr>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8</td>
<td>0.3</td>
<td>0.40</td>
<td>10</td>
<td>202</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8</td>
<td>0.3</td>
<td>0.40</td>
<td>20</td>
<td>195</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8</td>
<td>0.3</td>
<td>0.40</td>
<td>30</td>
<td>181</td>
<td></td>
</tr>
</tbody>
</table>

Adding 0.1% of sp

<table>
<thead>
<tr>
<th>Mix design</th>
<th>Cement (g)</th>
<th>Sand (g)</th>
<th>SP-430 0.3 (ml)</th>
<th>VMA 0.3 (ml)</th>
<th>W/C</th>
<th>Time (min)</th>
<th>Flow (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8+0.3</td>
<td>0.3</td>
<td>0.40</td>
<td>40</td>
<td>205</td>
</tr>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8+0.3</td>
<td>0.3</td>
<td>0.40</td>
<td>50</td>
<td>190</td>
</tr>
<tr>
<td>3b</td>
<td>300</td>
<td>450</td>
<td>1.8+0.3</td>
<td>0.3</td>
<td>0.40</td>
<td>60</td>
<td>176</td>
</tr>
</tbody>
</table>

Fig.3. Graphical representation of TOT.

3.1.3 Manual check

Manual evaluation of Buildability, printability and extrudability in 3D printing using a 20 mm diameter syringe. These include careful observation of material ejection through the syringe, evaluation of the ability to maintain the desired shape and layer adhesion during printing, and evaluation of the stability of the extruded layers for uniformity and stability (Refer with : Fig.4, Fig.5).
Fig. 4. Manual evaluation of buildability, printability and extrudability (a) One layer, (b) Four layers. This analysis provides valuable insights into the performance of the printing material and the effectiveness of the printing process, helping to optimize print parameters and material formulations to achieve desired printing results.

Fig. 5. Six layers (Manual check)

3.1.4 Extrudability

Extrudability in 3D printed concrete refers to how easily the concrete mixture can be pushed out or squeezed through the nozzle of the 3D printer. It's like how toothpaste flows out of a tube when you squeeze it. If the concrete is too thick or sticky, it might not flow smoothly, causing problems with the printing process. On the other hand, if it's too runny, it might not hold its shape well after being printed. So, finding the right balance of consistency is important for successful 3D printing. Engineers and researchers study extrudability to make sure the concrete can be printed efficiently and accurately to create strong and durable structures. The 3b mix is perfectly extruded through the 20mm nozzle (Refer with: Fig. 6).
Printability in 3D printed concrete refers to how well the concrete mixture can be shaped and formed into the desired structure by the 3D printer. Just like how a regular printer needs the right kind of ink and paper to print a document neatly, a 3D printer needs the concrete mix to be just right to create accurate and precise shapes. If the concrete isn't print-friendly, it might not stick together properly or could collapse during printing, leading to errors in the final structure. Engineers and researchers study printability to ensure that the concrete can be successfully printed layer by layer to create strong and reliable buildings and other structures. The 3b mix is perfectly printable (Refer with : Fig.7).

Fig.6. Extrudability of 3b mix

3.1.5 Printability

Fig.7. Printability of 3b mix
3.1.6 Buildability

Buildability in 3D printed concrete refers to how well the concrete structure can be built layer by layer using the 3D printing process. Imagine building a tower with blocks - each block needs to fit properly on top of the other without falling over. Similarly, in 3D printing, each layer of concrete needs to be accurately placed on top of the previous layer to create a sturdy and stable structure. Factors like the printing speed, layer thickness, and material properties all affect buildability. Engineers and researchers study buildability to ensure that the 3D printing process runs smoothly and produces high-quality concrete structures that are strong and durable. The buildability of 3b mix is good and 6 layers were printed (Refer with: Fig.8).

Fig.8. Buildability of 3b mix (a) buildability of 2nd layer, (b) buildability of 3rd layer, (c) buildability of 4th layer.

3.2 3D Modelling

First, when creating a 3D model for printing using Fusion 360, you design the object you want to print (Refer with : Fig.9). Once the design is finished, you save it as an STL file. This file contains all the information needed for the 3D printer to understand how to create the object layer by layer. After saving, you can then import the STL file into the 3D printing software or system you're using, which prepares the file for printing. From there, the 3D printer reads the file and starts building the object according to the design you created in Fusion 360. The slicing process, which divides the 3D model into layers, is automatically handled by the 3D printer software before printing begins. For our model height of layer is 10mm.

Fig.9. 3D modelling using fusion 360 software.

3.3 3D printed concrete using ppc
After successfully ensuring that the 3D printed concrete meets requirements for printability, buildability, flowability, and extrudability, the concrete mixture using PPC cement with 35% fly ash content is printed with a layer height of 6 layers. Each layer has a thickness of 10mm, and a 20mm nozzle is used for printing. The quantity of materials used for printing 3 numbers of modeled concrete structures is mentioned (Refer with: Table 4).

<table>
<thead>
<tr>
<th>Mix design</th>
<th>Cement (g)</th>
<th>Sand (g)</th>
<th>SP-430 0.6% (ml)</th>
<th>VMA 0.1% (ml)</th>
<th>Water (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3b</td>
<td>6000</td>
<td>9000</td>
<td>36</td>
<td>6</td>
<td>2400</td>
</tr>
</tbody>
</table>

The structure being printed has a width of 40mm and a height of 60mm with length of 400mm. This means that the printer is stacking 6 layers of concrete on top of each other to create the structure (Refer with: Fig.10). Each layer is 10mm thick, and the printer is using a 20mm-wide nozzle to lay down the concrete. The final structure will be 40mm wide and 60mm tall once all the layers are printed.

**Fig.10.** 3D printed concrete using ppc (a) 3DPC with 6 layers, (b) 3 numbers of 3DPC structures.

### 3.4 Strength of 3DPC

After fixing the 3D printing concrete mix, Cubes measuring 50x50mm were casted and allowed to cure. Following the ASTM C109 standard, a compressive strength test was conducted. The resulting strength of the 3D printed concrete mix, utilizing Portland Pozzolana Cement (PPC), was determined to be 24.68 MPa (Refer with: Fig.11).

**Fig.11.** Strength of 3D printed concrete using ppc (a) compression test on cube-3b mix, (b) Peak load.
4 Conclusion

In conclusion, this project represents a thorough investigation into the feasibility and characteristics of 3D printed concrete utilizing Portland Pozzolana Cement (PPC) with a 35% fly ash content. By meticulously examining various fresh properties, including extrudability, printability, flowability, setting time and thixotropic open time, alongside robust evaluations of compressive strength, invaluable insights have been uncovered. The findings unequivocally highlight the potential of PPC-fly ash-based concrete mixes for 3D printing applications, showcasing their ability to achieve the desired flow and workability while maintaining adequate strength properties. Through the refinement of mix proportions and printing parameters, the opportunity arises to manufacture high-quality 3D printed concrete structures that meet industry standards and sustainability objectives. Continued research and development endeavors in this realm are poised to further enhance the utilization of PPC-fly ash based concrete for additive manufacturing, thereby catalyzing progress in construction technology and promoting sustainable building practices. Moreover, this project's successful demonstration of 3D printing concrete using PPC-fly ash-based formulations underscores the viability and promise of this innovative approach for constructing enduring and sustainable infrastructure. This showcases the potential of integrating eco-friendly materials like PPC with advanced technologies, paving the way for resilient and environmentally conscious construction practices. By integrating 3D printing technology with eco-friendly cementitious materials, a transformative evolution in construction methodologies is underway. Leveraging the capabilities of PPC-fly ash based concrete presents an avenue to revolutionize the construction landscape, ushering in an era characterized by resource efficiency and resilience. As contemporary construction challenges persist, embracing such cutting-edge methodologies offers a pathway towards the realization of resilient structures that mitigate environmental impact and address evolving societal needs. Embracing innovation in this manner holds the potential to not only reshape the built environment but also to foster a sustainable legacy for future generations.

References


10. Luong Pham, Phuong Tran, Jay Sanjayan, Mohsen Saneian, Peihua Han, Shan Jin, Yong Bai (2020) "Steel fibers reinforced 3D printed concrete: Influence of fiber sizes on mechanical performance." Construction and Building Materials.


