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Review Paper on Investigating the Hardened Properties of Extrusion Based 3D Concrete Printing with Agro-Industrial Waste Materials

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Abstract: Three-dimensional (3D) concrete printing (3DCP) is a transformative construction technique that offers the potential for greater efficiency, customization, and architectural flexibility. This technology is becoming increasingly necessary in the construction industry due to its ability to reduce labour costs, increase productivity, and minimize waste.
The use of alkali-activated materials in 3DCP is gaining attention due to their superior mechanical properties and lower carbon footprint compared to traditional Portland cement. These materials, which include agro-industrial by-products like fly ash, slag and bagasse ash are activated by alkaline solutions to form a binder. The development of sustainable, alkali activated 3DCP materials is a critical step towards environmentally friendly construction practices.
The primary focus of this research is to investigate the hardened properties of 3DCP materials, including compressive strength, flexural strength, split tensile strength, bond strength, and Poisson's ratio. These properties are fundamental for predicting the performance of 3D printed structures under various loading conditions.
One of the unique challenges in 3DCP is the anisotropic behaviour of the printed concrete, which can exhibit different properties in different directions. This behaviour is influenced by factors such as layer interfaces, printing direction, and material composition.
The findings from this research will contribute to the development of design guidelines and standards for 3DCP, paving the way for broader adoption of this innovative technology in the construction industry.

I. INTRODUCTION

A. General (Unveiling 3D Concrete Printing)

Historically, the construction industry has been slow and labour-intensive, facing issues like delays, cost overruns, and safety concerns. However, 3D concrete printing (3DCP) offers a promising solution, revolutionizing construction by enabling faster, more precise, and sustainable practices.

Three-dimensional concrete printing (3DCP) is an innovative technology that uses computer control to precisely position materials, eliminating the need for moulds and formwork. This technology employs concrete extruder to deposit concrete layer-by-layer, to create structures. It's a viable solution to many industry issues, including low quality, slow efficiency, safety risks, and a lack of skilled workers.

A key advantage of 3DCP is its design flexibility. Unlike traditional methods, it imposes no geometric limitations, allowing designers and architects to create unique and customized structures. The material can be pumped, extruded through a nozzle, and maintain its shape under additional layers without traditional formwork.

B. Comparison With Conventional Concrete

3D concrete printing (3DCP) integrates concrete mixing, block making, labour, and tools into a single process. Its distinctive characteristic is the removal of formwork, which enables the production of unconventional shapes.

When comparing 3D printing technology to conventional design and manufacturing methods, it offers greater modeling flexibility, reduces material usage, and minimizes environmental impact. As a result, it becomes a viable choice for sustainable and intelligent construction practices[1].

This technology entirely eliminates the expenses associated with formwork. It also cuts down the labour costs by a significant 50-80%, and reduces the waste of construction materials onsite by a substantial 30-60%.

Three-Dimensional Concrete Printing (3DCP) holds significant potential for deployment in challenging environments such as high-altitude regions, border areas, and locations with extreme temperature conditions. Its applicability extends to complex construction scenarios where manual labour may not yield efficient results.

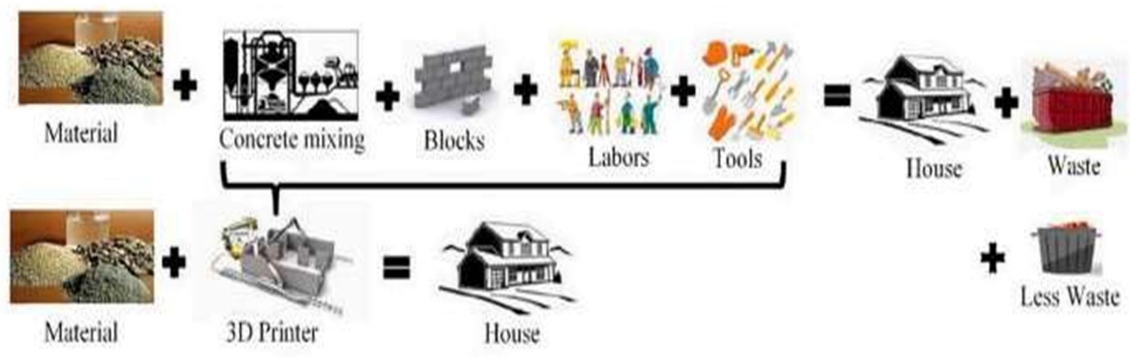

Figure 1 Schematic Diagram of Difference Between Conventional Concreting and 3DCP [2].

II. NEED AND SCOPE OF STUDY

With increasing environmental concerns, it's important to explore sustainable alternatives in construction. This could lead to more eco-friendly construction practices.

Understanding the anisotropic behaviour of 3DPC is key to predicting its performance under different loading conditions. This knowledge can guide the design and construction of 3D printed structures.

Determining the hardened properties of 3DPC is essential for ensuring the safety and durability of 3D printed structures. These properties can influence the choice of materials and printing parameters.

By studying these aspects, we can improve the reliability, performance, and sustainability of 3D printed concrete structures, contributing to the advancement of 3D concrete printing technology in the construction industry. It also opens up new possibilities for innovative design and construction methods.

The potential of this research is extensive, as it could pave the way for the creation of construction materials that are more eco-friendly, effective, and superior in performance.

The research will focus on developing sustainable printing materials for 3D Printable Concrete (3DPC) through the utilization of Agro-Industrial waste. This involves creating and testing new concrete mixes in the lab and assessing their performance in real-world settings. Another key area is the investigation of the anisotropic behaviour of 3DPC, which is crucial for understanding its performance under different loading conditions. This could involve testing 3D printed specimens under various conditions and analyzing the results. Lastly, determining the hardened properties of 3DPC, this could involve conducting lab tests and using computational modeling to predict these properties. These areas of focus could significantly contribute to the field of 3D Printable Concrete (3DPC) and form the basis of a robust and impactful research project

Furthermore, it could also foster the progress of 3DCP technology and broaden its applications in the field of construction.

III. LITERATURE REVIEW

Brettel et al. (2014) [3]. Additive manufacturing (AM), commonly referred to as 3D printing, has recently emerged as a significant technological advancement in the construction industry. It serves as a key catalyst toward the digitalization of the construction sector. AM holds the potential to enhance product quality and overall performance in construction.

M. Hossain et al. (2020) [4]. The use of 3D printing in construction is an emerging technique that promises to automate processes. It employs an automated robotic system to build structures out of concrete. Unlike traditional methods that rely on formwork, 3D Concrete Printing (3DCP) enables systematic material placement without the need for formwork, guided by computer-controlled algorithms. This approach reduces labor - intensive work, minimizes material waste, and enhances construction efficiency. By layering cementitious materials, 3D printing can create intricate structures with precision. This makes it a promising technology for the future of construction.

S. Bhusal and S. B. Kshirsagar (2020) [5]. Globally, the construction industry has a significant environmental impact, accounting for 40% of global energy consumption, 38% of carbon emissions, and 12% of water eutrophication. To address this, there is a growing demand for decarbonization within the industry. 3D printing, also known as additive manufacturing, has emerged as a promising solution to reduce energy requirements, water waste, and carbon emissions. Notably, the industry has transitioned from using polymers and steel to incorporating concrete in 3D printing, leading to reduced production time, minimized waste, and lower labor costs.

3D printing in construction is an innovative process that fabricates 3D objects layer by layer. Comparative studies between 3D construction printing and traditional concrete methods reveal potential improvements in time, cost management, and sustainability. Concepts like contour crafting—on-site dwelling printing—may reshape architectural design. However, achieving this requires developing eco-friendly materials. Architects can now unleash their creativity, overcoming past limitations of conventional building techniques.

Jittin et al. (2021) [6]. Given the environmental challenges posed by cement production, it becomes imperative to address the emission of CO2 into the atmosphere. One effective strategy is to utilize various industrial and agricultural by-products. By doing so, we achieve dual benefits: reducing waste disposal and promoting sustainable production of agricultural and industrial goods on a global scale. This integrated approach aligns with environmental conservation and economic viability.

Memon et al. (2009) [7].Numerous research studies focus on incorporating industrial waste materials into concrete production. Leveraging agro-industrial waste in the construction industry presents a transformative opportunity to minimize waste generated by both industrial and agricultural sectors. By doing so, we can create sustainable solutions and reduce the environmental impact caused by agro-industrial waste disposal in landfills.

B. S. Thomas (2018) [8]. Researchers are investigating the features of binders made from agricultural and industrial waste. Agro-industrial waste materials, such as silica fume (SF), ground granulated blast furnace slag (GGBS), rice husk ash (RHA), bagasse ash (BA), fly ash (FA), and coconut-based waste ash, are high in silica and have been widely used in concrete production for decades. Research suggests that using by-products can improve durability and strength, reduce construction costs by reducing cement usage, benefit the environment by lowering carbon dioxide emissions, and aid in waste disposal.

Kaur et al. (2018) [9]. The process of geopolymerization converts waste materials rich in alumina and silica, such as fly ash, into valuable binders with characteristics akin to those of cement-based materials. Geopolymer mortar presents a greener alternative to conventional cement-based mortar. In the creation of geopolymer mortar, Class F fly ash was utilized as the primary material. Alkaline activator solutions, specifically sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), were used. The mix proportions were designed to resemble those of Ordinary Portland Cement (OPC) mortar. An increase in the molar concentration of sodium hydroxide (NaOH) and extended curing periods resulted in an increase in compressive strength. The inclusion of sodium silicate (Na_2SiO_3) notably boosted the compressive strength. The maximum strength of 40.42 MPa was achieved with a 16 M concentration of NaOH and sodium silicate (Na_2SiO_3).

Askarian et al. (2018) [10]. Alkali-activated materials (AAMs) commonly utilize chemicals such as sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), potassium hydroxide (KOH), potassium silicate (K_2O_3Si), calcium hydroxide ($Ca(OH)_2$), and sodium carbonate (Na_2CO_3). However, two significant challenges arise during AAM preparation:

Handling Alkaline Liquids: Dealing with highly concentrated, viscous, and corrosive alkaline solutions poses practical difficulties.

Heat Curing Requirement: To enhance polymerization and activation, AAMs typically require heat treatment. This involves subjecting them to temperatures of 50°C or higher for several hours.

Provis (2018) [11]. “Alkali activation” (AA) refers to the process where a solid aluminosilicate, known as the “precursor”, reacts in an alkaline setting (created by the “alkali activator”) to form a hardened paste. Alkali-activated binders can be produced via two primary methods: a one-part mix (dry powder mixed with water) or a two-part mix (liquid activator) system.

The two-part mix is currently the predominant method used in the initial deployment of alkali-activation across most markets, with the majority of existing products being produced this way. However, as the technology matures and issues related to the often-slow strength development of one-part mixes are resolved, it is anticipated that one-part systems will become more scalable in the future. This is due to their potential for factory production and distribution as a bagged material.

The two-part mixture is seen as more scalable for precast work, where the handling of chemicals and curing regimes can be more tightly controlled. The development of a One-Part Mix Alkali-Activated Binder System has been demonstrated to be feasible through cocalcination or intergrinding of different aluminosilicate powder precursors and solid activators. These activators are typically an alkali carbonate, silicate, or hydroxide.

Mehrotra et al. (1992) [12]. In 2019, the worldwide cement production, a key driver for infrastructure growth, was approximately 4 billion tons. This production resulted in a staggering emission of 3.5 billion tons of carbon dioxide. Additional concerns linked to this production include environmental contamination and degradation, as well as the exhaustion of natural resources during the extraction of raw materials. A potential strategy to mitigate these negative impacts is to replace cement clinker with supplementary cementitious materials (SCMs), also known as pozzolans. SCMs are typically plentiful and sustainable waste products from industrial or agricultural processes that possess latent hydraulic reactivity that can be activated. Over a hundred studies, starting as early as 1992, have explored the potential of sugarcane bagasse ash (SCBA) as a viable SCM.

Ganesan et al. (2007) [13]. The study investigates the effects of bagasse ash (BA) content as a partial replacement of cement on the physical and mechanical properties of hardened concrete. The researchers found that BA is an effective mineral admixture, with 20% as the optimal replacement ratio of cement. The properties of concrete investigated include compressive strength, splitting tensile strength, water absorption, permeability characteristics, chloride diffusion, and resistance to chloride ion penetration.

The study contributes to the field by providing a potential solution to some of the environmental concerns and problems associated with waste management. It suggests that agro wastes such as rice husk ash, wheat straw ash, hazel nutshell, and sugarcane bagasse ash can be used as pozzolanic materials for the development of blended cements. Kumar et al. (2022) [14].The stickiness of fly ash in 3D printing of geopolymers is influenced by the type and class of the fly ash used. Typically, fly ash with a high degree of fineness and strong pozzolanic activity will enhance the adhesion in 3D geopolymer printing. The inclusion of sodium silicate in the geopolymer mixture also boosts the adhesive properties of fly ash. Fly ash can be employed to decrease shrinkage and enhance the characteristics of 3D geopolymer printing. The fineness of fly ash generally ranges from 50 to 90%. The greater the fineness, the smaller and finer the particles. Shilar et al. (2022) [15]. The inclusion of GGBS improves the compressive strength, bending strength, and longevity of the printed items. The pozzolanic reaction between GGBS and alkaline activators results in a denser geopolymer gel structure, enhancing the mechanical properties and chemical resistance of the printed structures. GGBS also has beneficial thermal properties, such as low thermal conductivity, which can be beneficial for specific applications.

H.M. et al. (2023) [16]. The enhanced stickiness can aid in preventing the peeling or distortion of 3D-printed components over time. GGBS is composed of finely milled particles with sizes ranging from 5 to 25 μm. The non-crystalline nature of GGBS particles contributes to its pozzolanic reactivity, enabling it to react with alkaline activators and create a geopolymer matrix. The particle size distribution of GGBS impacts the flow properties and ease of use of the geopolymer paste, affecting the printability and structural stability of the 3D printed items.

Özalp et al. (2020) [17]. 3D printing demands a rethinking of concrete mix design. The mix must be adjusted for desired properties in both fresh and hardened states. The concrete should be designed for nozzle extrusion, balancing viscosity, layer adhesion, weight-bearing capacity, and pumpability. It should set quickly but retain moisture for bonding. The design involves balancing conflicting objectives like high strength, low water-to-cement ratio, and workability. The base layers should deform minimally and bond well with upper layers. Achieving flowability during extrusion and structural development requires a balanced mix design.

Le et al. (2012) [18]. The layered structure of 3D Printed Concrete (3DPC) exhibits an anisotropic nature, and the formation of voids between layers can diminish its structural strength. Interlayer bonding is a crucial factor affecting the hardened properties of 3DPC. The goal for 3DPC structures is to achieve high compressive strength, flexural strength, and tensile bond strength in all directions. Since 3DPC structures are built without formworks, it leads to high water evaporation in the concrete, which can cause cracking. The printed structure is likely to be anisotropic and form voids between filaments, making high compressive strength a primary objective for the printed objects.

Kaliyavaradhan et al. (2022) [19]. In conventional construction, minor alterations in concrete properties or mix design don't drastically affect the end product. However, in 3D Concrete Printing (3DCP), where thin layers are continuously extruded, slight mix changes can modify rheology, impact buildability, and potentially lead to structural failure. This calls for comprehensive research into materials, processes, printing parameters, and quality assurance. Unlike traditional construction, which allows for manual inspections and corrections, 3DCP can finish construction in a day, necessitating uninterrupted printing to ensure interlayer bonding and avoid material hardening in the printer's delivery system. Current 3D concrete printers, mainly using open-loop controls, need well-defined print parameters and sturdy systems for quality 3DCP. However, material quality can fluctuate, and each printable mix is influenced by factors like building rate, printing path, curing, temperature, and surface moisture. Printer operators must rely on experience to manually adjust for these factors and visually confirm print quality. This becomes more complicated for large-scale, on-site construction where environmental factors are significant. As 3DPC transitions from lab to site, understanding the testing pattern for fresh and hardened characteristics of 3DPC will aid in preserving the quality of the layered structure.

Nerella et al. (2019) [20]. In the context of 3D Concrete Printing (3DCP), the absence of densification or compaction processes could potentially lead to an increased occurrence of voids both within and between the extruded filaments. This is a significant consideration as these voids can impact the structural integrity of the printed object.

Furthermore, it's essential to examine how various operational variables associated with the pumping and printing processes influence the hardened properties of the 3D printable concrete. These variables include the time interval between the deposition of layers, the speed of the printing process, and the distance between the nozzle and the point of layer deposition. Each of these factors plays a crucial role in determining the final characteristics of the printed concrete structure. For instance, the interlayer interval time can affect the bond strength between layers, the printing speed can influence the uniformity and quality of the extruded concrete, and the height of the nozzle can impact the precision of the layer deposition.

Therefore, a comprehensive understanding of these variables and their effects on the hardened properties of 3D printable concrete is vital for optimizing the 3D printing process and ensuring the production of high-quality printed concrete structures.

Panda et al. (2017) [21]. Analyze the tensile bond strength with respect to the printing time gap between layers, nozzle speed, and nozzle standoff distance. They used a novel formulation of fly ash-based geopolymer and printed it using a four-axis automated gantry system.

The study found that the bond strength is a function of the state of the interface material between two nearby layers, which can be influenced by the material strength development rate and 3D printing parameters. This understanding is crucial as the bond strength is considered one of the key parameters to ensure stability in the structure of 3D printed geopolymer mortar.

Kruger et al. (2023) [22]. The Poisson ratio, which defines the lateral to longitudinal strain of a material under uniaxial load, is widely used in engineering analysis and design. For conventionally cast concrete, an isotropic static Poisson ratio typically ranges between 0.15 to 0.25. However, no ratio has been established for 3D printed concrete, and it is currently widely assumed to be 0.2 and isotropic in computational modelling applications.

This layer-wise additive manufacturing technology is known for yielding orthotropic mechanical properties due to the presence of weak interlayer regions at the structural level and elongated oblate voids at the material level. The study aims to characterize the static Poisson ratio of printed concrete. Specimens were prepared from a printed element and uniaxially tested both parallel and perpendicular to the printing direction.

Digital image correlation technology was employed to facilitate the capturing of specimen strains, followed by micro-computed tomography scans to determine void topography. The results indicate larger Poisson ratios apply for 3D printed concrete compared to its cast counterpart; up to 17 and 33% increases were obtained when printed specimens were tested perpendicular and parallel to the printing direction, respectively. This orthotropic behavior is ascribed to the oblate voids present in the printed specimens.

Tay et al. (2022) [23].3D printing holds promise in making the construction industry more sustainable. Traditional construction is responsible for generating 27% of global CO2 emissions. 3D printing can potentially revolutionize the construction industry by making housing construction faster, more affordable, and sustainable. It allows for the creation of unique and customizable designs directly on-site with high precision[2].

However, 3D printing can only become truly sustainable if materials and processes are also ecologically sound. Some builders using green processes still rely on traditional materials, such as cement, which alone is responsible for 8% of global CO2 emissions. Therefore, the use of sustainable materials is crucial. For example, polymer composite is as strong and durable as concrete, weighs 30% less than concrete, and has five times the tensile and flexural strength. These innovative materials can be stored in compact liquid or semi-liquid form in barrels, which helps keep the factory footprint small.

The concept of net zero architecture aims at achieving a balance between energy consumption and renewable energy generation in buildings. A Net Zero home is designed and constructed to produce as much energy as it consumes over the course of a year. This is achieved through a combination of energy-efficient design, on-site renewable energy generation, and a meticulous balance between energy consumption and production.

IV. GAPS IN LITERATURE REVIEW

1) Lack of Standard Building Codes: Absence of universally accepted guidelines for 3D-printed structures.
2) Poisson's ratio of conventionally cast concrete is well established and typically ranging between 0.15–0.25, but no research data are currently available for the Poisson ratio of 3D printed concrete.
3) Not much sustainable material has been developed for 3DCP.
4) Printing Cantilever and Overhangs is the major challenge of 3DCP
5) Currently, no norms are available for the direct tensile test in the 3DPC. Hence, there are discrepancies between the test setups.

6) The formation of voids in 3D printed objects due to layer-by-layer construction affects density and performance. However, accurate methods for assessing these are lacking.
7) 3DCP's anisotropic nature, due to layer-by-layer construction, affects its structural properties. The full impact of this is not fully understood.
8) In 3D Concrete Printing (3DCP), minor mix variations can alter rheology, affect the buildability, and potentially cause structural failure as well. Previous research has not been undertaken to determine the effect of such factors.
9) The inclusion of RF in 3DCP concrete poses a significant challenge, as there is a lack of extensive research on this subject.

V. RESEARCH METHODOLOGY

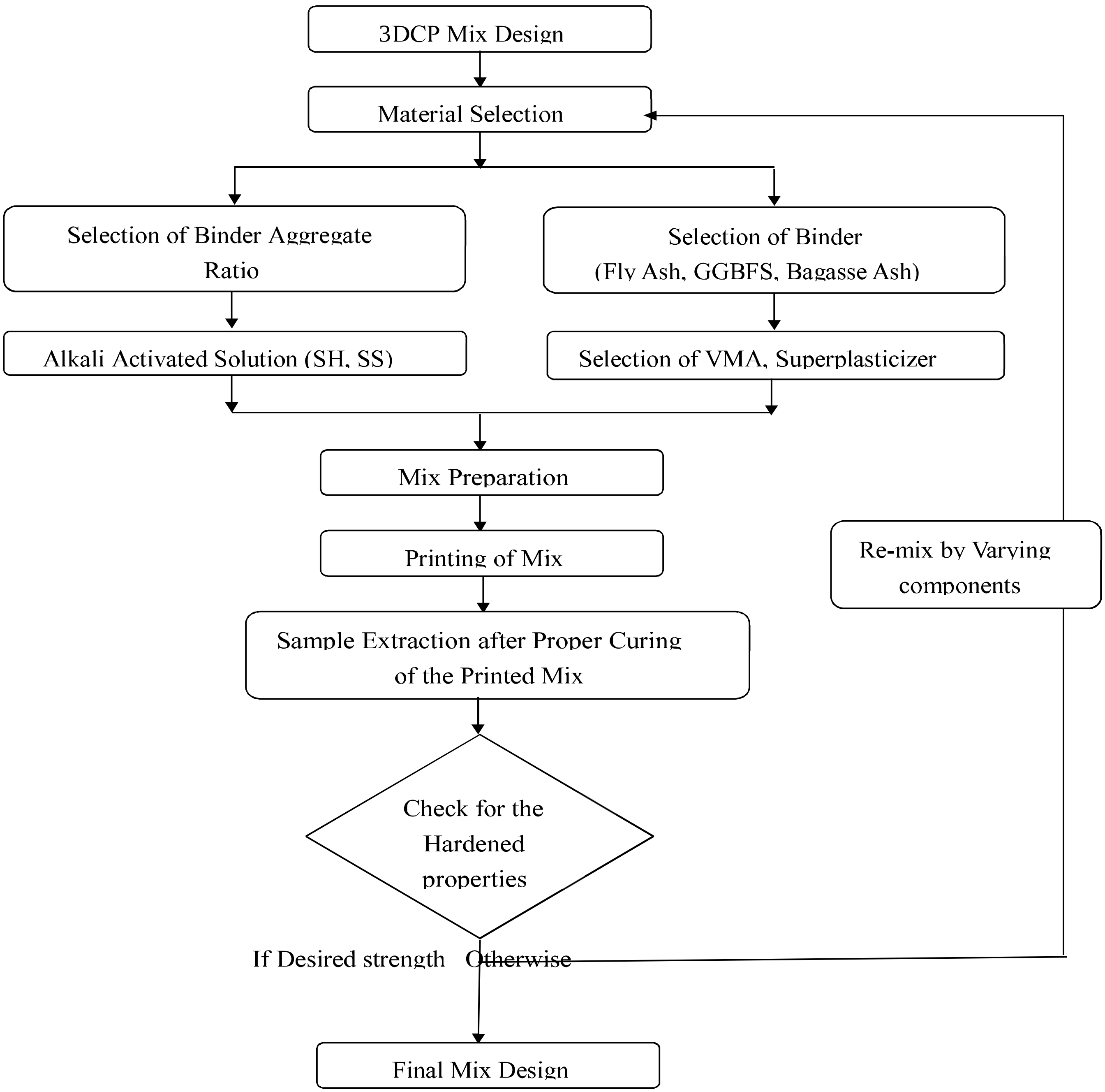

Figure 13 Methodology Flowchart

VI. EXPECTED OUTCOMES

1) Development of sustainable printing materials using Agro-Industrial waste.
2) Hardened properties of 3D printed materials, such as compressive strength, flexural strength, bond tensile strength, split tensile strength and Poisson's ratio will be determined.
3) The anisotropic behaviour of 3D printed materials will be analysed and it will provide valuable insights into their structural properties.

VII. CONCLUSION

Following conclusions has been derived after reviewing various research works:

1) *3D Printing in Construction:* Additive manufacturing (AM) enhances product quality and performance. 3DCP automates processes, reduces waste, and enables precise material placement. Transition from polymers to concrete improves efficiency.
2) *Environmental Impact and Sustainability:* 3D printing reduces CO2 emissions and offers sustainable solutions. Comparative studies show benefits in time and cost management. Concepts like contour crafting reshape architectural design.
3) *Utilizing Agro-Industrial Waste:* Incorporating waste materials (e.g., silica fume, slag) improves concrete properties. By-products enhance durability, reduce costs, and address waste disposal.
4) *Geopolymerization and Alkaline Activators:* Geopolymer mortar is a greener alternative to cement-based mortar. Alkaline activators (e.g., sodium hydroxide, sodium silicate) enhance strength. Optimal replacement ratio for BA is 20%.
5) *Challenges in AAM Preparation:* Handling alkaline liquids and heat curing are considerations. One-part and two-part mix methods exist for alkali-activated binders.
6) *Fly Ash in 3D Geopolymer Printing:* Fineness affects stickiness in 3D printing. Sodium silicate improves adhesive properties. Fly ash reduces shrinkage.
7) *GGBS and Static Poisson Ratio:* Inclusion of GGBS enhances strength and chemical resistance. Printed concrete exhibits orthotropic behavior. Larger Poisson ratios apply compared to cast concrete.
8) *Sustainability Potential of 3D Printing:* 3D printing reduces CO2 emissions and enables customized designs.

VIII. FUTURE SCOPE

From the reviewed study it has been derived those following investigations also be conducted in future:

1) *Standard Building Codes:* Collaborative efforts are needed to establish universally accepted guidelines for 3D-printed structures. Research institutions, industry experts, and regulatory bodies should work together to develop comprehensive standards.
2) *Poisson's Ratio for 3D Printed Concrete:* Conduct research to determine the Poisson's ratio specifically for 3D printed concrete. Understanding its anisotropic behaviour and variations across different printing orientations is crucial.
3) *Sustainable Material Development:* Invest in research and development of sustainable materials tailored for 3DCP. Explore eco-friendly alternatives to traditional concrete, considering both performance and environmental impact.
4) *Overhangs and Cantilevers:* Address the challenges related to printing overhangs and cantilevered structures. Develop optimized printing strategies and support systems to ensure stability during construction.
5) *Direct Tensile Testing Norms:* Establish norms and standardized procedures for direct tensile testing in 3DPC. Consistent testing protocols will enhance reliability and comparability of results.
6) *Void Assessment and Structural Integrity:* Research accurate methods for assessing voids formed during layer-by-layer construction. Understand how voids affect density, strength, and overall performance.
7) *Minor Mix Variations and Rheology:* Investigate the impact of minor mix variations on rheology and buildability. Ensure that small changes in material composition do not compromise structural integrity.
8) *Inclusion of Reinforcing Fibers (RF):* Explore the use of reinforcing fibers in 3DCP concrete. Conduct extensive research to understand their behaviour, bonding, and reinforcement effects.

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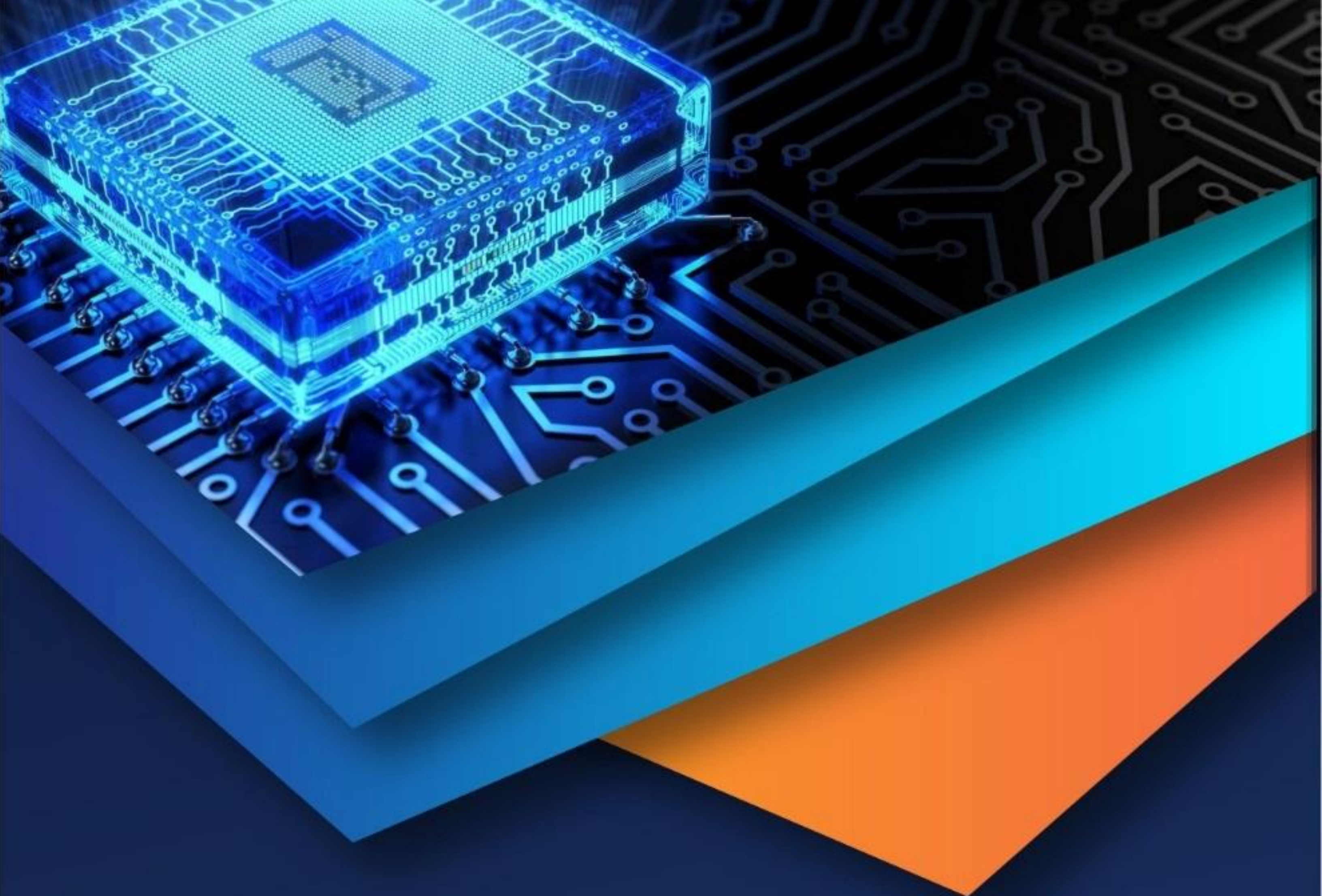

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