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# A Review on Development of 3D Printable Concrete by Utilizing Agro-Industrial Waste: Evaluation of Fresh Properties

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***Abstract: The primary challenge in achieving 3D printable concrete lies in balancing conflicting characteristics of Pumpability and Buildability. On one hand, the concrete must be sufficiently flowable to be pumped through hoses, while on the other hand, it needs to exhibit enough strength for layer-by-layer construction. Overcoming internal shear resistance due to particle interactions is crucial for pumpability, and the material must also retain its shape after extrusion. This thesis presents a comprehensive study on the optimization of mix proportions for Alkali Activated Concrete (AAC) tailored for 3D concrete printing applications, with a focus on the utilization of Agro-Industrial waste. The primary objective is to optimize the mix proportions of AAC by varying the composition of Agro-Industrial waste, thereby contributing to sustainable construction practices.***

***A detailed investigation of the rheological properties of the tailored material is conducted to understand its behaviour and suitability for 3D printing processes. Comparative analyses are performed to evaluate the Rheological Properties of Controlled Mix, Cement replaced concrete, and AAC.***

***This includes assessing the variations in these properties at the Green Stage during the Pumping phase, which is critical for ensuring the quality and consistency of printed structures. Furthermore, the thesis systematically investigates the buildability, rheological properties (viscosity, yield stress, and thixotropy), workability, green-strength, open time and hydration heat of the fresh 3D printing AAC using Agro-Industrial waste. The outcomes of this research are expected to contribute significantly to the field of 3D concrete printing by providing insights into the development of more sustainable and efficient 3D printable building materials. The findings will also aid in the advancement of construction techniques that are eco-friendly and cost-effective.***

***Keywords: 3-Dimensional Concrete Printing (3DCP); Sustainability; Ordinary Portland Cement (OPC); Additive Manufacturing; Alkali Activation; Geopolymers; Agro-Industrial waste.***

## I. INTRODUCTION

### *A. 3D Concrete Printing*

It is an additive manufacturing technique for constructing numerous types of products and structures using various raw materials, directly from three-dimensional (3D) model data[1,2]. The process consists of printing successive layers of materials on top of each other. There has been a growing interest upon 3D printing for civil engineering applications over the past decades due to the advantages this method possesses compared to traditional construction methods, such as the ability to construct complex geometry without the need of formwork, construction speed and minimize waste material and labour cost. There are many examples of such applications both from private companies and researchers.

It is an innovative construction method that promises to be highly advantageous in the construction field in terms of optimizing construction time, cost, design flexibility, error reduction, and environmental aspects. This method of layering materials is the basis of the most widely used and cost-effective concrete printing methods available today. Instead of using formwork, a pump delivers 3D printable concrete (3DPC), which is pushed out through a nozzle of a 3D printer and keeps its shape under the force of more concrete layers on top of it.

*B. Advantage and Limitation of 3DCP*

*1) Advantages*

a) *Reduced Labor and Material Costs:* 3DCP can significantly reduce labour and material costs. It eliminates the need for formwork, which can contribute up to 60% of the overall cost in conventional concrete casting.[3–5]

b) *Environmental Benefits:* By reducing material waste and greenhouse gas emissions[6–8],[9,10] 3DCP promotes sustainability. It also consumes less water compared to traditional construction methods.

c) *Design Freedom:* 3D printing allows for intricate and customized designs that are challenging to achieve using conventional techniques.[11,12]

d) *Speed:* The layer-by-layer construction process can be faster than traditional methods, especially for complex geometries.

e) *Building Information Modelling (BIM) Integration:* 3DCP can be integrated with BIM algorithms, enhancing project coordination and management.[13]


Figure Constructibility IN 3DCP


Figure Sustainability IN 3DCP

2) *Limitations of 3DCP*
a) *Material Properties:* Finding suitable materials with the required properties for 3D printing remains a challenge. Research is ongoing to identify optimal mixtures.
b) *Printability and Buildability:* Ensuring consistent print quality and structural integrity is crucial. Printability and buildability constraints need further exploration.[14–16]
c) *Scale and Size:* Large-scale 3DCP is still limited due to printer size and transportation constraints.[12,17,18]
d) *Surface Finish:* Achieving a smooth surface finish comparable to traditional concrete surfaces can be challenging.
e) *Standardization:* The adoption of 3DCP require proper Standard Code. [18]

### C. Design of 3DCP Material

3DCP is still developing and has limited options for inking materials. Researchers from various universities and industries around the world are trying to find the best inking materials and their ideal proportions for 3D concrete printing that have all the necessary characteristics[14,18]. They have also successfully used byproducts like steel slag, fly ash, and some chemicals to create 3D printed geopolymers. All ingredients must be balanced to achieve the required performance from the concrete.[19]

3D printed concrete is a semi-solid material that flows when a shear force is applied to it. The maximum shear force needed to make static concrete flow is called static yield stress.[19] Dynamic yield stress is the shear force needed to maintain the flow of concrete once it starts flowing. Concrete stops flowing when the shear force is removed and the particles start to cluster together due to contact, and static yield stress is restored. This is called thixotropy.[20]

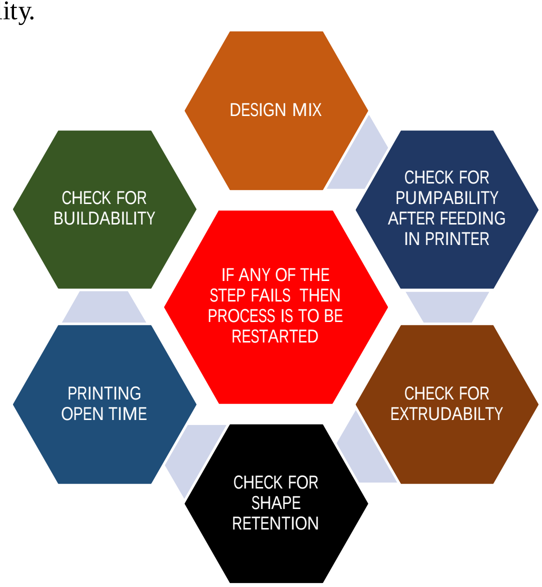
The 3D concrete printing method has conflicting rheological requirements as shown in figure. This means that the concrete needs to be highly workable before extrusion, but less workable and more thixotropic after extrusion for better concrete buildability [21–23],[24][25]. A proper balance must be kept throughout the concrete printing process between the rheological needs of the pumping, extrusion, and buildability stages[5,26].

## II. NEED AND SCOPE OF STUDY

The investigation of most existing material research for 3D concrete printing has explored the use of rheometers to examine the yield stress and viscosity. The use of rheology for characterization is a complex technique and the result is sensitive to the protocol.

A test using a simple apparatus with a standardize procedure would be preferred. Furthermore, there is a lack of existing research to examine the printability region of the material. The consistency of a printable material may reach the maximum limit of most rheometers and enter the region of hardened material testing [9]. This investigation of the printability region can be used as a benchmark to characterize other types of material for printing.

Most of the time the rheological properties are measured without feeding in printer. However, it experiences excessive shearing during Pumping through pipe to nozzle and that is potential enough to change Rheology of Material. One more major objective is to optimise material mix toward sustainability.



1) To study the rheological properties of tailored material by utilizing the agro-industrial waste.
2) To make the comparison among the Rheological properties of Controlled Mix, Cement Replaced Concrete and Alkali Activated Concrete.
3) To determine the variation in the Rheological Properties at Green Stage during the Pumping phase.
4) The buildability, rheological properties (viscosity, yield stress and thixotropy), workability, green strength, open time and hydration heat of the fresh 3D printing Alkali Activated Agro-Industrial waste concrete will be systematically investigated.

### *A. A Step Towards Sustainable 3D Printed Material in Construction*

Every energy count be it at the time of fabrication process or the energy used in its operation after construction.[17]

The implementation of passive designs can dramatically reduce energy consumption and is an area where 3D concrete printing can potentially make a significant contribution because of the ease of creating a structure with high complexity. Printing passive design maximizes the potential of 3D printing to create comfortable space for the users. A passive system is a combination of energy-efficient design to take advantage of the climate to maintain the comfort level in an infrastructure. Such an approach reduces energy consumption during operation. However, such passive design has to be implemented during the design phase.

Apart from these passive designs, there are several *sustainable materials that have a low carbon footprint* that will amplify the use of 3D printing as a sustainable solution.

*Fly ash, geopolymer and recycled glass* are some of the green materials that has been used by the industry[19], [42], [43] [38]. Although these sustainable materials have been used in conventional casting methods, the rheological behaviour for printing is different. The mixtures have to be tailored to this new manufacturing process for printing to be successful.

### *B. Environmental Analysis Of 3d Printed Structure*

Global warming is increasing at the alarming rate, the construction industry is one of the major contributors, so it's a high time to take the responsibility to reduce carbon emissions. The balance between economic and environment is crucial for 3D printing pro motion. 3D printing and conventional casting showed totally inverse results in different regions. The production energy and material consumption in different cases can be converted to $CO_2$-equvient by applying a transfer factor. However, due to the difference of local market and policy condition in different countries, the factor in different countries will be different, which make the results incomparable. The same thing happened to economic cost, 3D printing has higher productivity compared with the conventional construction, and it can also save labour and formwork costs [4]. But the construction machine and special concrete requirements increase the unit cost of concrete. When 3D printing was used in low labour price region such as China, the cost of 3DPC was lower than that of casting method. However, for the high labour prices region such as Singapore, 3D printing demonstrated a significant cost advantage [4] .This issue poses a challenge in finding a balance between economic considerations and environmental impact. Moreover, researchers also pointed out the cost and environmental impact of 3DPC were strong relative to the shape of the element. The environmental impacts of global warming and human toxicity would be lower than that of the conventional construction, when the geometric complexity increased.[27–29] In that way, 3D printing might be a competitive method for customized building or crafts exhibition in high labour price region.

## III. LITERATURE REVIEW

Some of the literatures which are relevant and related to the area of interest of this topic are as described below:

Khan et al. 2020[30]explores how 3-D printing technology is changing the construction industry, by showing how it has progressed from making small products to building large structures using concrete and other materials. The text gives a comprehensive overview of the current state and practice of 3-D printing of concrete, including its history, equipment, materials, and computer modelling. The text also shows some examples of 3-D printed projects, and identifies the opportunities and challenges of this technology, such as the importance of using local materials for ink, developing large-scale printers, and creating innovative mixtures. The text also foresees the future of 3-D printing in construction, where some facilities could be printed on-site in a few hours or days, and suggests the need for a multidisciplinary workforce and a new academic curriculum to deal with this technology.

Schutter et al. 2018[31]presents a comprehensive vision for the future of 3D printing with concrete, addressing technical, economic, and environmental aspects. While showcasing various global examples of 3D printed concrete structures, the text emphasizes existing challenges in the limited range of printable construction materials due to insufficient rheological and stiffening properties. The introduction of active rheology control (ARC) and active stiffening control (ASC) is proposed as a solution to expand the material palette for 3D printing applications.

The environmental impact of 3D printing with concrete is discussed in relation to the structural complexity of the created structures. Through strategies like structural optimization and functional hybridization in design, the use of material is optimized, increasing shape complexity while reducing overall material consumption.

Buswell et al. 2018 [32] discusses the challenges and advancements in 3D concrete printing technology, emphasizing material properties, design complexity, and process control. It explores the relationship between fresh and hardened concrete properties, the importance of reinforcement and measurement of hardened properties, and the need for standardized testing methods. The goal is to provide insight and structure for future research and development in 3D concrete printing for construction applications.

Zhang et al. 2018[33] focused on the use of a novel 3D printing concrete ink with nano clay and silica fume additives. The research found that the addition of nano clay and silica fume improved the thixotropic behaviour, green strength, buildability, and hydration heat release of the concrete. Nano clay enhanced the structure rebuild rate at rest, while silica fume had a stronger hydration reaction. Overall, the study concluded that the 3D printing concrete ink with these additives exhibited good fluidity and standing behaviour.

Kamal et al. 2021[34] explores the workability of fresh concrete for 3D printing in construction, utilizing tests like flow table, ICAR rheometer, Vicat, and electric power consumption measurement. It aims to assess printability, buildability, and properties of hardened concrete, including compressive strength and density, to optimize mixtures for 3D printing applications.

Kapoor ASHISH et al. 2024[35] explores the impact of different parameters on the mechanical properties of 3D printed concrete through experiments and numerical analysis. It discusses the effects of factors like bond strength, stiffness, number of printed layers, and presence of pores on the load capacity of additively manufactured concrete beams. The study aims to provide insights for optimizing printing parameters to enhance the load capacity of printed concrete structures.

Chougan et al. 2020,[36] The shape retention capability by first printing six layers of concrete and then measured the height of each layer after one hour. As this new shape retention test focuses on the height of multiple layers instead of one layer, therefore it gives a more accurate assessment of the shape retention capability of a potential concrete mix after extrusion. Shape retention can be affected by the printing speed.

Tay et al. 2022[37] investigates how 3D printing can help achieve net zero emissions in the building and construction sector. It covers different aspects of 3D printing, such as materials, reinforcements, and design, and their environmental impacts. It shows that 3D printing can reduce resource consumption, carbon footprint, and energy demand, while enabling novel and green design solutions.

Zhang et al. 2022, [19]A linear relationship between the static yield stress of 3DPC and the dynamic/static yield stress of its corresponding paste. This implies that the yield stress of paste can be used as a base to estimate the yield stress of 3DPC, regardless of the type and content of rheological modifiers in the paste.

Baz et al. 2020 [38]referred pull-out strength test in this paper as a method used to evaluate the bond between steel bars and concrete in the context of 3D printed construction materials. It measures the force required to pull a steel bar out of concrete, which reflects the bond strength developed between the two materials. It further investigates the bond between steel and printed mortars as a function of the mortar's workability and the printing method. It is found that neither the workability of the ink, the printing method, nor the layers' direction majorly affect the pull-out strength in respect to the steel bar. These outcomes contribute to the understanding of 3D printing in construction, particularly regarding the integration of steel reinforcement in printed structures.

Soda et al. 2024, [39]presents the creation of stabilized earth-based materials for 3D printing, utilizing excavated soil as a partial replacement for natural sand. The research found that natural clay in the soil contributes to flow retention, enhancing the extrusion quality of the printable mortars. The addition of ground granulated blast furnace slag (GGBS) to the mix doubles the buildable height compared to traditional OPC-sand mortars. This approach offers a sustainable solution by reducing the demand for natural sand and Ordinary Portland Cement (OPC), aiming to lower the carbon footprint of construction materials. These findings provide a feasible method for 3D printing with earth-based materials, sustainable structures with lower sand demand and OPC.

Panda B. et al. 2018,[26] aims to investigate the rheological behaviour and strength properties of geopolymer mixtures specifically for extrusion-based 3D printing. The researchers prepared geopolymer mixtures using specific raw materials and activators.

They evaluated the rheological properties, including viscosity and flow behaviour. The compressive strength of the printed geopolymer samples was tested. The mixtures exhibited pseudoplastic behaviour, which is desirable for extrusion-based printing. Here the, viscosity decreased with increasing shear rate, facilitating smooth extrusion. The samples achieved satisfactory compressive strength, making them suitable for 3D printing applications. The strength was influenced by factors such as curing time, activator concentration, and aggregate content.

Kaur et al. 2018's,[40] observation on employing alkaline activator solutions (sodium hydroxide and sodium silicate). Mix proportions were designed to mimic ordinary Portland cement (OPC) mortar. Compressive strength increased with higher molar concentration of sodium hydroxide (NaOH) and longer curing periods. Incorporating sodium silicate ($Na_2SiO_3$) significantly enhanced compressive strength. Maximum strength (40.42 MPa) was achieved with 16 M NaOH and sodium silicate.

Adaloudis et al. 2021,[8] commented as per research that 3DCP can reduce concrete production's carbon footprint by minimizing material usage and waste. It also offers the potential for energy-efficient designs. This advancement addresses the skilled labour shortage in the construction sector by automating tasks. It reduces reliance on seasonal foreign workers. While 3DCP materials are more expensive, the technology can save costs related to formwork and failures. Some challenges to be still focussed on scarce of 3DCP materials and lack of demand hinder cost reduction. Standardized procedures are lacking, affecting long-term performance. Addressing moisture-related issues remains a challenge. Tools for comparing 3DCP costs and benefits are needed.

Le et al. 2012 [41]focuses on the hardened properties of HPPC when extruded through a 9 mm diameter nozzle for layer-by-layer construction of structural components. The study is situated within the broader context of additive manufacturing in construction, which offers the potential to create architectural and structural components without traditional formwork. It highlights the evolution of concrete printing and the need for specialized concrete with suitable properties for the printing process. The printed concrete showed indicating a better quality of the material with fewer defects. These findings underscore the potential of HPPC in 3D printing applications, demonstrating that the material can maintain its high-performance characteristics even after being subjected to the printing process.

Alghamdi et al. 2019[42] get into the broader context of sustainable building materials, particularly focusing on the synthesis of geopolymeric foams. It builds upon prior research on geopolymer technology and 3D printing, highlighting the need for materials that offer both structural integrity and thermal efficiency. The authors successfully synthesized 3D-printable geopolymeric foams, which are shown to be suitable for building thermally efficient envelopes. The foams demonstrated significant potential in thermal insulation, which is critical for energy conservation in buildings. The study characterized the mechanical and physical properties of the foams, ensuring they meet the requirements for construction applications.

Han et al. 2021 [43]provides a comprehensive life-cycle environmental assessment of 3D printed structures using recycled concrete, highlighting the potential for significant reductions in carbon footprint. An economic analysis reveals that incorporating recycled concrete in 3D printed buildings can lead to cost savings without compromising structural integrity. The findings support the notion that 3D printing with recycled materials can contribute to more sustainable construction practices.

Chen et al. 2022 [44]tested the Printing Open Time of printable cementitious mixes made of limestone-calcined clay by printing several concrete filaments of 80 cm length and 4 cm width with a 10 min interval. The extrusion rate and the nozzle speed were constant, and the concrete was pre-sheared before pumping to remove any structure. The moment when the concrete filaments began to rip after printing marked the end of the Printing Open Time.

Setayesh Gar et al. 2017,[45]0.62% of bagasse burnt can be turned to ash, where an approximate yearly production of sugarcane bagasse as 11.42 MT.[46] It is been noted that 3 tonnes of bagasse can be generated from every 10 tonnes of sugarcane, broadly after the milling process.

Testing Methods for flowability

We review some of tests, namely the Flow Table Test, Squeeze Flow Test, V-Funnel Test, and Slump Flow Test, drawing insights from the following referenced papers:

Toutou et al. (2005) [47]: Introduces the squeezing test as a tool to evaluate extrusion ability in cement-based materials. While not specific to 3DCP, this test could be adapted or combined with other tests to assess fresh properties in the context of 3DCP.

Laskar (2009) [48]: Although not specifically focused on 3D concrete printing, Laskar's work correlating slump, slump flow, vebe, and flow tests to rheological parameters of high-performance concrete may offer valuable insights into the relevance and interpretation of slump flow test results in the context of concrete workability.

Paul, van Zijl, Tan, Gibson (2016)[22] [49]: In their review of 3D concrete printing systems and materials properties, Paul et al. may discuss the importance of workability assessment methods such as the slump flow test. Understanding the flow behavior of printing materials is crucial for achieving accurate deposition and structural integrity in printed components.

Paul et al. (2016)[50]: This review paper provides an overview of 3DCP systems and materials properties. While not specifically addressing fresh properties testing methods, it emphasizes the importance of material workability and flowability, which are parameters often assessed through the mentioned tests.

Ma, Li, Wang (2018)[51]: While the primary focus may not be on the slump flow test specifically, it likely includes assessments of material workability, which could be indicative of slump flow characteristics.

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Paul, Tay, Panda, Tan (2018): Investigates the fresh and hardened properties of 3D printable cementitious materials for building and construction. This study may include assessments of workability using the slump flow test, providing insights into the flow behaviour of printing materials.[50]

Tay et al. (2019) [21,22]: Explores the printability region for 3DCP using the Slump and Slump Flow Test. This study directly addresses the relevance of these tests in evaluating the printability of concrete mixes, offering practical insights into their application.

Ozalp, Yilmaz (2020) [52]: Investigates the fresh and hardened properties of 3D high-strength printing concrete and its recent applications. While the focus may not be solely on slump flow testing, this study may provide insights into how workability assessments, including the slump flow test, influence the performance of high-strength printing concrete.

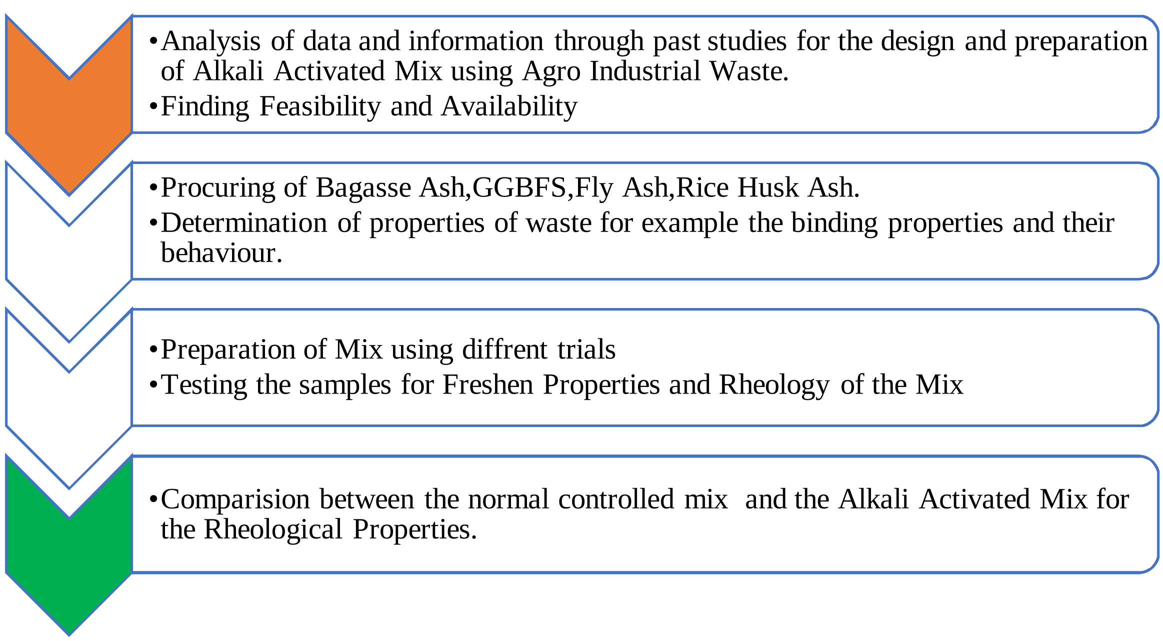
Tay, Qian, Tan (2019) [21]: This study explores the printability region for 3D concrete printing using the slump and slump flow test. The authors likely discuss how variations in slump flow characteristics affect the printability of concrete mixes, providing practical guidance for optimizing printing parameters.

## IV. GAPS IN LITERATURE REVIEW

These gaps represent areas where limited or insufficient information is available:

1) The previous studies have not emphasis much on the effect of vibration on the workability and mechanical properties of 3D printed concrete.
2) The optimal vibration frequency and amplitude for different concrete mixtures and nozzle sizes may allow the use of coarse aggregate in printing mortar, but available studies are very limited.
3) The Implication of Researches studied that the Agro-Industrial waste can be tailored for 3D printing by adjusting formulation parameters. Further research should explore optimization mix strategies for enhanced Rheological properties.
4) No consideration has been given to the 3DCP with building design for user comfort.
5) No standardization or IS codes are available till date.
6) The long-term durability and performance of 3D printed concrete structures under various environmental conditions are still to be investigated.
7) The previous literatures have been mostly measured the rheological properties without feeding the concrete in the 3D concrete printer. However, concrete is subjected to excessive shearing when pumped through a pipe to the nozzle of the printer, and this process changes the concrete rheology
8) More research is required to establish the tests required to determine the printability of the material for benchmarking.

## V. RESEARCH METHODOLOGY



## VI. EXPECTED OUTCOMES

The expected outcomes from this study are as follows:

1) Development of mix proportions of alkali activated concrete for 3d concrete printing material by utilizing Agro-Industrial waste by variation of composition.
2) Variation in the Rheological Properties of material before feeding and after extrusion from the printer.
3) An Insensitive and Onsite applicable method to test static yield stress, dynamic yield stress and plastic viscosity using vane shear apparatus.
4) The Buildability, Rheological Properties (viscosity, yield stress and thixotropy), Workability, Green Strength, Open Time and Hydration Heat of the fresh 3D Printing Concrete been systematically investigated.
5) Comparison of rheological properties of Controlled Mix and Alkali Activated 3DCP material.

## VII. CONCLUSION

Following conclusions has been derived after reviewing various research works:

1) The literature review highlights the advancement in construction industry from conventional to 3DCP. The use of agro-industrial wate can improve the fresh properties, durability, and environmental sustainability of 3D concrete printing. However, further research is required to optimize the dosage and understand the long-term performance of Agro-Industrial waste based printable concrete under different environmental conditions.
2) In majority of the literatures, the cementitious material is replaced partially. The main purpose of partial replacement of cementitious material is to cut down the carbon emission incurred during the manufacturing of cement. As per the different researches, 1 Ton of carbon emission occur for production of equal amount of cement.
3) We can not just replace the cement but can make its percentage to zero in 3DCP material mix by Alkali activation different Agro-Industrial based binder. It performs better than regular concrete in case of chemical attack , encouraged low-cost infrastructure and it is a step towards the sustainability as it help to utilize the Agro-industrial waste.

## VIII. FUTURE SCOPE

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

Optimization of Agro-Industrial Waste Mixtures: Investigate different combinations of agro-industrial waste materials (such as rice husk ash, sugarcane bagasse ash, etc.) to determine the most effective blend for 3D printable concrete. Consider variations in particle size, proportions, and curing conditions.

Rheological Studies: Conduct in-depth rheological studies to understand the flow behaviour, viscosity, and workability of the fresh 3D printable concrete mix. Explore additives or admixtures that enhance printability without compromising mechanical properties.

Printability Assessment: Evaluate the printability of the developed concrete mix using various 3D printing techniques (extrusion-based, powder-based, etc.). Investigate factors like layer bonding, surface finish, and dimensional accuracy.

Mechanical Properties Characterization: Extend the study to assess the mechanical properties (compressive strength, flexural strength, etc.) of the 3D printed concrete. Compare these properties with conventional concrete and identify areas for improvement.

Durability Studies: Investigate the durability aspects of 3D printed concrete, including resistance to freeze-thaw cycles, sulphate attack, and carbonation. Explore surface treatments or coatings to enhance durability.

Sustainability Assessment: Perform a life cycle assessment (LCA) to quantify the environmental impact of using agro-industrial waste in 3D printable concrete. Consider factors such as embodied energy, greenhouse gas emissions, and resource depletion.

Real-World Applications: Explore practical applications of 3D printed concrete in construction. Collaborate with industry partners to implement prototypes in building components, infrastructure, or architectural elements.

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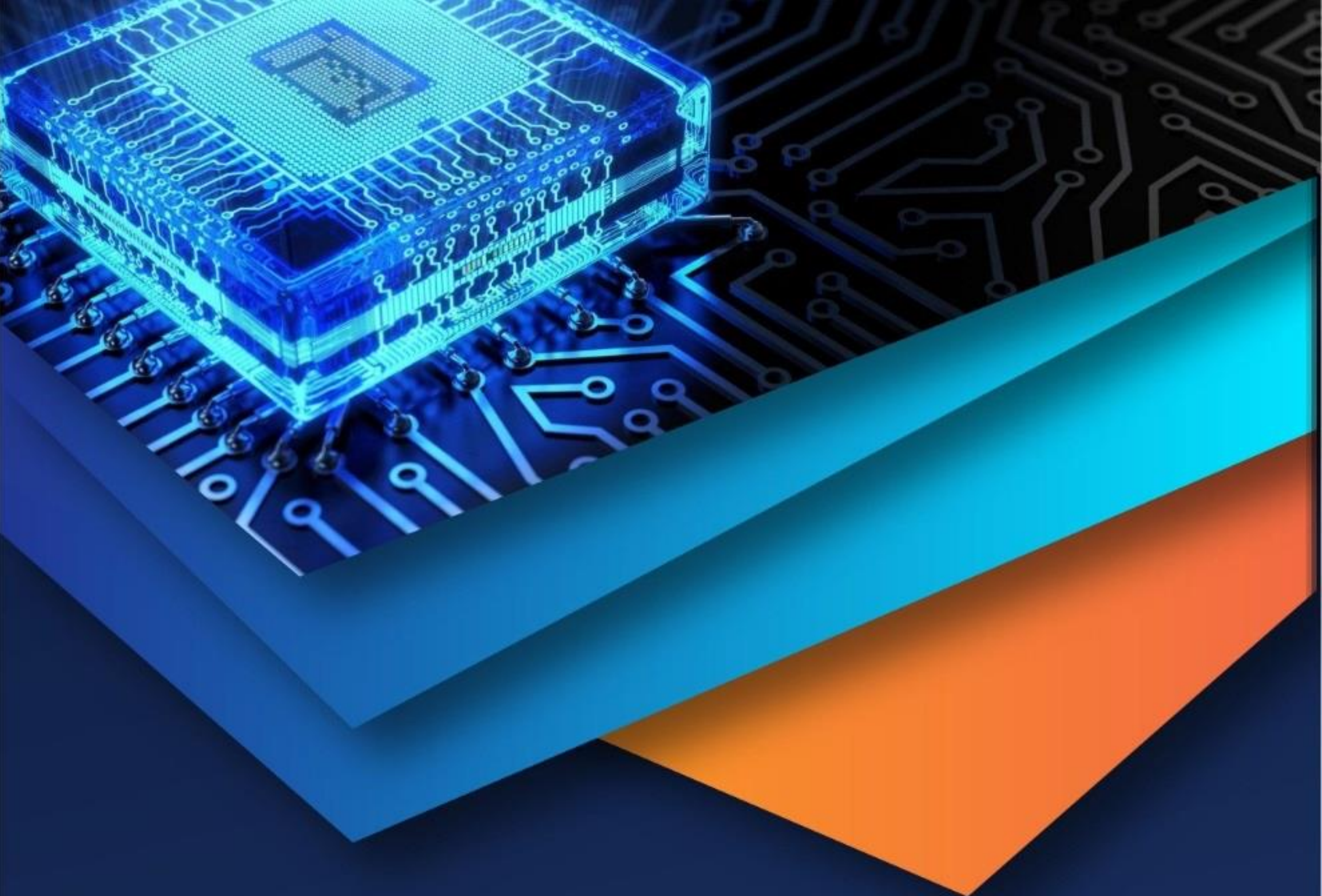


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