A Review on Finite Element Analysis of 3d Printed Geopolymer Hollow Bricks for Load Reduction and Strength Enhancement

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Abstract— **The construction industry is continuously seeking sustainable, lightweight, and high-strength building materials to reduce environmental impact and improve structural efficiency. Geopolymer concrete has emerged as an eco-friendly alternative to conventional cement-based materials due to its low carbon emissions and utilization of industrial by-products such as fly ash and slag. The present study proposes a comparative structural analysis of 3D printed geopolymer precast bricks with different hollow sections using ANSYS software. Various hollow geometries such as circular, square, rectangular sections will be modeled and analyzed to evaluate their structural behavior. The finite element analysis will be performed to determine deformation, stress distribution, strain, and load-carrying capacity under compressive loading conditions. The study aims to identify the most efficient hollow configuration that provides maximum strength with minimum self-weight. The reduction in material consumption and dead load due to hollow sections will also be evaluated. The results obtained from ANSYS analysis will help in understanding the feasibility of lightweight 3D printed geopolymer masonry units for sustainable and economical construction applications.**

Index Terms—**3D Printing, Geopolymer Brick, Hollow Brick, Finite Element Analysis (FEA), ANSYS Workbench.**

I. INTRODUCTION

The construction industry is one of the largest consumers of natural resources and energy worldwide. Rapid urbanization, population growth, and increasing infrastructure demands have significantly increased the consumption of conventional construction materials such as cement, concrete, and fired clay bricks. Although these materials have been extensively used for decades, their production processes contribute substantially to environmental degradation, carbon dioxide emissions, and depletion of natural resources. Consequently, researchers and engineers are actively exploring sustainable alternatives that can reduce environmental impacts while maintaining or improving structural performance.

In recent years, geopolymer technology has emerged as a promising solution for sustainable construction. Geopolymers are inorganic polymeric materials produced through the chemical activation of alumino-silicate-rich industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, and metakaolin. Unlike Ordinary Portland Cement (OPC), geopolymer materials require significantly lower energy during production and generate considerably less carbon dioxide emissions. Due to their excellent mechanical properties, durability, chemical resistance, and environmental benefits, geopolymer materials are increasingly being considered as replacements for conventional cement-based products.

Simultaneously, the construction sector has witnessed remarkable advancements in digital fabrication technologies, particularly three-dimensional (3D) printing. Construction 3D printing is transforming traditional manufacturing methods by enabling automated production of structural and non-structural components with high precision, reduced labor requirements, and minimal material wastage. This technology allows complex geometries and customized designs that are difficult to achieve through conventional manufacturing processes. The integration of geopolymer materials with 3D printing technology offers a highly sustainable and innovative approach for future construction practices.

A. Geopolymer Materials in Construction

Geopolymer materials are synthesized through the reaction of alumino-silicate source materials with alkaline activators. Common source materials include:

- Fly Ash
- Ground Granulated Blast Furnace Slag (GGBS)
- Metakaolin
- Silica Fume
- Rice Husk Ash

The geopolymerization process involves dissolution, transportation, and polymerization of silica and alumina compounds, resulting in the formation of a strong three-dimensional network structure.

The major advantages of geopolymer materials include:

- Reduced carbon dioxide emissions.
- High compressive strength.
- Excellent durability.
- Superior resistance to chemical attack.
- Improved fire resistance.
- Utilization of industrial waste products.
- Lower shrinkage and creep characteristics.

Due to these advantages, geopolymer materials are increasingly being used in precast elements, pavements, retaining structures, masonry blocks, and infrastructure

Table 1 Physical Material Properties of Geopolymer Concrete

Property	Value
Density	2350 kg/m³
Young's Modulus (E)	30000 MPa
Poisson's Ratio (ν)	0.22
Shear Modulus (G)	12295 MPa
Compressive Strength	45 MPa
Tensile Strength	4 MPa
Flexural Strength	6 MPa
Bulk Modulus (K)	17857 MPa
Thermal Expansion Coefficient	1.0×10^{-5} /°C
Thermal Conductivity	1.2 W/m·K

II. STATE OF DEVELOPMENT

The literature review is an important part of the present research because it provides the technical background required to understand the development of 3D printed geopolymer hollow bricks and their structural performance. The present study is based on three major areas, namely geopolymer materials, 3D printing technology in construction, and hollow masonry units analysed using finite element methods. Geopolymer concrete has been widely studied as a sustainable replacement for ordinary Portland cement concrete because it uses alumino-silicate industrial by-products such as fly ash, slag, and metakaolin. At the same time, 3D printing has introduced a new method of automated construction where complex shapes can be produced with minimum wastage and improved dimensional control.

Table 2 Literature Review

Sr. No.	Author(s) & Year	Findings
1	Rehman & Sglavo (2020)	Demonstrated successful 3D printing of geopolymer components with satisfactory mechanical performance.
2	Panda et al. (2017)	Identified printability, buildability, and interlayer bonding as key parameters in 3D concrete printing.
3	Buswell et al. (2018)	Highlighted the need for structural modelling and standardization in 3D printed construction.
4	Wangler et al. (2016)	Established the importance of rheology and shape retention in digital concrete fabrication.
5	Lim et al. (2012)	Demonstrated the feasibility of construction-scale additive manufacturing for complex structures.
6	Shekhar et al. (2016)	Found that activator composition significantly affects geopolymer rheology and workability.
7	Sanjayan et al. (2018)	Concluded that machine parameters and mix design jointly control printing quality.
8	Gosselin et al. (2016)	Successfully produced complex concrete elements using large-scale 3D printing technology.

9	Kazemian et al. (2017)	Developed testing methods for evaluating printable cementitious mixtures.
10	Bos et al. (2016)	Identified design freedom and material efficiency as major advantages of 3D printing.
11	Wolfs et al. (2018)	Showed that numerical modelling effectively predicts deformation and stability of printed elements.
12	Nerella et al. (2019)	Established extrudability as a critical property for successful digital construction.
13	Chougan et al. (2021)	Demonstrated that alkali-activated materials can achieve suitable printability and strength.
14	Barve et al. (2023)	Reported that geopolymer 3D printing offers significant sustainability benefits but requires further optimization.
15	Ricciotti et al. (2023)	Confirmed the suitability of geopolymer materials for extrusion-based 3D printing.
16	Shilar et al. (2023)	Highlighted the structural and environmental advantages of 3D printed geopolymer composites.
17	Şahin et al. (2023)	Found that chemical additives can effectively control setting time and early strength.
18	Amran et al. (2021)	Identified material optimization and structural validation as major challenges in 3D printing.
19	Almutairi et al. (2021)	Concluded that geopolymer concrete is a sustainable alternative to conventional concrete.
20	Matsimbe et al. (2022)	Reported that geopolymer properties strongly depend on raw materials and activator composition.
21	Luhar et al. (2020)	Demonstrated the potential of combining geopolymer technology with additive manufacturing.
22	Rahimpour et al. (2023)	Highlighted the environmental advantages of geopolymer-based 3D printing systems.
23	Zhang et al. (2021)	Emphasized the importance of mix design in achieving successful printable concrete.
24	Janardhanan et al. (2022)	Reported that material, process, and structural parameters collectively affect printing performance.
25	Rudziewicz et al. (2025)	Found that porosity significantly influences density, insulation, and strength of geopolymer materials.
26	Girskas et al. (2025)	Reviewed advancements in equipment, materials, and applications of 3D concrete printing.
27	Mishra (2025)	Identified durability, structural validation, and standardization as major research needs.
28	Becher et al. (2025)	Demonstrated the feasibility of additively manufactured geopolymers for civil engineering applications.
29	Li et al. (2026)	Optimized one-part alkali-activated concrete for improved extrusion and strength performance.
30	Kligys et al. (2026)	Reported that mineral additives significantly influence printability and mechanical properties.
31	Baral et al. (2026)	Highlighted sustainable construction benefits of 3D printed concrete and optimized geometries.

III. FINDING

The reviewed literature shows that geopolymer concrete is a sustainable construction material with good compressive strength, durability, fire resistance, and chemical resistance. Studies on geopolymer materials confirm that fly ash, slag, and metakaolin can be effectively used as alumino-silicate sources. The review also shows that 3D printing technology can reduce formwork, labour, construction time, and material wastage. For successful 3D printing, the material must have suitable rheological properties such as pumpability, extrudability, buildability, shape retention, and controlled setting time. Several researchers have emphasized that interlayer bonding and anisotropic behaviour are important concerns in printed concrete. Literature related to geopolymer 3D printing indicates that alkali-activated materials can be adapted for additive manufacturing, but more research is needed on structural performance and long-term durability. Studies on lightweight and porous geopolymer materials show that internal voids and porosity can reduce density and improve insulation, but they may also affect strength. Numerical modelling studies confirm that finite element analysis is useful for predicting deformation, stress concentration, strain distribution, and failure-prone regions in structural elements. Tthe literature supports the need for a detailed finite element investigation of 3D printed geopolymer hollow bricks with different hollow geometries.

IV. RESEARCH GAP

From the literature review, it is observed that many researchers have studied geopolymer concrete, 3D concrete printing, alkali-activated materials, and printable mix design. However, most of the available studies focus on material development, rheology, extrusion behaviour, and general printing technology. Very limited research has been carried out on 3D printed geopolymer masonry units, particularly hollow bricks. Existing studies on hollow masonry units mainly focus on conventional clay or cement blocks and do not consider geopolymer-based 3D printed materials. Further, limited work is available on comparing different hollow geometries such as circular, square, rectangular, and hexagonal openings in a standard brick size. The influence of hollow geometry on deformation, equivalent stress, strain distribution, load-carrying capacity, and weight reduction has not been sufficiently investigated. There is also a lack of ANSYS-based comparative finite element studies for optimizing the strength-to-weight ratio of 3D printed geopolymer hollow bricks. Therefore, the present study attempts to bridge this research gap by developing finite element models of geopolymer hollow bricks with different void shapes and evaluating their structural performance under compressive loading conditions. The study will help identify the most efficient hollow configuration suitable for lightweight, sustainable, and structurally efficient masonry construction.

REFERENCES

[1] U. Rehman and V. M. Sglavo, "3D printing of geopolymer-based concrete for building applications," *Rapid Prototyping Journal*, vol. 26, no. 10, 2020, doi: 10.1108/RPJ-09-2019-0244.

[2] K. Panda, M. J. Tan, and S. C. Paul, "Current challenges and future potential of 3D concrete printing," *Materials*, vol. 10, no. 9, 2017, doi: 10.3390/ma10091002.

[3] R. A. Buswell, W. Y. Leal de Silva, S. Z. Jones, and J. Dirrenberger, "3D printing using concrete extrusion: A roadmap for research," *Cement and Concrete Research*, vol. 112, pp. 37–49, 2018, doi: 10.1016/j.cemconres.2018.05.006.

[4] T. Wangler, N. Roussel, F. P. Bos, T. A. M. Salet, and R. J. Flatt, "Digital concrete: Opportunities and challenges," *RILEM Technical Letters*, vol. 1, pp. 67–75, 2016, doi: 10.21809/rilemtechlett.2016.16.

[5] S. Lim, R. A. Buswell, T. T. Le, S. A. Austin, A. G. F. Gibb, and T. Thorpe, "Developments in construction-scale additive manufacturing processes," *Automation in Construction*, vol. 21, pp. 262–268, 2012, doi: 10.1016/j.autcon.2011.06.010.

[6] S. Shekhar, S. Bishnoi, and M. Santhanam, "Influence of activator composition on the rheology of fly ash-based geopolymer pastes," *Cement and Concrete Composites*, vol. 73, pp. 196–207, 2016, doi: 10.1016/j.cemconcomp.2016.07.003.

[7] J. G. Sanjayan, B. Nematollahi, M. J. Tan, and B. Panda, "3D concrete printing: Machine and mix design," *International Journal of Advanced Manufacturing Technology*, vol. 95, pp. 1221–1232, 2018, doi: 10.1007/s00170-017-1216-8.

[8] Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger, and P. Morel, "Large-scale 3D printing of ultra-high-performance concrete: A new processing route for architects and builders," *Materials & Design*, vol. 100, pp. 102–109, 2016, doi: 10.1016/j.matdes.2016.03.097.

[9] Kazemian, X. Yuan, E. Cochran, and B. Khoshnevis, "Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture," *Construction and Building Materials*, vol. 145, pp. 639–647, 2017, doi: 10.1016/j.conbuildmat.2017.04.015.

[10] F. P. Bos, R. J. M. Wolfs, Z. Y. Ahmed, and T. A. M. Salet, "Additive manufacturing of concrete in construction: Potentials and

challenges of 3D concrete printing," *Virtual and Physical Prototyping*, vol. 11, no. 3, pp. 209–225, 2016, doi: 10.1080/17452759.2016.1209867.

[11] R. J. M. Wolfs, F. P. Bos, and T. A. M. Salet, "Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing," *Cement and Concrete Research*, vol. 106, pp. 103–116, 2018, doi: 10.1016/j.cemconres.2018.02.001.

[12] V. N. Nerella, M. Krause, V. Mechtcherine, *et al*., "Inline quantification of extrudability of cementitious materials for digital construction," *Cement and Concrete Composites*, vol. 95, pp. 260–270, 2019, doi: 10.1016/j.cemconcomp.2018.09.015.

[13] R. R. Chougan, S. Hamid, A. Ghaffar, *et al*., "Rheological and mechanical properties of 3D printable alkali-activated materials," *Construction and Building Materials*, vol. 272, Art. no. 121881, 2021, doi: 10.1016/j.conbuildmat.2020.121881.

[14] P. Barve, A. Bahrami, and S. Shah, "Geopolymer 3D printing: A comprehensive review on rheological and structural performance assessment, printing process parameters, and microstructure," *Frontiers in Materials*, vol. 10, 2023, doi: 10.3389/fmats.2023.1241869.

[15] L. Ricciotti, A. Apicella, V. Perrotta, and R. Aversa, "Geopolymer materials for extrusion-based 3D-printing: A review," *Polymers*, vol. 15, no. 24, 2023, doi: 10.3390/polym15244688.

[16] F. A. Shilar, S. V. Ganachari, V. B. Patil, B. E. Bhojaraja, T. M. Y. Khan, and N. Almakayeel, "A review of 3D printing of geopolymer composites for structural and functional applications," *Construction and Building Materials*, vol. 400, Art. no. 132869, 2023, doi: 10.1016/j.conbuildmat.2023.132869.

[17] H. G. Şahin, M. Y. Yardim, and A. E. Kurt, "Effect of borax, sucrose, and citric acid on the setting time and early strength of alkali-activated slag," *Materials*, vol. 16, no. 8, 2023, doi: 10.3390/ma16083010.

[18] M. Amran, R. Fediuk, N. Vatin, Y. Vasilev, G. Murali, and T. Ozbakkaloglu, "3D printing in construction: A systematic review of applications, materials, and challenges," *Buildings*, vol. 11, no. 9, 2021, doi: 10.3390/buildings11090398.

[19] Almutairi, B. A. Tayeh, A. Adesina, H. F. Isleem, and A. M. Zeyad, "Potential applications of geopolymer concrete in construction: A review," *Case Studies in Construction Materials*, vol. 15, Art. no. e00733, 2021, doi: 10.1016/j.cscm. 2021.e00733.

[20] J. Matsimbe, O. O. Ajayi, *et al*., "Geopolymer: A systematic review of methodologies," *Materials*, vol. 15, no. 19, 2022, doi: 10.3390/ma15196858.

[21] S. Luhar, S. Luhar, and I. B. Shaikh, "Additive manufacturing in the geopolymer construction technology: A review," *The Open Construction and Building Technology Journal*, vol. 14, pp. 150–170, 2020, doi: 10.2174/1874836802014010150.

[22] H. Rahimpour, N. Khatibinia, *et al*., "Geopolymer vs ordinary Portland cement: Review of the 3D printing construction technology," *Advances in Engineering Technology*, vol. 4, 2023.

[23] J. Zhang, G. Ma, *et al*., "Mixture design of 3D printable concrete: A review," *Cement and Concrete Composites*, vol. 122, Art. no. 104155, 2021, doi: 10.1016/j.cemconcomp.2021.104155.

[24] S. Janardhanan, V. N. Nerella, and V. Mechtcherine, "Extrusion-based 3D concrete printing: A review of material, process, and structural performance," *Construction and Building Materials*, vol. 343, Art. no. 128144, 2022, doi: 10.1016/j.conbuildmat.2022.128144.

[25] M. Rudziewicz, A. Łaźniewska-Piekarczyk, *et al*., "Comparison of porosity and thermal conductivity of geopolymer materials containing mineral and waste additives," *Materials*, vol. 18, no. 19, 2025, doi: 10.3390/ma18194498.

[26] G. Girskas, A. Šapalas, *et al*., "3D concrete printing review: Equipment, materials, mix design, and applications," *Buildings*, vol. 15, no. 12, 2025, doi: 10.3390/buildings15122049.

[27] J. Mishra, "Limitations and research priorities in 3D-printed geopolymer concrete,"

Sustainable Structures, vol. 8, no. 2, 2025, doi: 10.3390/susstruct8020047.

[28] F. Becher, M. Schneider, *et al*., “Shaping and characterization of additively manufactured geopolymers for civil engineering applications,” *Applied Sciences*, vol. 15, no. 7, 2025, doi: 10.3390/app15073449.

[29] H. Li, X. Zhang, *et al*., “Optimization of one-part alkali-activated concrete for extrusion-based three-dimensional concrete printing,” *Buildings*, vol. 16, no. 5, 2026, doi: 10.3390/buildings16051021.

[30] M. Kligys, R. Boris, *et al*., “Influence of the amount of mineral additive on the rheological and mechanical properties of printable concrete,” *Buildings*, vol. 16, no. 3, 2026, doi: 10.3390/buildings16030490.

[31] S. Baral, A. Kumar, *et al*., “Opportunities and challenges related to 3D printed concrete for sustainable construction,” *Buildings*, vol. 16, no. 12, 2026, doi: 10.3390/buildings16122300.

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