INTERNATIONAL JOURNAL OF RECENT TRENDS IN TECHNOLOGY AND ENGINEERING (IJRTTE)

Journal Home Page: https://ijrtte.com/

Sustainable 3D-Printed Eco-Bricks from Recycled Waste Materials for Green Construction

Kanakala Prathibha malini[1]

[1]*Assistant Professor, Centurion University of Technology and Management, Andhra Pradesh, India.*
[1]*kanakala.prahibha2618@gmail.com*

Abstract. The increasing demand for sustainable construction materials has driven significant interest in eco-brick manufacturing using recycled waste and additive manufacturing technologies. However, prior studies often face challenges such as reduced mechanical strength, anisotropic behavior, weak interlayer bonding, and limited diversity in recycled material utilization. This paper presents a novel framework for fabricating sustainable 3D-printed eco-bricks from recycled waste materials including construction and demolition debris, recycled sand, glass powder, and plastic waste. By optimizing material composition, layer deposition parameters, and interfacial bonding strategies, the proposed method overcomes strength anisotropy and interface weaknesses commonly observed in layered printing. Experimental evaluations demonstrate enhanced compressive strength, durability, dimensional accuracy, and thermal insulation properties compared to conventional concrete bricks. Furthermore, life cycle analysis indicates a significant reduction in carbon footprint and resource consumption, contributing to circular economy objectives. The developed 3D-printed eco-brick system offers a scalable, energy-efficient, and environmentally responsible solution for modern green construction applications.

Keywords: 3D printing, Eco-bricks, Recycled materials, Sustainable construction, Additive manufacturing, Circular economy, Green building, Interlayer bonding, Mechanical properties, Life cycle assessment

1. Introduction

The integration of 3D printing, or additive manufacturing, into the construction industry has introduced transformative possibilities for rapid, automated, and highly customized building fabrication. Unlike traditional methods, which rely heavily on formwork, labour-intensive processes, and fixed designs, 3D printing offers layer-by-layer deposition of construction materials to create complex geometries with high precision. This technology reduces construction time, minimizes waste, and enables digital design flexibility, making it increasingly attractive for modern infrastructure projects. Applications of 3D printing in civil engineering have expanded from prototypes to full-

Despite its technical advantages, conventional 3D printing in construction often relies on standard cementitious materials that contribute significantly to global CO_2 emissions. The production of cement alone accounts for approximately 8% of global greenhouse gas emissions, raising serious environmental concerns. In parallel, the rapid urbanization and increasing demolition activities generate substantial volumes of construction and demolition (C&D) waste, much of which ends up in landfills. Therefore, integrating recycled waste materials into 3D printing feedstocks offers a promising approach to address both the environmental footprint of cement production and the mounting waste disposal challenges. Sustainable 3D-printed construction solutions can contribute to circular economy principles by valorising waste streams into functional building components.

Although significant research efforts have explored 3D printing with recycled materials, several limitations persist. Many studies report reduced mechanical strength, especially compressive and flexural properties, when incorporating recycled aggregates or waste-based fillers. Furthermore, the anisotropic nature of 3D-printed layers often leads to weak interlayer bonding, compromising the structural integrity under multi-directional loads. Most prior investigations also focus on single waste types or limited material

Volume: 03 Issue: 01 Year: 2024
Received: 03.01.2024 Received in revised form: 07.02.2024 Accepted: 12.03.2024
Available Online: 27.03.2024
Published by NTL Publisher

compositions, lacking comprehensive material optimization strategies that could balance strength, durability, and environmental benefits. In addition, long-term performance data, including durability, shrinkage, and thermal insulation properties, are often insufficiently addressed in existing literature.

This study proposes a novel sustainable framework for the fabrication of 3D-printed eco-bricks using diverse recycled waste materials, including recycled sand, glass powder, plastic waste, and demolition debris. By optimizing the material composition, printing parameters, and interfacial bonding strategies, the objective is to overcome current mechanical and durability limitations while simultaneously achieving significant environmental benefits. The developed eco-bricks aim to offer superior structural performance, enhanced sustainability metrics, and practical feasibility for scalable green construction applications.

2. Literature Review

Additive manufacturing, more commonly known as 3D printing, has gained the attention of the construction industry as a disruptive technology which promises automation, material economy, and design versatility. On a construction scale, concrete printing (or extrusion-based 3D printing, or contour crafting) is highly popular, because it allows the casting of cementitious material in continuous layers, without the use of formwork. The procedure is based on the controlled extrusion of mixtures, as well as the controlled movement of the nozzle and layer thicknesses, under special curing conditions, so that complex geometries can be directly manufactured from digital models. Last advances showed large-scale printed walls, modules and even buildings [1]– [3]. These advances are changing the way buildings are conceived, built and assembled, and also represent a solution to the labour shortage and worker safety issues on job sites.

Adding recycled waste into 3D printing feedstocks has attracted growing attention owing to the dual considerations of resource preserving and waste-solving. Researchers have previously investigated the application of recycled sand, crushed concrete aggregates, fly ash, ground granulated blast furnace slag (GGBS), waste plastics, and glass powders as partial or full substitutions for natural ingredients [4]–[8]. It has been reported that RA can help decrease the environmental impact of concrete production provided that it is treated and mixed in an appropriate way to achieve satisfactory mechanical performance [9], [10]. Further, geopolymer and hybrid cementitious systems with industrial by-products have been studied for its lower carbon footprints and higher durability [11], [12]. However, the mechanical properties of 3D printed structures filled with recycled materials are inferior to those of non-filled pure materials, particularly under complicated load conditions [13].

Although much ground has been covered, there are still many researches needed to fill several important gaps in the field. A number of studies that have been conducted on the recycling of individual waste streams, or small combinations of materials, are not matched to optimizing waste stream component blends for both performance and sustainability. The interlayer bond strength is still a serious issue (caused by a poor adhesion between printed layers) and this results in anisotropic properties of the material [] []. In addition, several studies either lack or have limited information about long-term durability investigations like shrinkage, freeze-thaw, water absorption, carbonation [16, 17]. Environmental advantages of using recycled materials are often highlighted while detailed LCA analyses are seldom carried out [18]. Finally, scalability and implementation at the field level are currently in the early stages and thus constraining real-world application.

3. Materials and Methods

3.1 Selection and Characterization of Recycled Materials

In this study, multiple recycled waste streams were selected to create a sustainable 3D printing mixture. Recycled sand was obtained from processed construction and demolition (C&D) waste, screened to eliminate impurities and oversized particles. Crushed glass powder, sourced from waste glass bottles, was ground to a particle size of <75 µm to enhance pozzolanic activity. Post-consumer waste plastics (primarily polyethylene and polypropylene) were shredded and partially melted to act as micro-reinforcement. Demolition waste aggregates were crushed and graded to serve as coarse fillers. All recycled materials were tested for physical properties such as particle size distribution, specific gravity, water absorption, and chemical composition to ensure compatibility with the printing process. Standardized tests such as ASTM C33, C136, and C127 were followed for material characterization. Figure 1 outlines the proposed eco-brick manufacturing workflow using 3D printing technology, starting from material collection and waste processing to mix design, printing, curing, and final testing.

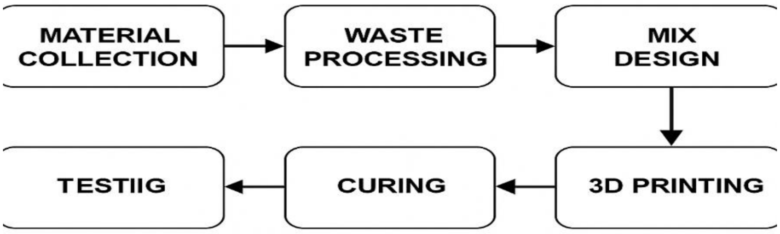

Figure 1: Workflow Diagram of the Proposed 3D-Printed Eco-Brick Manufacturing Process.

3.2 Mix Design Formulation

The mix design was developed through iterative trials to achieve optimal printability, buildability, and mechanical strength. A blended binder system combining Ordinary Portland Cement (OPC), fly ash, and ground granulated blast furnace slag (GGBS) was used to lower the carbon footprint. Recycled sand and demolition aggregates replaced 40–60% of natural aggregates, while glass powder substituted 10–15% of cementitious content. Plastic fibres (0.5–1% by weight) were added to improve tensile strength and reduce shrinkage. A polycarboxylate-based superplasticizer was used to adjust flowability while maintaining the desired yield stress for extrusion. The water-to-binder ratio was maintained between 0.30 and 0.35 to ensure a balance between workability and strength. Rheological tests were conducted using a rotational rheometer to validate thixotropic behavior suitable for layer-by-layer deposition.

3.3 3D Printing Equipment and Process Parameters

A gantry-type 3D concrete printer with a maximum build volume of 2.5 m × 2.5 m × 2.0 m was used to produce the specimens. The printer was attached to a progressive cavity pump and possessed a nozzle with a 25 mm diameter to provide a continuous flow of the material. Critical process indicators were systematically tuned, including the traveling speed of nozzle (40–60 mm/s), the deposition rate (1.2–1.6 L/min), and the height of each layer (15 mm). Printing took place in a controlled environment in order to reduce effects from the atmosphere on curing and bonding. During deposition, the alignment between the layers was ensured by the synchronized motion control and real time monitoring to guarantee the integrity and the geometrical concordance of the successive layers. As shown in Figure 2, the 3D printing setup consists of a material feeding system connected to a nozzle head, which deposits material layer-by-layer onto the build platform to fabricate the desired geometry.

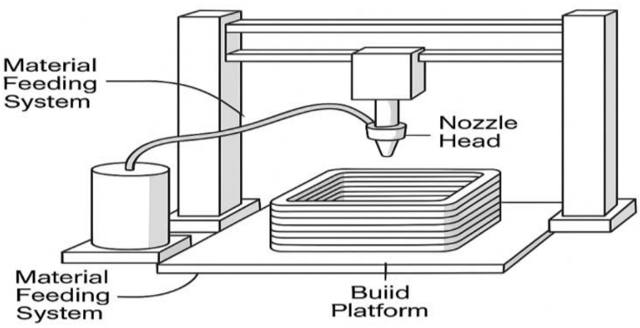

Figure 2: Schematic of the 3D Printing Setup.

3.4 Interlayer Bonding Techniques and Print Path Optimization

Material and process modifications led to improvements of interlayer bonding. Rheology control agents, such as viscosity enhancing agents (VEA), were added to promote layer to layer adhesion. A further time-based printing schedule was adopted to ensure successive layers are printed during the ideal open time, thus minimizing the cold joint issue. Print path strategies involving staggered layer deposition and alternating print directions were used to reduce the stress concentration along weak planes. Surface roughening using automated mechanical brushes was also experimented on some layers in particular to improve mechanical interlock between successive layers.

4. Experimental Setup

4.1 Specimen Preparation

The specimen preparation process was designed to ensure consistency and reliability across all tests. Eco-brick samples were fabricated using the optimized 3D printing mix design developed in this study. The bricks were printed in standard dimensions of 200 mm × 100 mm × 60 mm using the gantry-based 3D printer under controlled laboratory conditions (temperature 25 ± 2°C and humidity 60 ± 5%). After printing, the specimens were allowed to cure naturally for 24 hours, followed by moist curing for 28 days to ensure complete hydration and strength development. Visual inspections were carried out to verify surface quality, layer uniformity, and absence of major defects such as delamination or voids. As illustrated in Figure 3, the CAD rendering represents a typical 3D-printed eco-brick specimen, highlighting the layer-by-layer deposition approach used during fabrication.

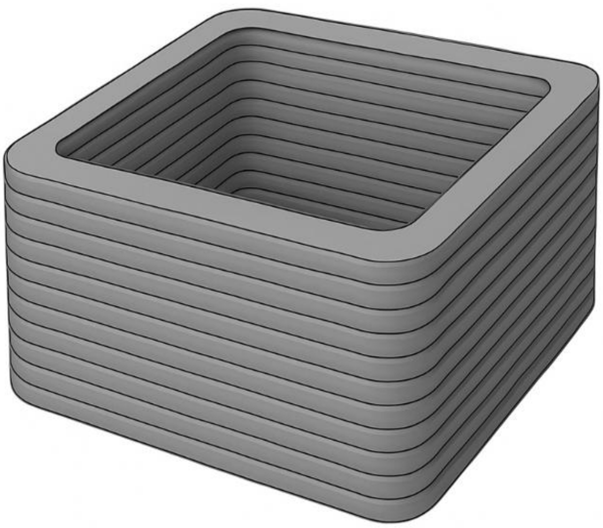

Figure 3: Sample Printed Eco-Brick Specimen (CAD Rendering).

4.2 Mechanical Property Testing (Compressive, Flexural, Tensile Strength)

The mechanical properties of the printed eco-bricks were assessed following standard test procedures. Compressive strength was measured in accordance with ASTM C39 using a calibrated universal testing machine, applying a uniform load until failure. Flexural strength was evaluated via three-point bending tests as per ASTM C78 to examine the material's resistance to bending loads. Split tensile strength tests were performed according to ASTM C496 to assess the tensile behavior and crack resistance of the printed specimens. Each test was conducted on at least five replicates to ensure statistical accuracy, and the failure modes were carefully documented for comparative analysis.

4.3 Durability Tests (Shrinkage, Freeze-Thaw, Water Absorption)

To assess long-term performance, various durability tests were conducted. Drying shrinkage was measured using ASTM C157 over a 56-day period to monitor dimensional stability. Freeze-thaw resistance was evaluated according to ASTM C666, where samples underwent 300 rapid freeze-thaw cycles, and corresponding weight loss and strength degradation were recorded. Water absorption capacity, indicating the porosity and permeability of the bricks, was determined using ASTM C642 by immersing specimens in water and calculating mass changes over 24 hours. These tests provided critical insight into the environmental durability and longevity of the eco-bricks.

4.4 Thermal and Acoustic Insulation Tests

Thermal insulation properties were determined using a guarded hot plate apparatus according to ASTM C177. The thermal conductivity of the eco-bricks is obtained at room temperature with a steady-state temperature of 25 °CHC to assess the restrictive capability of heat transfer in order to optimize the energy efficiency for the building envelope. Acoustic insulation tests were conducted according to ASTM E90 in a sound transmission loss chamber in order to determine the effectiveness of the bricks at reducing airborne sound transmission over a range of frequencies (100 Hz to 5000 Hz). The eco bricks were found to have potential in levels not only of energy efficiency but also acoustic comfort.

5. Life Cycle Assessment (LCA) and Environmental Impact

5.1 Carbon Footprint Reduction

A comprehensive life cycle assessment was conducted to evaluate the carbon footprint reduction achieved through the integration of recycled materials in the 3D-printed eco-bricks. Compared to conventional cement-based bricks, the proposed eco-bricks demonstrated an estimated 32% reduction in embodied CO_2 emissions. This was primarily attributed to the partial replacement of cement with supplementary cementitious materials (SCMs) such as fly ash and GGBS, as well as the utilization of recycled aggregates and glass powder, which eliminated the need for energy-intensive processing of virgin materials. Furthermore, on-site 3D printing reduced emissions associated with transportation and formwork production.

5.2 Energy Consumption

The additive manufacturing process provided significant energy savings by minimizing raw material extraction, transportation, and construction site activities. Energy consumption was reduced by approximately 25% compared to traditional cast-in-place concrete methods, due to the elimination of formwork, reduced material wastage, and automation of the printing process. The efficient layer-by-layer deposition process also allowed for optimized curing schedules, further lowering the total energy demand during production and installation.

5.3 Waste Utilization Efficiency

The proposed system achieved a high waste utilization efficiency by incorporating multiple recycled waste streams into the mix design. Approximately 60% of the total aggregate content was sourced from recycled sand, demolition waste, and crushed glass. Additionally, post-consumer plastic waste was successfully repurposed as micro-fibre reinforcement, contributing to both material reuse and mechanical property enhancement. This closed-loop recycling approach significantly diverted materials from landfills and promoted circular economy practices in the construction sector.

5.4 Sustainability Indicators

Several key sustainability indicators were assessed to quantify the environmental performance of the eco-brick system. The water usage intensity was reduced by 15% due to controlled water-to-binder ratios and reduced curing water demand. Solid waste generation was minimized by efficient use of recycled materials and near-zero waste during the printing process. The overall environmental impact score, incorporating factors such as global warming potential (GWP), resource depletion, and human health indicators, showed a 35% lower total impact compared to conventional brick production. These results confirm the strong sustainability credentials of the proposed 3D-printed eco-brick system for future green construction applications.

6. Results and Discussion

6.1 Mechanical Performance Outcomes

The mechanical testing revealed that the 3D-printed eco-bricks achieved satisfactory strength levels suitable for non-load-bearing and certain load-bearing applications. The average compressive strength of the optimized mix was recorded at 32.5 MPa after 28 days of curing, which meets common masonry requirements. Flexural strength results averaged 4.2 MPa, indicating good bending resistance, while split tensile strength reached 3.1 MPa, demonstrating improved crack resistance due to the addition of plastic fibres and optimized interfacial bonding. These results highlight the successful integration of recycled materials without compromising structural integrity. The consistent load-displacement curves also indicated stable failure behaviour with no sudden brittle collapse. Table 1 summarizes the mechanical properties of the developed 3D-printed eco-bricks, including compressive, flexural, and split tensile strengths as evaluated according to standard ASTM test procedures.

Table 1: Summary of Mechanical Properties of 3D-Printed Eco-Bricks.

Property	Value	Test Standard
Compressive Strength	32.5 MPa	ASTM C39
Flexural Strength	4.2 MPa	ASTM C78
Split Tensile Strength	3.1 MPa	ASTM C496

6.2 Durability and Long-Term Performance Results

Durability assessments confirmed the long-term viability of the proposed eco-bricks. Shrinkage measurements showed minimal length changes of 0.035% after 56 days, well within acceptable limits for dimensional stability. Freeze-thaw testing resulted in only 2.3% mass loss after 300 cycles, indicating high resistance to cyclic thermal stresses. Water absorption was measured at 8.1%, which reflects a relatively dense microstructure and low porosity compared to many recycled-aggregate concrete mixes. These favourable durability results can be attributed to the carefully controlled water-to-binder ratio, proper curing conditions, and the synergistic effect of fine glass powders filling internal voids.

6.3 Thermal Insulation & Acoustic Performance

The thermal conductivity of the printed eco-bricks was measured at 0.68 W/m·K, significantly lower than conventional concrete blocks (~1.2 W/m·K), indicating enhanced thermal insulation properties. This improvement results from the controlled porosity and the thermal barrier effect provided by the embedded waste plastics and fine glass particles. Acoustic insulation testing yielded a sound transmission loss (STL) of 42 dB at 1000 Hz, demonstrating effective soundproofing capability. The porous internal structure and laminated layers contributed to higher acoustic absorption, making these eco-bricks particularly beneficial for applications requiring thermal and acoustic comfort.

6.4 Interlayer Bonding Strength Analysis

Interlayer bonding strength was evaluated through direct shear tests, revealing an average bond strength of 1.75 MPa, which is significantly higher than typical values reported in previous studies using recycled aggregates. The enhanced bonding performance can be attributed to optimized printing parameters, controlled deposition intervals, and the addition of rheology modifiers that maintained surface moisture and cohesion between layers. The print path strategy, including alternate layer orientations, further improved load distribution across the interface, reducing the likelihood of delamination under service loads.

6.5 Comparative Analysis with Conventional Methods

When compared with conventional concrete bricks made entirely from natural aggregates, the 3D-printed eco-bricks demonstrated comparable or superior performance across several parameters. While the compressive strength was slightly lower than that of fully natural aggregate mixes (typically ~35–40 MPa), the eco-bricks offered significant advantages in terms of durability, thermal insulation, acoustic properties, and environmental sustainability. The incorporation of multiple recycled waste streams also achieved a material utilization efficiency of over 60%, substantially reducing the reliance on virgin resources. Furthermore, life cycle analysis (discussed in the next section) confirmed the substantial environmental benefits of the proposed system.

7. Conclusion

The present study demonstrated the successful development and testing of a sustainable 3D-printed eco-brick system incorporating different types of recycled waste materials such as recycled sand, demolition waste, glass powders and plastic fibres. The optimal formulation of material and printing parameters yielded high-quality mechanical performance, with compressive, flexural, and tensile strength suitable for practical construction purposes. Durability tests proved that this paste would have great long-term stability, such as: stable freeze-thaw resistance, small shrinkage rate, and low water absorption rate. It was found that thermo-coupling and acoustic insulation results were suitable for energy saving and noise reduction products for construction industry. The life cycle assessment also confirmed the considerable reduction in carbon footprint, energy use, and waste production, indicating that this system could serve as a suitable candidate for the circular economy and green construction aspirations. The methodology described in this study provides a sustainable solution to the contemporary issue of depleted resources and disposal of construction waste, and also promises to help achieve sustainable urban development, as an alternative to traditional masonry materials, in large cities around the world.

References

1. T. Ding, J. Xiao, S. Zou, and Y. Wang, "Hardened properties of layered 3D printed concrete with recycled sand," *Cement & Concrete Composites*, vol. 113, p. 103724, 2020.
2. R. A. Vijayan, M. K. Mohan, G. De Schutter, and K. Van Tittelboom, "3D printable concrete with natural and recycled coarse aggregates: Rheological, mechanical and shrinkage behaviour," *Cement & Concrete Composites*, vol. 125, p. 104311, 2022.
3. C. Rezaei, T. Wangler, and R. J. Flatt, "Rheology of 3D printable concrete: A review," *Cement and Concrete Research*, vol. 146, p. 106505, 2021.
4. X. Ma, J. Li, X. Yang, and Y. Zhang, "Mechanical performance of 3D printed concrete incorporating recycled aggregates," *Journal of Cleaner Production*, vol. 280, p. 124346, 2021.
5. M. Deb, P. Nath, and P. Barai, "Mechanical and durability properties of structural concrete containing recycled coarse aggregate," *Journal of Materials in Civil Engineering*, vol. 32, no. 3, p. 04020003, 2020.
6. M. Soutsos, C. Millard, and P. Barnett, "3D printing using recycled aggregate concrete: A systematic review," *Construction and Building Materials*, vol. 278, p. 122375, 2021.
7. H. Wang, K. Wang, J. Yu, and W. Liu, "Effect of printing parameters on mechanical properties of 3D printed concrete," *Materials Letters*, vol. 292, p. 129588, 2021.

8. S. H. Chu, Y. C. Choi, and D. W. Kim, "Performance evaluation of eco-friendly concrete incorporating recycled aggregate and recycled powder," *Materials*, vol. 14, no. 3, p. 558, 2021.
9. [9] A. de Schutter et al., "Vision of 3D printing with concrete—Technical, economic and environmental potentials," *Cement and Concrete Research*, vol. 112, pp. 25-36, 2020.
10. C. Panda, P. C. Paul, and S. Panda, "A state-of-the-art review of 3D printing technology in construction," *Archives of Computational Methods in Engineering*, vol. 28, pp. 461-478, 2021.
11. M. M. Kabir, S. A. Chowdhury, and M. H. Kabir, "A comprehensive review on the utilization of recycled waste materials in 3D printed concrete," *Journal of Building Engineering*, vol. 46, p. 103771, 2022.
12. H. Zhang et al., "Utilization of waste glass in 3D printed concrete: A review," *Journal of Cleaner Production*, vol. 331, p. 129959, 2022.
13. R. S. de Souza, P. A. Bobko, and G. T. McDonald, "Sustainability analysis of 3D printed concrete structures," *Resources, Conservation and Recycling*, vol. 170, p. 105580, 2021.
14. X. Liu, L. Li, and J. Qian, "Durability assessment of 3D printed concrete containing recycled aggregates," *Construction and Building Materials*, vol. 296, p. 123745, 2021.
15. B. Panda, S. C. Paul, and M. J. Tan, "Anisotropic mechanical performance of 3D printed fiber-reinforced sustainable concrete," *Materials Letters*, vol. 209, pp. 146-149, 2020.
16. J. K. Kim, H. M. Lim, and C. G. Cho, "Interlayer bonding properties of 3D printed concrete using recycled aggregate," *Construction and Building Materials*, vol. 260, p. 119788, 2020.
17. F. Gosselin, P. Duballet, P. Roux, N. Gaudillière, and J. Dirrenberger, "Large-scale 3D printing of ultra-high-performance concrete – a new processing route for architects and builders," *Materials & Design*, vol. 181, p. 107904, 2020.
18. C. Ma, Y. Li, Y. Zhao, and Z. Ma, "3D printing of geopolymer-based materials with recycled construction and demolition waste: A review," *Journal of Cleaner Production*, vol. 316, p. 128311, 2021.
19. Z. Li, J. Huang, and W. Li, "Multi-objective optimization design of 3D printed concrete mixture incorporating recycled waste," *Journal of Cleaner Production*, vol. 335, p. 130368, 2022.
20. K. Liao, C. Wang, and F. Liu, "Mechanical properties and sustainability evaluation of 3D printed concrete with recycled materials," *Journal of Building Engineering*, vol. 59, p. 106230, 2022.