INNOVATIVE 3-D PRINTING TECHNIQUES SHAPING THE FUTURE OF CONCRETE CONSTRUCTION

Udugula Praveen Goud and Dr. Prashant S. Lanjewar
Department of Civil Engineering, Dr. A.P.J. Abdul Kalam University, Indore (M.P.) - 452016, India
Corresponding Author Email : upraveengoud@gmail.com

Abstract:

This comprehensive study explores the transformative advancements in large-scale 3-D printing within the realm of concrete construction. Investigating the mechanical behavior and design considerations of 3-D printed structures, the research addresses challenges, proposes design perspectives, and provides structural insights. Mechanical characterization of 3-D printed elements reveals weaker and more porous interfaces, impacting axial compression, out-of-plane flexure, and shear. The study establishes design guidelines by drawing comparisons with traditional concrete structures. Additionally, it delves into the rheological model of cement paste, considering shear rate conditions and thermodynamics-based improvements. The research extends to a comparison between 3-D printed blocks and Autoclaved Aerated Concrete blocks, analyzing properties, costs, and environmental concerns. In conclusion, this study offers valuable insights for architects, engineers, and stakeholders in navigating the evolving landscape of large-scale 3-D printing in concrete construction.

Keywords:3-D Printing, Concrete Construction, Mechanical Characterization, Rheological Model, Sustainable Building Materials.

1. Introduction

The research on "Revolutionizing Concrete Construction: A Comprehensive Study on the Advancements of 3-D Printing" aims to explore the transformative potential of 3-D printing in the realm of concrete construction [1]. This investigation is driven by the imperative to understand and enhance the industrial applications of large-scale 3-D printing technology. In order to contextualize the study, the introductory sections delve into the historical evolution, current industry landscape, and the pressing need for industrialization within the field of 3-D printing in concrete construction [2].

1.1 Emergence of 3-D Printing in Concrete Construction

The emergence of 3-D printing in concrete construction represents a paradigm shift in the way structures are designed and built. This section provides a historical overview of the evolution of 3-D printing techniques, exploring key milestones and breakthroughs that have paved the way for innovative applications in construction. By understanding the trajectory of 3-D printing in concrete, the research sets the stage for evaluating its current state and potential future developments [13].

1.2 Current Industry Landscape

An integral aspect of this study involves assessing the current state of the industry in terms of 3-D printing in concrete construction. This section scrutinizes ongoing projects, technological advancements, and collaborative efforts within the construction sector [21]. By examining the existing landscape, the research seeks to identify areas of progress, challenges, and opportunities that will inform the subsequent investigations into large-scale 3-D printing for industrial applications.

1.3 Addressing the Need for Industrialization

In the pursuit of advancing 3-D printing in concrete construction, there is a critical need to address challenges hindering its widespread industrialization. This section explores specific obstacles and gaps in current practices, emphasizing the urgency of transitioning from experimental applications to large-scale, industrial adoption. By articulating the need for industrialization, the research establishes a clear rationale for its focus on large-scale 3-D printing technology and its potential impact on revolutionizing concrete construction [19].

2. Progression in Concrete 3-D Printing Technology

2.1 Historical Development:

The historical development of concrete 3-D printing provides a crucial backdrop to understanding the evolution of this innovative construction technology [20]. Beginning with the pioneering experiments and early applications, this section explores key milestones that have shaped the trajectory of concrete 3-D printing. Insights into the historical context enable a comprehensive grasp of the technological advancements achieved over time.

2.2 Technological Innovations and Breakthroughs:

This section delves into the cutting-edge technological innovations and breakthroughs that have propelled concrete 3-D printing into the forefront of modern construction methodologies. It examines advancements in printing techniques, material formulations, and the integration of automation [11,15]. By highlighting specific breakthroughs, the research aims to showcase the state-of-the-art technologies that contribute to the efficiency and precision of 3-D printing in concrete construction and setup of the printer is shown in Figure 2a and b.

2.3 Existing Challenges and Potential Solutions:

While concrete 3-D printing has witnessed remarkable progress, it is not without its challenges. This section critically assesses the existing challenges faced by the technology, such as structural limitations, material constraints, and scalability issues [4,8]. Moreover, it explores potential solutions and innovative strategies to address these challenges. By identifying areas requiring improvement, the research aims to contribute to the ongoing discourse on enhancing the reliability and applicability of 3-D printing in the concrete construction domain.

3. Research Objectives

1. To Enhance Predictive Capabilities for Large-Scale 3-D Printing
   - Evaluate water retentivity in cementitious materials to anticipate phase separation under high extrusion pressure in large 3-D printer systems. Utilize this knowledge to formulate mixes incorporating coarse aggregate, specifically tailored for optimal performance in large-scale 3-D printing.

2. To Investigate Material Properties and Performance:
   - Measure the compressive, flexural, and bond strength of 3-D printable concrete. Assess porosity in bulk and at interfaces between layers in 3-D printed specimens, drawing

comparative analyses with traditionally cast ones to gain insights into the material's structural characteristics.

4. Data Collection and Processing

4.1 Materials and Methods

In this study, various materials such as Portland cement, Class 'F' fly ash, and silica fume, along with additives like PCE-based superplasticizer and methylcellulose-based VMA, were meticulously selected. Polypropylene fibers and nano-clay were incorporated for specific enhancements. Fine aggregates, quartz dust, and two grades of quartz sand (sand 1 and sand 2) were also part of the material composition, each characterized by specific gravities and particle size distributions [9,17]. The mixing procedure involved a Hobart planetary mixer, with a sequential addition of water, superplasticizer, and dry ingredients. An additional step was introduced for mixtures with VMA. The lab-scale 3-D printer by Tvasta with specific specifications was employed for the study, showcasing its capabilities through the production of various printed elements. The printing process was described in detail, involving material loading, pumping, and extrusion through a rectangular nozzle [3]. All tests were conducted at a consistent extrusion speed of 44 mm/s. While the study acknowledged the influence of printing parameters on mixture design, it did not delve into specific investigations in this regard and shown in Figure 1.

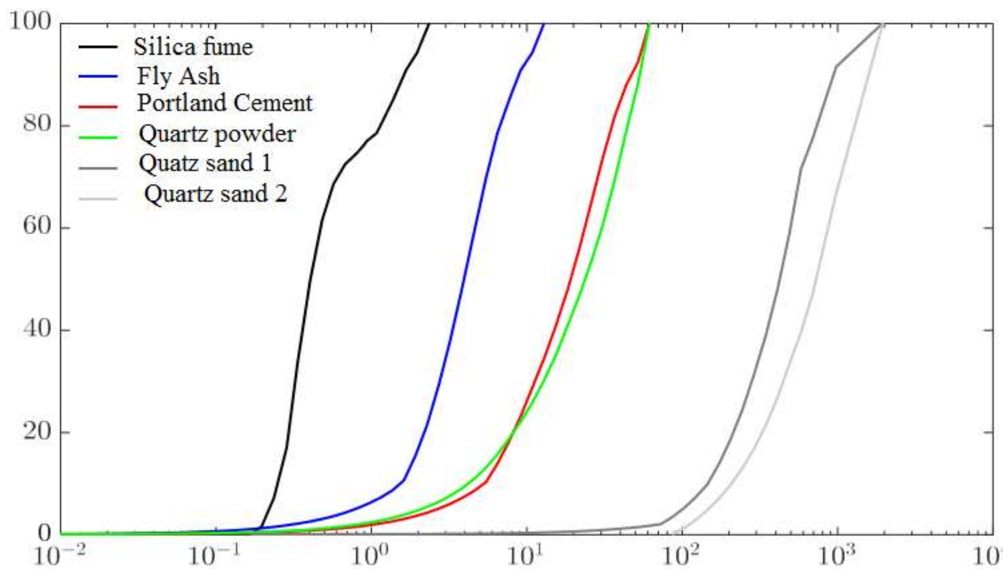

Fig.1: Depiction of Particle Size Distributions for Materials According to Grain Size Diameter (microns)

Fig.2: Printer Testing Setup and Printed Elements

4.2 Material Composition and Experimental Procedures

For the Extrudability Test, the study focuses on the consistent extrusion of a 30 cm sheet from a test bed printer, ensuring it meets dimensional criteria with good print quality [7]. The Yield Stress by Vane Shear Apparatus measures tension using a four-blade vehicle, calculating yield stress based on torque values [22]. The Buildability Test evaluates the structure of deposited layers, measuring compression after printing successive layers. The Robustness Test assesses reliability for industrial applications, introducing superplasticizer dosage variations. Lastly, the Flow Table Test determines the mixture's flow value according to ASTM standards [18]. The evaluation includes structural properties through intermittent shear tests, penetration tests, and semi-adiabatic calorimetry. Printing time is defined as the maximum time to pass the Extrudability Test, excluding mixing time.

4.3 Shear Rate Ramp-Up and Ramp-Down - Test and Model Prediction:

In the upper and lower tests, the shear rate of the cement paste gradually increased, maintained for a period, and then decreased to zero, investigating dichotropic behavior. During the test, torque exhibited a typical thixotropic pattern. Interestingly, torque advantage in the ascending part was lower due to a lack of rest time between test steps. In static shear tests, specimen rest allows microstructure recovery, yielding higher torque advantage, unlike the uplift test where shear stress prevents complete recovery [12]. The model captures dichotropic behavior, correlating structural parameters with shear rate and predicting torque changes. Model predictions align well with experimental data, showcasing its ability to capture time-dependent changes and the effect of continuous shear stress on microstructure.

4.4 Comprehensive Analysis and Cost Evaluation

This section navigates the complexities of formulating concrete mixes tailored for large-scale 3-D printing, emphasizing the evaluation of stability under heightened extrusion pressures. The introduction of an index to assess phase separation and the incorporation of coarse aggregates, particularly Light Expanded Clay Aggregate (LECA), expands the study's scope [6]. A pivotal role is played by the control mix, derived from a VM mixture initially developed with a small-scale 3-D printer. The control mix, featuring quartz sand 1, maintains a consistent water-cement ratio and polypropylene fiber dosage. Noteworthy variations encompass mixes with 15%, 30%, and 45% LECA as a substitution for fine aggregate [25]. The experimental procedure encompasses meticulous mixing using a pan-type mixer for large-scale 3-D printers, involving precise ingredient addition and specific mixing times. This comprehensive approach covers mixing procedures, desorptivity tests, assessments of workability loss, and density measurements [24]. Altogether, these elements provide a holistic overview of the experimental methodology, addressing the intricate nuances of concrete mix development for large-scale 3-D printing.

The large-scale 3-D printer, as showcased in Figure 3, plays a pivotal role in this study. Comprising a piston pump for extrusion, a material accumulator, and a 3-D printer with a nozzle assembly, this automated system enables the printing of mixtures containing coarse aggregates. With a printer bed size of 750 × 750 mm and a maximum height of 500 mm, it facilitates substantial-scale printing (refer Figure 4a and b). Extrudability tests involve extruding about 6 liters of material at a constant shear rate of 44 mm/s for 330 seconds, categorizing mixtures as "failed" or "passed" based on phase separation behaviour. Additionally, uniaxial compression tests assess buildability, emphasizing the elastic modulus for long, thin elements in large-scale additive manufacturing [26]. These tests, conducted with a Zwick Roell machine and a video extensometer system, provide valuable insights into the composite structure development and overall performance of the concrete mixes in the large-scale printing process [16].

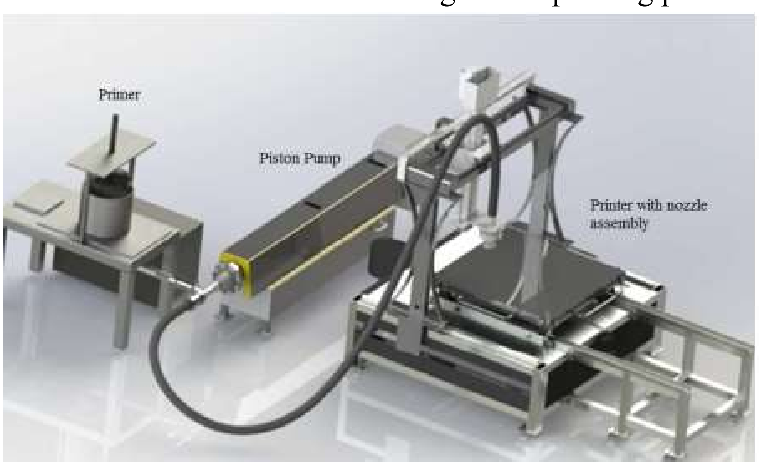

Fig.3: Illustrative Diagram of Various Components in the Large-scale 3-D Printing System

(a)

(b)

Fig.4: (a) Uniaxial Compression Test Setup with Video Extensometer System, (b) Gauge Point Detection in the Video Extensometer System

5. Data Analysis

5.1 Effect of methylcellulose on desorptivity

This data analysis section examines the influence of methylcellulose on sorptivity in large-scale 3-D printing mixtures, revealing an inverse correlation between methylcellulose content and desorptivity. Extrudability tests indicate that only the highest methylcellulose mixture (0.25%) successfully passed, showcasing the positive impact of methylcellulose in reducing phase separation [5]. The proposed index (Inorm) effectively distinguishes between "pass" and "fail" categories in extrudability tests, offering a promising method for assessing mixture stability. Transitioning to the AAC block analysis (see Figure 5 and 6), uniaxial compression tests provide insights into predicting plastic and buckling failures during 3-D printing, emphasizing the critical role of numerical modeling and experimental studies for accurate predictions in large-scale additive manufacturing where conducting extensive printing trials is challenging [19,20]. The results of flow table test and Stress-Displacement Curve for Control Mix at Various Ages is shown in Table 1 and Figure 7.

Fig.5: AAC Block Analysis

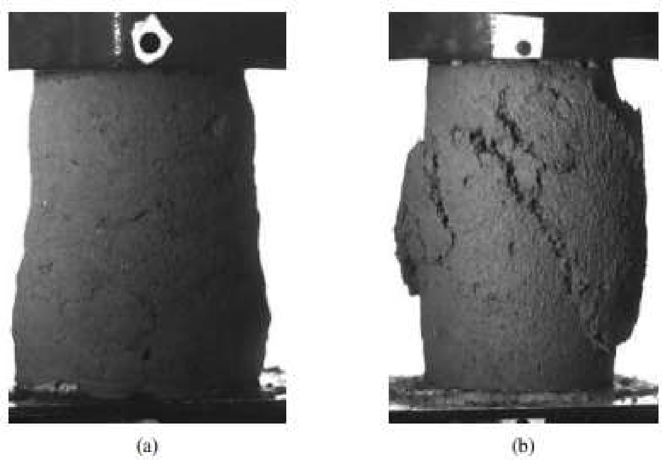

Fig.6: Failure Modes of Control Mix Specimen at Different Ages

Table 1: Results of flow table tests

Mix name	Initial flow value (cm)	Final flow vaue (cm)	Reduction in flow value (%)
Control	18.5	18.3	1.1
CA15	18.4	17.6	4.3
CA30	18.7	17.0	9.1
CA45	18.3	15.6	14.8

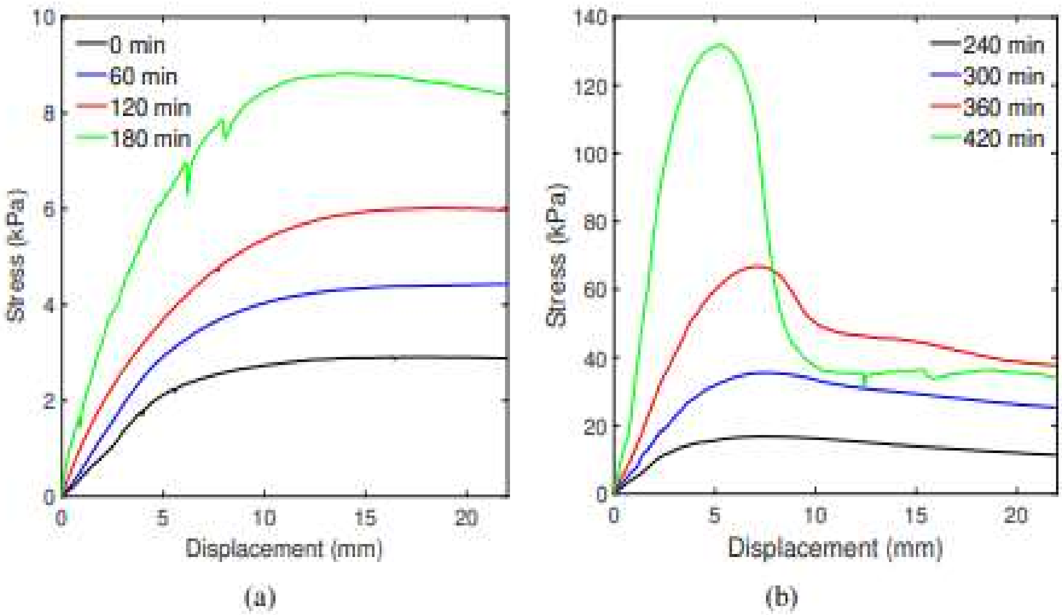

Fig.7: Stress-Displacement Curve for Control Mix at Various Ages: (a) 0 to 180 min and (b) 240 to 420 min

6. Results and Discussion

The study comprised two phases: firstly, examining the prestressed concrete interface, determining porosity, and conducting bond shear tests, and secondly, studying anisotropy in 3-D-printed wall prototypes. Mix formulations designed for small-scale testing were adapted for a larger nozzle size [6]. Concrete samples were subjected to various tests, including compressive and flexural strength, bond shear tests, and porosity assessments.Porosity at the interfaces of 3-D-printed elements was significantly higher than in monolithic cast concrete, leading to weaker interfaces. Bond shear strength reduction was observed between vertical and horizontal layers. Compressive strength of printed concrete was lower than cast concrete, attributed to weak interfaces and increased porosity. Flexural strength showed anisotropic behavior, with reductions along certain directions. The findings underscore the impact of interface properties on 3-D-printed concrete's mechanical characteristics [11].

The current challenge in utilizing 3-D-printed structures lies in the absence of standardized procedures for characterizing their mechanical behavior. Addressing this, the study proposes design perspectives for 3-D-printed walls based on mechanical test results, emphasizing the weaker and more porous interfaces between layers [8]. The design considerations parallel those for concrete walls with bed joints, accounting for axial compression, out-of-plane flexure, and in-plane and out-of-plane shear. Equations are provided for calculating axial compressive stress, bearing load, and flexural strength, considering the height-to-thickness ratio. The study highlights the importance of understanding post-cracking behaviour and suggests exploring reinforcement possibilities for bidirectional structural reliability. Additionally, a rheological model for cement paste using a thermodynamic framework is discussed, emphasizing the need for further improvements [21].

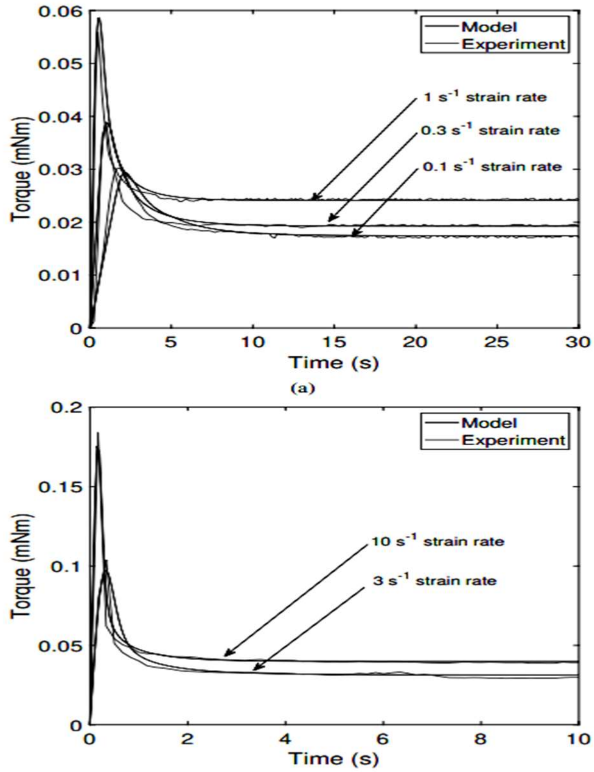

Fig.8: A Comparative Analysis of Torque Evolution at (a) 0.1, 0.3, and 1 s^{-1} and (b) 3 and 10 s^{-1}: Model Prediction versus Experimental Values.

The chapter concludes with a comprehensive analysis of 3-D-printed blocks and AAC blocks, detailing their properties, costs, and environmental considerations, providing valuable insights for construction decision-making. A Comparative Analysis of Torque Evolution is shown in Figure 8.

7. Conclusions

- **Water Retentivity and Phase Separation:** The study emphasizes the crucial role of water retentivity in controlling flow and extrudability during 3-D printing. This insight helps anticipate and prevent phase separation issues, optimizing concrete mix designs for enhanced reliability in large-scale 3-D printing.
- **Mechanical Characteristics and Porosity:** Mechanical characteristics and porosity are vital in ensuring 3-D-printed structures meet or exceed conventional building requirements. The research contributes to validating and optimizing 3-D printing technology, providing insights for its broader implementation in construction practices.
- **Continuum Mechanics and Thermodynamics Model:** The incorporation of a continuum mechanics and thermodynamics-based model enhances the accuracy and stability of printed layers. This modeling approach acts as a reliable tool for predicting and addressing issues related to layer deformation, advancing our understanding of the complex dynamics in 3-D printing.
- **Economic Viability:** The study comprehensively evaluates the financial aspects of block production using 3-D printing technology. Analyzing raw material costs,

production complexities, and environmental considerations, the research addresses sustainability issues, aligning with modern building industry practices.

- **Strategic Planning and Decision-Making:** The research supports strategic planning and informed decision-making for future building projects. Stakeholders gain a comprehensive understanding of the economic environment related to 3-D printing, enabling them to weigh benefits against drawbacks and make well-informed decisions considering long-term sustainability, efficiency gains, and project timelines.

References

1. Alami, A.H., Olabi, A.G., Ayoub, M., Aljaghoub, H., Alasad, S. and Abdelkareem, M.A., 2023. 3D Concrete Printing: Recent Progress, Applications, Challenges, and Role in Achieving Sustainable Development Goals. Buildings, 13(4), p.924.
2. Asprone, D., Auricchio, F., Menna, C. and Mercuri, V., 2018. 3D printing of reinforced concrete elements: Technology and design approach. Construction and Building Materials, 165, pp.218-231.
3. Baigarina, A., Shehab, E. and Ali, M.H., 2023. Construction 3D printing: a critical review and future research directions. Progress in Additive Manufacturing, pp.1-29.
4. Bedarf, P., Dutto, A., Zanini, M. and Dillenburger, B., 2021. Foam 3D printing for construction: A review of applications, materials, and processes. Automation in Construction, 130, p.103861.
5. Bischof, P., Mata-Falcon, J. and Kaufmann, W., 2022. Fostering innovative and sustainable mass-market construction using digital fabrication with concrete. Cement and Concrete Research, 161, p.106948.
6. Bos, F., Wolfs, R., Ahmed, Z. and Salet, T., 2016. Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. Virtual and physical prototyping, 11(3), pp.209-225.
7. Buswell, R.A., De Silva, W.L., Jones, S.Z. and Dirrenberger, J., 2018. 3D printing using concrete extrusion: A roadmap for research. Cement and Concrete Research, 112, pp.37-49.
8. De Schutter, G., Lesage, K., Mechtcherine, V., Nerella, V.N., Habert, G. and Agusti-Juan, I., 2018. Vision of 3D printing with concrete—Technical, economic and environmental potentials. Cement and Concrete Research, 112, pp.25-36.
9. Furet, B., Poullain, P. and Garnier, S., 2019. 3D printing for construction based on a complex wall of polymer-foam and concrete. Additive Manufacturing, 28, pp.58-64.
10. Ghaffar, S.H., Corker, J. and Fan, M., 2018. Additive manufacturing technology and its implementation in construction as an eco-innovative solution. Automation in construction, 93, pp.1-11.
11. Khan, M.A., 2020. Mix suitable for concrete 3D printing: A review. Materials today: proceedings, 32, pp.831-837.
12. Lee, Y.S., Kim, S. and Hischke, G., 2018. 3D printing in concrete materials and its applications. Int J Civil Struct Eng Res, 6, pp.187-195.

13. Lowke, D., Dini, E., Perrot, A., Weger, D., Gehlen, C. and Dillenburger, B., 2018. Particle-bed 3D printing in concrete construction–possibilities and challenges. Cement and concrete research, 112, pp.50-65.
14. Mai, I., Brohmann, L., Freund, N., Gantner, S., Kloft, H., Lowke, D. and Hack, N., 2021. Large particle 3D concrete printing—a green and viable solution. Materials, 14(20), p.6125.
15. Nguyen-Van, V., Li, S., Liu, J., Nguyen, K. and Tran, P., 2023. Modelling of 3D concrete printing process: A perspective on material and structural simulations. Additive Manufacturing, 61, p.103333.
16. Nguyen-Van, V., Panda, B., Zhang, G., Nguyen-Xuan, H. and Tran, P., 2021. Digital design computing and modelling for 3-D concrete printing. Automation in Construction, 123, p.103529.
17. Ning, X., Liu, T., Wu, C. and Wang, C., 2021. 3D printing in construction: current status, implementation hindrances, and development agenda. Advances in Civil Engineering, 2021, pp.1-12.
18. Oke, A.E., Atofarati, J.O. and Bello, S.F., 2022. Awareness of 3D printing for sustainable construction in an emerging economy. Construction Economics and Building, 22(2), pp.52-68.
19. Pan, Y., Zhang, Y., Zhang, D. and Song, Y., 2021. 3D printing in construction: state of the art and applications. The International Journal of Advanced Manufacturing Technology, 115(5-6), pp.1329-1348.
20. Raval, A.D. and Patel, C.G., 2020. Development, challenges and future outlook of 3d concrete printing technology. International Journal on Emerging Technologies, 11(2), pp.892-896.
21. Rollakanti, C.R. and Prasad, C.V.S.R., 2022. Applications, performance, challenges and current progress of 3D concrete printing technologies as the future of sustainable construction–A state of the art review. Materials Today: Proceedings, 65, pp.995-1000.
22. Sakin, M. and Kiroglu, Y.C., 2017. 3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM. Energy Procedia, 134, pp.702-711.
23. Salman, N.M., Ma, G., Ijaz, N. and Wang, L., 2021. Importance and potential of cellulosic materials and derivatives in extrusion-based 3D concrete printing (3DCP): Prospects and challenges. Construction and Building Materials, 291, p.123281.
24. Shakor, P., Nejadi, S., Paul, G. and Malek, S., 2019. Review of emerging additive manufacturing technologies in 3D printing of cementitious materials in the construction industry. Frontiers in Built Environment, 4, p.8
25. Tay, Y.W.D., Panda, B., Paul, S.C., Noor Mohamed, N.A., Tan, M.J. and Leong, K.F., 2017. 3D printing trends in building and construction industry: a review. Virtual and Physical Prototyping, 12(3), pp.261-276.
26. Xiao, J.Z., Liu, H.R., Ding, T. and Ma, G.W., 2021. 3D printed concrete components and structures: An overview. Sustain. Struct, 1(000006), pp.10-54113.