Construction Industry with 3D Printer: A New Era

Shivam Sharma, Soham Mitra, Adeyemi Adesina, and Sreekanta Das

1 Introduction

The concept of 3D printing started with the invention of stereolithography by Charles W. Hull of the USA in 1983. This technology, also known as rapid prototyping (RP), uses a photochemical process to polymerize synthetic resins, leading to a fast, precise, and repeatable production of elements with the help of computer support. Using this technology objects with very high precision and extremely complicated geometry can be built. Hence this technology found its use in various fields such as medicine and automotive industries [1]. The first commercially available 3D printing system, built using RP technology, known as SLA-1 was developed in 1987 [2].

The foundation for additive manufacturing using cement-based materials was laid through the work of Pegna [3]. This study used the techniques of depositing layers of reactive material over layers of the matrix material. Currently, the techniques used in large-scale concrete 3D printing are contour crafting, D-shape, and concrete printing [4]. The N2MBuild or the nano to meter build technique is used along with other concrete 3D printing techniques for building the utilities [5]. There has been a

S. Sharma · S. Mitra · A. Adesina · S. Das (✉)
University of Windsor, Windsor, ON, Canada
e-mail: sdas@uwindsor.ca

S. Sharma
e-mail: sharm189@uwindsor.ca

S. Mitra
e-mail: mitras@uwindsor.ca

A. Adesina
e-mail: adesina1@uwindsor.ca

S. Das
Department of Civil and Environmental Engineering, University of Windsor, 401 Sunset Avenue, Windsor, ON, Canada

D. K. Maiti et al. (eds.), *Recent Advances in Computational and Experimental Mechanics, Vol II*, Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-16-6490-8_26

huge growth in 3D concrete printing activities since its inception by Pegna in 1997. Figure 1 shows the growth in activities in 3D printing since 1997.

Contour crafting: Khoshnevis through his studies conducted during the period of 1998–2004 developed the contour crafting technique, in which a cement-based paste is continuously deposited in the form of layers and involves the use of a trowel to smoothen the printed material [7, 8]. The printing for this process is done using a gantry-based setup. This layer-by-layer method has the potential to render a paradigm shift, thus leading to a revolutionary change in the construction industry [9]. Moreover, contour crafting was chosen by NASA to explore its potential to build a swift and reliable lunar infrastructure [10]. Figure 2 shows the layer-by-layer contour crafting printing using a gantry-based system.

D-shape: The D-shape method, developed by Enrico Dini, was first exhibited in 2007 in London [12]. In this process, a 3D printer is used with sand as a building material.

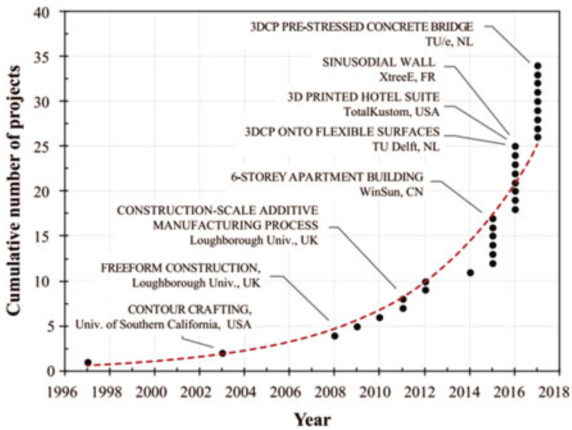

Fig. 1 Growth in projects involving 3D concrete printing [6]

Fig. 2 Contour crafting printing using a gantry-based system [11]

Fig. 3 Structure printed using the D-shape method [4]

It uses a stereolithography 3D printing process in which sand, a binder, is sprayed on the surface of each sequential layer, hardening the surface selectively. The process is repeated several times for the full structure to develop as per the digital model. Any material that is not glued by the binder is used as a support to the subsequent layers and can be removed from the printed structure using a vacuum cleaner. Thus, this method is beneficial to print complex structures that have overhangs and voids. This process like contour crafting uses a gantry for the printing process but the structures are printed off-site with much human intervention. Figure 3 shows an egg-shaped structure printed using the D-shape method.

Concrete printing: Concrete printing is also an off-site manufacturing process using a gantry system. This process, like the other two processes, is also based on the extrusion of cement mortar. But this process has more control over internal and external geometries. It uses a single deposition nozzle through which only the required material volume is deposited in the structure. The print resolution for concrete printing can vary from 4 to 6 mm. However, this layer-by-layer printing method introduces anisotropy to the structure and can cause a staircase—sausage-like—effect on the printed surface. This layering error—staircase effect—can substantially affect the quality of external surfaces. Furthermore, the deposition rate for this process is slower than that of the other two processes. Figure 4 shows a full-scale build using the concrete printing process [4].

N2MBuild: The N2MBuild or the nano to meter build was developed to reduce the number of raw materials, pollution, and energy consumption that is caused by traditional building technologies. This process utilized carbon dioxide to print the structures by extracting carbon dioxide from the atmosphere. Nanorobots, controlled

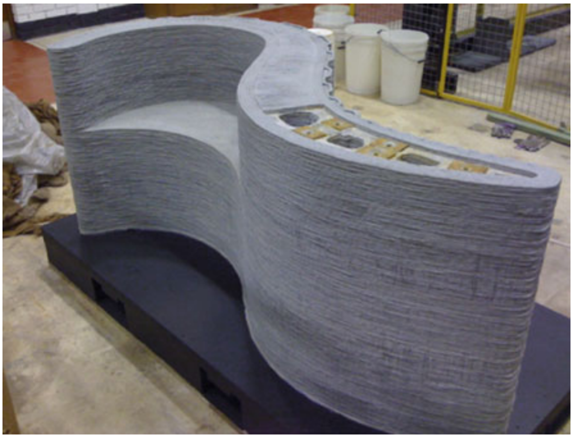

Fig. 4 A full-scale build using the concrete printing process [4]

and powered by light, are used for printing. Light of a particular wavelength is emitted by a projector, which uses a detailed 3D digital model as an input, from above the site. This is used mostly to print the utilities of a building such as pipelines, communication lines, etc. [5].

2 Critical Properties of Concrete Used in 3D Printing

It is not viable to use conventional concrete as a raw material for 3D printing due to its composition and fresh properties. Since 3D concrete printing is done without any supporting framework [4], the printed layers should be able to bear the weight of subsequent layers without a large deformation. Additionally, the material, in its fresh state, should be able to smoothly extrude through the pipes and the nozzles [13, 14]. Hence, concrete (cementitious material) used in 3D printing needs to be workable enough to pass through the printing nozzle and set as quickly as possible in order to have the capacity to support layers of the concrete. Buildability and flowability are also found to be crucial for 3D printing and have a certain mutual relationship [15]. Therefore, high-performance materials are required to obtain a high extent of control during the printing process [16]. The fresh and hardened properties of 3D concrete can be enhanced with the use of various mineral and chemical admixtures alongside additives such as fibres. The following sub-sections discuss various properties that are needed for 3D concrete printing.

2.1 Rheological Properties

The rheological properties of concrete are indicators that describe the fresh properties of concrete in terms of its flowability and deformation. To ensure proper 3D printing of concrete, the viscosity of the concrete must be low initially and increase significantly soon after it is extruded from the nozzle to be able to support the self-weight of the printed layers. Therefore, it is of utmost importance to have adequate control of rheological properties for smoother pumpability and the rapid setting of the concrete after it is extruded from the nozzle [17]. In the past, researchers have been able to influence the rheological properties of concrete by tailoring the mix designs using various methods. For instance, rheological parameters such as viscosity and yield stress can be significantly improved by increasing the coarse aggregate (CA) and fine aggregate content in the mix [18]. However, the size of coarse aggregates used must be small enough for easy printing of the concrete and preventing clogging of the printer. Chemical admixtures such as superplasticizer (SP) and viscosity modifying admixture (VMA) can also be used to improve the rheology properties. The SP can be used to increase the workability of the concrete mixture without any significant determinantal impact on the mechanical properties while the use of VMA will prevent possible segregation of bleeding of the concrete. Mineral admixtures such as fly ash and silica fume can also be incorporated as the binder component to improve the workability of the concrete. It is worth mentioning that majority of the mineral admixtures are wastes products from various industrial processes, hence, their use in concrete will improve the overall sustainability of the 3D printed concrete.

Another critical rheology property of concrete used in 3D printing is the setting time. The concrete used for 3D should be able to be set within a timeframe such that it is fluid enough to be printed and set fast before the next layer is printed. Hence, a shorter set times (i.e. initial and final) lower than that of the conventional concrete is required for the concrete to be used in 3D printing. The setting time can be controlled with the use of chemical admixtures such as accelerators which accelerates the hydration process.

2.2 Pumpability of Concrete

As the name implies, the pumpability of concrete for 3D printing is an indication of the ability to pump the concrete without any detrimental impact on the performance of the concrete and the 3D printer. Mobilizing the ability of concrete under pressure and keeping its initial properties unchanged is termed concrete pumpability [19]. The applied pressure, required to move the concrete through the pipes, causes some deformation in the concrete material in the direction of the applied force. Since fresh mortar gets deformed more easily than the coarse aggregate (CA), the deformation characteristic of the concrete significantly depends on the fresh mortar. Therefore, carefully tailored mix designs are required to optimize the rheological properties of the fresh concrete [20].

2.3 Extrudability of Concrete

The capability to steadily print concrete by passing it through pipes and nozzles of the 3D printer is referred to as extrudability. It has been reported that the particle sizes of the constituent materials used for the production of concrete significantly affect the corresponding extrudability for 3D printing. Segregation can be caused due to the high content of sand, therefore, it should be avoided [13, 14]. Zareiyan and Khoshnevis demonstrated a concrete mixture that can be extruded without a framework. In that study, to analyze the extrudability of the concrete, four key factors were considered, and these factors included bonding agents (cementitious and supplementary cementitious materials), water-cement ratio, fibres for reinforcement, and superplasticizers [21]. Generally, to improve the extrudability of concrete used in 3D printing, the components of the concrete should be made up of particles possessing spherical morphology instead of angular.

2.4 Buildability of Concrete

The buildability of concrete which is an indication of the capability of printed concrete to maintain its form during the printing process is essential to the overall performance of the 3D concrete. Shear strength of fresh concrete can be varied by varying the dosage of superplasticizer and ultimately resulting in optimum buildability [13, 14]. Apart from modifying the constituent material properties, buildability can be improved by changing the type of nozzle. For instance, making use of a rectangular or square nozzle instead of a circular nozzle can increase the contact area between the subsequent layers [22]. Le et al. found that the buildability of a given mix can be improved by increasing the number of adjacent filament layers [13, 14].

2.5 Mechanical Properties

Regardless of how concrete is produced; the mechanical properties are critical to its overall performance as it is an indication of the ability of the produced concrete to withstand various loads. A review by Paul et al. suggests that limited research has been conducted on the mechanical properties of 3D printed concrete [22]. Wolfs et al. did a recent experimental study on the effect of 3D concrete printing parameters (interlayer print-time, nozzle height, and surface dehydration) on the mechanical properties (compressive strength and tensile strength) [23]. Intriguingly, the study has exhibited the use of geotechnical (soil) tests to evaluate the properties of early age printed concrete, in the range of 0–90 min after deposition [24]. They posit Mohr–Coulomb theory as a satisfactory failure criterion for early age 3D printed concrete. Furthermore, it was found that cohesion varied linearly with time, and internal friction was independent of age. The study also concluded that Young's modulus, shear strength, and compressive strength were a linear function of time for a freshly printed concrete.

In a study conducted by Nerella et al., compressive and flexural strengths of printed concrete were found to be higher than the conventionally casted prism specimens produced from the same batch of mortar [25]. However, recent research at the Eindhoven University of Technology indicates that the compressive strength of printed specimens was about 31% lower than that of casted specimens [23]. It is interesting to note that the compressive strength of the printed material had no directional dependency. In contrast, Feng et al. have concluded that the loading direction and the size of the specimen influence mechanical properties like elastic modulus, strength, and Poisson's ratio [26]. Their research exhibited a higher compressive strength when the specimens were tested parallel to the layer depositions compared to when loaded perpendicular to the printed layers. Therefore, suggesting that 3D printed materials are orthotropic. The finite element analysis of a thin shell structure conducted by them also indicated the influence of the printing direction on the overall structural performance.

2.6 Inter-layer Bond Strength of 3D Printed Concrete

Weak inter-layer strength of printed concrete is regarded as one of the major challenges in the extrusion-based 3D printing method since there is a high possibility of flaws occurring in-between the extruded layers. Sanjayan et al. found that the moisture level at the surface of the printed layers significantly affects the inter-layer strength. The moisture level was further found to be a function of various parameters: the evaporation rate, the printing process, and the rate of the bleeding of the mixes [27].

The structural performance of 3D printed concrete is critically affected by the bond strength between the layers and it was found that the manufacturing process has a clear impact on this bond strength [23]. The bond between the substrate and overlay of the cast-in-mould concrete is influenced by several factors such as the moisture content and interface texture of the existing concrete surface [28]. However, in 3D concrete printing, the layers are in a fresh state and their inter-layer strength is majorly influenced by the adhesion between them. This adhesion further depends on the print-time between subsequent layers, which should be optimized in such a way that the delay time is long enough to let the extruded layers be strong enough to support the upper layers, but not that long to ensure proper bonding between the layers [13, 14, 27]. In the study carried out by Le et al., it was found that increasing the print-time between two layers led to weak tensile bond strength. Further, the study established a relationship between characteristic bond strength and print-time [13, 14].

3 Reinforcement in 3D Printed Concrete

As concrete is weak in tension, concrete structures require reinforcement for better structural performance. Current techniques of additive manufacturing of concrete do not cater to the ductility and tensile capacity of the structure since most of the approaches focus on the placement of concrete. In addition, the current solutions for automation in reinforcement are still rudimentary. Therefore, there is a need to resolve this recurring issue [29–31].

The 3D printing of fibre-reinforced geopolymer was studied, leading to an improvement in flexural and tensile strength [32]. However, the fibre content of up to only 1% was investigated to avoid clogging during the extrusion process. Hack and Lauer developed the Mesh Mould approach, where the first step is to print a corrugated framework of thermoplastic polymers. Then, concrete is poured over this framework, and finally, to achieve a smoother finish, the surface is troweled manually [32]. As polymers have low stiffness and to increase the functionality of this method, the study further enhanced the method by allowing the automation of metal reinforcement [33].

A reinforcement entrainment device has been developed at the Eindhoven University of Technology that can insert the steel reinforcement into the concrete filament before it is released from the nozzle. The beams printed with this device had a significant post-crack moment capacity [29, 30]. They further refined the method by establishing pull-out characteristics such as the bond strength and anchorage length of both the printed and the traditionally cast concrete. It was found that the bond strength of printed concrete was significantly lower than that of the traditionally cast concrete [29, 30].

Mechtcherine et al. developed a novel technique of 3D printing steel bars with geometric precision and freedom, using gas-metal arc welding. The printed steel bars exhibited a lower yield stress by 28% and a lower tensile strength by 16% than the conventionally used reinforcement rebars. Nonetheless, a ductile mode of failure was observed in the printed steel bars [31].

4 Structures Built Using Concrete 3D Printing Technology

In the recent past, many commercial structures have been build using 3D printing technology. The DFAB House in Switzerland is the world's first inhabited house, with a floor area of about 200 sq. meters, that was both digitally planned and built. This project was completed in 2019 by the professors at ETH Zurich in collaboration

Fig. 5 DFAB house in Switzerland [36]

with various industry partners. The project combined six new digital fabrication technologies in the building. These technologies are in situ fabricator, which is a mobile onsite construction robot equipped with sensing and feedback systems to operate autonomously in the construction sites in any environment; Mesh Mould, which is a formwork free fabrication process for the cast-in-situ concrete structures; Smart Slab, which is a prefabricated concrete slab introducing large-scale 3D sand print technology as formwork; Smart Dynamic Casting, which is an automated concrete slip-forming process, a process in which a reusable moving formwork is used, eliminating the need for disposable formwork; Spatial Timber Assemblies, which are robotic prefabrication processes for timber frame system and Lightweight translucent façade, which was developed to integrate the facade systems of the project. This project exemplifies the first inhabited house which is both digitally planned and digitally built [35]. The picture of the completed DFAB house is shown in Fig. 5.

The BOD which stands for "Building on Demand", built-in Denmark is Europe's first 3D printed house completed in 2017. This building has a floor area of about 50 sq. m. This project was designed by the construction company, COBOD. This building illustrates the economic and architectural advantage of applying 3D printing in construction. The entire building is 3D printed, including its foundations and does not contain any straight elements or reinforcements. This would be a challenge both technically and with respect to cost if using traditional construction practices for construction and hence demonstrates the effectiveness of 3D printing. The 3D rendering of this building is shown in Fig. 6 [37].

A 40-foot-long Pedestrian Bridge in Madrid, Spain built in 2016 using concrete 3D printing technology is one of the first 3D printed bridges in the world. The bridge was built in eight parts using fused concrete powder with micro-reinforced thermoplastic polypropylene. This bridge was designed by the Advanced Architecture Institute of Catalonia (IAAC) and constructed by the infrastructure and renewable energy

Fig. 6 3D rendering of BOD building, Denmark [37]

Fig. 7 Forty-foot-long 3D printed Pedestrian Bridge in Madrid, Spain [39]

corporation, ACCIONA with assistance from Enrico Dini, who is the inventor of D-shape [38]. The bridge was opened to the public in December 2016 [39]. A picture of the 3D printed bridge is shown in Fig. 7.

The largest concrete 3D building built to date is constructed by the robotic construction company, Apis Cor and this building was completed in 2019. This building is a two-story-high office building located in Dubai with a floor area of 640 sq. m and a height of about 9.5 m. The building was built at the site on a conventionally built foundation work without using any extra assembly works using a mobile 3D printer. The material used for the construction was a gypsum-based mixture developed by Apis Cor. and procured locally. For constructing the columns, the formworks were first built using 3D printing and the reinforcements were then added manually, and finally, the formwork was filled with concrete. The entire construction of the building was conducted in the open area. This proved that the printing technology was resilient to harsh environments [40]. A picture of the office building during its construction process is shown in Fig. 8. These structures took much less construction time to complete than the time required for the traditional construction method. These infrastructures demonstrate the potential of concrete 3D buildings in the construction industry as well as call for conducting more research on this area.

Fig. 8 Construction of 3D printed office in Dubai [40]

The robotic construction company, Apis Cor has also taken up projects in the USA for building affordable houses. One such project is in Santa Barbara County, California. Once completed this project will be the first 3-D printed affordable home in the USA.

5 Potential of 3DCP and Research Need

The advent of concrete 3D printing technology has paved the way and increased the feasibility of conducting more innovative research into various types of building constructions with various art effects and also research needed for suitable concrete or other green materials that can be adopted in 3D printing. 3D printing makes it possible to use different building materials and build components of various shapes and sizes without the requirement of any formwork or mould, which is one of the main hurdles to cast components of various shapes and sizes. The development and testing of components of various shapes and sizes using various building materials will help to establish the feasibility of these building materials in the construction industry, as well as it will help to optimize the use of materials and labour for future constructions. Since 3D printing technology does not generate any waste or very little waste in materials, the use of 3D concrete printing will prove a greener method of constructing buildings and other infrastructures.

Geopolymer which is a green alternative to Portland cement, engineered cementitious composites (ECC) which is a high-performance concrete, and rubber infused concrete which uses recycled tire materials are being developed, and performances of these materials are being evaluated. However, applications of these materials in construction have been limited or none. The availability of 3DCP will allow researchers to use these materials for making various building components and elements for determining the structural performance and durability properties. It is hoped that the research outcomes from these studies will open the door for the applications of these materials in large-scale constructions. Additionally, 3DCP will allow the construction of various curved shape buildings that could not be done using the traditional construction method. Since 3DCP allows a cheaper and faster way of constructing dwelling houses, it is believed that the housing problem in many developing countries like India, Brazil, Nigeria, Mexico, and Bangladesh can be resolved using 3DCP technology and these houses can be made even more affordable and sustainable if geopolymers or durable clay products instead of Portland cement is used in making concrete materials for 3D concrete printing. Availability of 3DCP and sustainable and cheaper concrete materials does have the potential to solve the housing problem of homeless problem currently faced by megacities of developed countries like Canada and the USA. Additionally, with further research on materials and structures using 3DCP, houses, hospitals for emergency, and disaster relief operations due to flood, earthquake, hurricane, and even due to incidents like COVID-19 can be built within a short period of time and at a very low cost.

6 Concluding Remarks

This study is important for the researchers who are interested in research and development in the emerging technology of 3DCP, as this paper provides the general trend of research development of 3DCP. The review of the development of 3DCP in the recent past and the various works completed to date using this technology show the potential of 3DCP in bringing a significant upgrade and overhaul in the traditional construction process as well as in developing alternate and efficient building materials and their applications. This technology, with its numerous advantages, can provide cost-effective housing solutions which can be beneficial to the developing nations as well as to the megacities of developed countries. Hence this technology has a huge potential and working towards realizing its full potential should be the way forward.

Acknowledgements This research was undertaken with the financial assistance of the Natural Sciences and Engineering Research Council of Canada (NSERC).

References

1. Moussion A (2014) Interview d'Alain Le Méhauté, l'un des pères de l'impression 3D. Primante 3D. http://www.primante3d.com/inventeur/. Accessed 2 Feb 2020
2. Uppalla S, Tadikamalla M. A review on 3D printing of concrete—the future of sustainable construction. I-Manager's J Civ Eng 7(3):49–62. https://doi.org/10.26634/jce.7.3.13610
3. Pegna J (1997) Exploratory investigation of solid freeform construction. Autom Constr 5(5):427–437
4. Lim S, Buswell RA, Le T, Austin SA, Gibb AGF, Thorpe T (2012) Developments in construction-scale additive manufacturing processes. Autom Constr 21:262–268. https://doi.org/10.1016/j.autcon.2011.06.010

5. Rebolj D, Fischer M, Endy D, Moore T, Šorgo A (2011) Can we grow buildings? Concepts and requirements for automated nano- to meter-scale building. Adv Eng Inform 25(2):390–398. https://doi.org/10.1016/j.aei.2010.08.006
6. Buswell RA, Leal De Silva WR, Jones SZ, Dirrenberger J (2018) Cement and concrete research 3D printing using concrete extrusion: a roadmap for research. Cem Concr Res 112:37–49. https://doi.org/10.1016/j.cemconres.2018.05.006
7. Khoshnevis B (1998) Innovative rapid prototyping process making large sized, smooth surface complex shapes in a wide variety of materials. Mater Technol 13(2):53–56. https://doi.org/10.1080/10667857.1998.11752766
8. Khoshnevis B (2004) Automated construction by contour crafting—related robotics and information technologies 13:5–19. https://doi.org/10.1016/j.autcon.2003.08.012
9. Hwang, Dooil, and Behrokh Khoshnevis. 2004. "Concrete Wall Fabrication by Contour Crafting." In International Symposium on Automation and Robotics in Construction, 2004 Proceedings of the 21st ISARC, Jeju, South Korea. https://doi.org/10.22260/ISARC2004/0057
10. Khoshnevis, B, Carlson A, Leach N, Thangavelu M (2012) Contour crafting simulation plan for lunar settlement infrastructure buildup. Thangavelu 2000:1458–67
11. Contour Crafting, Architecture computing design engineering industry technology https://www.hisour.com/contour-crafting-40687/. Accessed 12 Mar 2020
12. Dini E (2009) D-SHAPE—the 21st century revolution in building technology has a name. http://www.cadblog.pl/podcasty/luty_2012/d_shape_presentation.pdf. Accessed 25 June 2020
13. Le TT, Austin SA, Lim S, Buswell RA, Gibb AGF, Thorpe T (2012) Mix Design and fresh properties for high-performance printing concrete. Mater Struct J 45:1221–1232. https://doi.org/10.1617/s11527-012-9828-z
14. Le TT, Austin SA, Lim S, Buswell RA, Law R, Gibb AGF, Thorpe T (2012) Hardened properties of high-performance printing concrete. Cem Concr Res 42(3):558–566. https://doi.org/10.1016/j.cemconres.2011.12.003
15. Zhang Y, Zhang Y, Liu G, Yang Y, Wu M, Pang B (2018) Fresh properties of a novel 3D printing concrete ink. Constr Build Mater 174:263–71. https://doi.org/10.1016/j.conbuildmat.2018.04.115
16. Lim S, Buswell R, Le T, Wackrow R, Austin S, Gibb A, Thorpe T (2011) Development of a Viable Concrete Printing Process. In: Proceedings of the 28th international symposium on automation and robotics in construction, ISARC 2011. 29 Jun–2 Jul 2011, Seoul, South Korea, pp 665–670. https://doi.org/10.22260/ISARC2011/0124
17. Weng Y, Lu B, Jen Tan M, Qian S (2016) Rheology and printability of engineered cementitious composites-a literature review. In: Proc. of the 2nd intl. conf. on progress in additive manufacturing, 427–32. Singapore. 16–19 May 2016
18. Hu J, Wang K (2011) Effect of coarse aggregate characteristics on concrete rheology. Constr Build Mater 25(3):1196–1204. https://doi.org/10.1016/j.conbuildmat.2010.09.035
19. Jolin M, Burns D, Bissonnette B, Gagnon F, Bolduc L-S (2009) Understanding the pumpability of concrete. In: Shotcrete for underground support XI. Davos, Switzerland, June 7–10, 2009
20. Mechtcherine V, Nerella VN, Kasten K (2014) Testing pumpability of concrete using sliding pipe rheometer. Constr Build Mater 53:312–323. https://doi.org/10.1016/j.conbuildmat.2013.11.037
21. Zareiyan B, Khoshnevis B (2018) Effects of mixture ingredients on extrudability of concrete in contour crafting. Rapid Prototyping Journal 24(4):722–730. https://doi.org/10.1108/RPJ-01-2017-0006
22. Paul SC, Van Zijl GPAG, Tan MJ, Gibson I (2017) A review of 3D concrete printing systems and materials properties: current status and future research prospects, no. September 2016. https://doi.org/10.1108/RPJ-09-2016-0154
23. Wolfs RJM, Bos FP, Salet TAM (2019) Hardened properties of 3D printed concrete: the influence of process parameters on interlayer adhesion. Cem Concr Res 119(February):132–140. https://doi.org/10.1016/j.cemconres.2019.02.017
24. Wolfs RJM, Bos FP, Salet TAM (2018) Early age mechanical behaviour of 3d printed concrete: numerical modelling and experimental testing. Cem Concr Res 106(January):103–116. https://doi.org/10.1016/j.cemconres.2018.02.001

25. Nerella VN, Krause M, Nather M, Mechtcherine V (2016) Studying the printability of fresh concrete for formwork-free concrete onsite 3D printing technology (CONPrint3D). In: Proceeding for the 25th conference on rheology of building materials, pp 333–47. https://doi.org/10.1016/b978-0-12-815481-6.00016-6
26. Feng P, Meng X, Chen JF, Ye L (2015) Mechanical properties of structures 3D printed with cementitious powders. Constr Build Mater 93:486–497. https://doi.org/10.1016/j.conbuildmat.2015.05.132
27. Sanjayan JG, Nematollahi B, Xia M, Marchment T (2018) Effect of surface moisture on inter-layer strength of 3D printed concrete. Constr Build Mater 172:468–475. https://doi.org/10.1016/j.conbuildmat.2018.03.232
28. Beushausen H, Alexander MG (2008) Bond strength development between concretes of different ages. Mag Concr Res 60(1):65–74. https://doi.org/10.1680/macr.2007.00108
29. Bos, Freek P., Zeeshan Y. Ahmed, Evgeniy R. Jutinov, and Theo A.M. Salet. 2017. "Experimental Exploration of Metal Cable as Reinforcement in 3D Printed Concrete." Materials 10 (11). https://doi.org/10.3390/ma10111314.
30. Bos FP, Ahmed ZY, Wolfs RJM, Salet TAM (2017) 3D printing concrete with reinforcement. In: Proceedings of the 2017 fib symposium, Maastricht, The Netherlands, 12–14 June 2017. https://doi.org/10.1007/978-3-319-59471-2
31. Mechtcherine V, Grafe J, Nerella VN, Spaniol E, Hertel M, Füssel U (2018) 3D-printed steel reinforcement for digital concrete construction—manufacture, mechanical properties and bond behaviour. Constr Build Mater 179:125–137. https://doi.org/10.1016/j.conbuildmat.2018.05.202
32. Panda B, Paul SC, Tan MJ (2017) Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material. Mater Lett 209:146–149. https://doi.org/10.1016/j.matlet.2017.07.123
33. Hack N, Lauer WV (2014) Mesh-mould: robotically fabricated spatial meshes as reinforced concrete formwork. Archit Des. https://doi.org/10.1002/ad.1753
34. Hack N, Lauer W, Gramazio F, Kohler M (2015) Mesh mould: robotically fabricated metal meshes as concrete formwork and reinforcement. In: Proceedings of the 11th international symposium on ferrocement and 3rd ICTRC international conference on textile reinforced concrete, pp 1–13
35. Graser K, Wang Y, Hoffman M, Bonanomi MM, Kohler M, Hall DM (2019) Social network analysis of DFAB house: a demonstrator of digital fabrication in construction. In: 17th annual engineering project organization conference, edited by Paul Chinowsky and John Taylor. Proceedings of EPOC 2019. Vail, CO. http://hdl.handle.net/20.500.11850/388870
36. The digitally-built DFAB HOUSE by ETH zurich opens in switzerland, https://www.designboom.com/architecture/eth-zurich-dfab-house-dubendorf-switzerland-02-27-2019/. Accessed 12 July 2020
37. THE BOD: Europe's first 3D printed building. https://cobod.com/the-bod/. Accessed 12 Mar 2020
38. Koslow T (2020) The greatest 3D printed houses, buildings & constructions. https://all3dp.com/1/3d-printed-house-building-construction/. Accessed 4 Jan 2020
39. Madrid gets first 3D-printed pedestrian bridge, is 40-feet long and made up of 8 parts https://www.techeblog.com/madrid-gets-first-3d-printed-pedestrian-bridge-is-40-feet-long-and-made-up-of-8-parts/. Accessed 2 Feb 2020
40. Block, India. 2019 "World's largest 3D-printed building completes in Dubai" https://www.dezeen.com/2019/12/22/apis-cor-worlds-largest-3d-printed-building-dubai/. Accessed 12 Mar 2020
41. Affordable Housing: First 3-D printed affordable home in Santa Barbara County, California. https://www.apis-cor.com/affordable-housing. Accessed 23 July 2020