Digital Concrete for Sustainable Construction Industry: A State-of-the-Art Review

Chiranjeevi Rahul Rollakanti, C. Venkata Siva Rama Prasad, and Adams Joe

Abstract Recent research and industry have seen a great deal of digital production techniques with concrete and cemented materials, and the advanced techniques of industrialisation such as the 3D printing. 3D printing is an attention seeking technology in recent times, which in future years can have huge social and economic effects. The building industry and research projects around the world have focused on automatic construction systems. The possibility of revolutionising building is not only through cost reduction but also through enhanced sustainability and usefulness. There are major challenges, including understanding the early age hydration, and regulating the connection to rheology, the integration of strengthening and the overall connection between the processing, material and performance, both in structural and in terms of durability. This research article describes a state of the art 3D concrete printing with historical knowledge and progress with equipment, materials and computer modelling. This paper presents current progress, modern and up to date approach. It is essential to interdisciplinary action since the subject combines many different areas and is led thus far by areas such as architecture. The literature review examines the state of the art in the recent advancements of construction industry of digital concrete manufacture guiding the research difficulties so far.

Keywords Digital concrete · 3D concrete printing · 3D printers · Sustainable construction

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1 Introduction

Concrete is one of the world's widely utilised building construction materials, both in terms of volume and in application. The use of concrete gives a number of distinct advantages in building construction sector and also regarding various types of structures. The concrete is commonly used for its high strength, durability and fire resistance, amongst other things. The second argument is that concrete fundamental elements may be available practically everywhere around the world [1]. Moreover, concrete is a versatile material which enables architects to make fantastic use of their designs. The enormous manufacturing and use of concrete affects our ecology, which we have to fight with. Portland cement production techniques utilise considerable energy and emit a large quantity of greenhouse gases into the atmosphere. Concrete will continue to be in high demand as a key building material for a long time to come. In order to ensure that concrete remains a competitive building material in the future, the durability of concrete structures is vital for the long term. In the current building sector, there are major long-term viability issues. The majority of construction procedures and materials in use presently have detrimental consequences on the environment [2]. Much greenhouse gas is emitted and huge quantities of energy are consumed throughout the construction process, such as on-site production, material transportation, installation, assembly and on-site building.

Recent studies suggest that formwork occupies a significant proportion of total construction projects expenditure. This is indeed a regular practise for concrete construction throughout the world. Another problem to tackle is the huge volume of waste produced throughout the building process. Formwork is a key source of trash as it is abandoned at some stage in the building construction process and it increases waste generated in the construction sector as a whole [3]. It has been proven that the building industry is responsible for the world's bulk of overall waste, which is incredible. The general procedure of concrete casting inside the formwork has limited the freedom of engineers and architects to construct structures in numerous methods, unless extremely costly tailor-made forms are achieved for the project. Concrete building frequently comprises numerous operations, including in-site manufacture, transport and production, and every stage takes a large amount of time. Furthermore, in the current concrete building sector, there is a lot of work and safety difficulties. Most of the construction fatalities are falls from height [4]. In addition, the safety of workers in the local concrete industry is becoming a big concern. In particular, qualified work is required for the insertion and connection of the reinforcing operation and the construction in casting geometries. Workers' safety is continually endangered with accidents and injuries at work.

The labour and working staff shall be shifted to technology-oriented workforce. Hence, accidents, fatalities, injuries and loss of life might be minimised. In future, more capable and technologically aware workers will replace unskilled workers. This would greatly reduce deaths and serious injuries. As discussed above, construction time and labour can be reduced with concrete printing, as no formwork is required. With today's technology advent and substantial breakthroughs in the area of additive manufacturing, which is generally known as 3D Printing (3DP). This task automation of the construction sector is observed to be increased in the future ahead [5]. 3DP has different advantages over the typical concrete construction technology. 3DP is also an environmentally favourable and sustainable building technique. Accurate control of the production process and optimisation of the use of materials should limit building waste. As mentioned in several studies, 3DP is going to be a future trend in the construction field and it could lead to be a low-CO_2 way for producing concrete if properly implemented.

This technological application might open the way for shorter construction durations as well as for more distant locations to be created and designs to be adaptable, so that 3D concrete printing not only can be a novelty of technological developments but can also revolutionise the building industries. It also offers a number of other environmental advantages that are not available in traditional buildings [6]. A new study shows that construction materials and human needs could be considerably minimised if automated 3D press technologies are further refined to improve their efficiency compared to present building methods. Construction Industry and scholars worldwide have recently paid great attention to 3D concrete printing. The additive manufacturing technology is used to create 3D products that incorporate the construction of subsequent layers of material under computer supervision. Additive Manufacturing (AM) for the printing of a broad and sophisticated structure employing quick prototype procedures with acceptable mechanical and structural integrity has been developed and standardised. The use of additive concrete production seems to be a practical way to tackling the issues facing today's concrete industry. Compared to subtractive manufacturing techniques, additive production describes the process for connecting materials to build things of 3D model data. In the last three decades, commercial application of additive manufacture (AM) was also taken place in the areas of aerospace, medical research and other fields. Recent deployments of additive manufacturing technology in the building sector, namely contour crafts, D-shape and concrete printing, illustrate the promise that large-scale AM techniques will be adopted [7].

3D printing is about to change the building industry and will impact the use by architects, engineers and designers of concrete in its design. In more than a dozen new technical papers on 3D concrete, a wide variety of issues were covered, including the different technologies of printed 3D concrete as well as elements of combining design and functionality of printed concrete material. However, in the literature just a few research papers on 3D concrete printing were published. The major objectives of the research and literature review paper are to showcase the current state-of-the-art computer modelling and 3D printing problems of cement-based materials.

2 Development of the 3D Printing Technology

During the period of mid-1980's, 3D printing has become more popular in the areas of biomedical industries and as well as manufacturing sectors. Users were able to use their computers to turn digital models into real three-dimensional products. In the earlier times, the 3D printers were being able to print little objects, however research and development activities eventually escalated to large-scale printing products such as cars due to technical improvements. Maybe it's the point when other companies began thinking of 3D printing [8]. Layered construction process is a new manufacturing approach, first established in the mid-1990s and known as Contour Crafting (CC). The 3DP technology got its patent in 2010. The technology, devised as the process of extruding ceramic pastes but cementitious materials were recently developed to generate large-scale structural components, and even whole equipment such as a printed building [9].

The major components of this technology are concrete tank, a hose, pumping mechanism, nozzle and robot arm. The robotic arm can steer the nozzle in three different directions up, down and diagonally. The concrete is poured layer-by-layer on the nozzle, and the concrete layers are healed and they are strong enough required to provide the support for the new layers. The pulling method, for example, employs pneumatic pressure which is required to transfer the material from a bucket to surface of the concrete sheet. One of the disparities between shotcreting and sculpting of contours. The substance exits faster than when the extrusion operation is carried out, using a piston pump mechanism comparable to a syringe, than the injection approach. In the mid-1990s a second manufacturing additive, known as Selective Aggregation has been developed, involving the preparation and targeted deposition of the cement on the sand matrix. A strong and dense material was created as a result of this process, which could be automated with computer-assisted design and analysis models. Mountain construction techniques were developed to combine the mountains by merging sand grains [10]. A device named "D-Shape," which is based on this principle of sand grain combination, appears to be invented. The grains were coupled with a sand binding agent, which originally was a polymer material and was then converted into an inorganic binder due to the difficulty of attaching the polymer binder to the machine. The selective throwing of the grains into the sand matrix.

Originally a technique like the fabrication of contours but changing the design of the extruder was described with the phrase "freeform building" or "concrete printing." It was utilised in the first decade of the twenty-first century. The dust used in this method may be printed in various resolutions, including enormous expansions and fine details. In terms of enormous structural components, the focus on increasing additive production in the construction sector was uncommon as compared to other technologies. It also provided additional functionality to structural components like sound, heat and ventilation [11]. Moreover, current 3D printing is being built for more than 25 years. Despite significant improvements, it is far from possible to print by merely pressing the "PRINT" button on a computer. 3D printers are still being developed in practical applications; nonetheless, laboratories and manufacturers still seek to improve existing 3D printers or create new printers.

3 3D Concrete Printing (3DCP) Technologies

Different technologies have been developed in recent years for the application of additive manufacture in concrete buildings. Three 3D printing processes are now used in the building sector: extrusion-based layering and powder bed technology. Extrusion-based layering is the most often used technology in construction (selected material deposition via extrusion). This is comparable to Fused Deposition Modelling (FDM) in which layer by layer combinations of specified materials have been deposited via extrusion printer head, the command of the crane, robot or arm of a 6- or 4-axis 3D printer with computer-supported design tools. The powder-based technologies are off-site processes designed to be developed on site for big and complex geometric structural printing. These massive, sophisticated geometric masterpieces are made using a number of printing methods, including Stereo-Lithography [12]. The production procedures and types of materials used in contour production, concrete printing and 3DCP are all quite comparable. Various studies on 3DCP are selected through literature review, this study summarises the major aspect of concrete printing technologies. The primary 3DCP experiments are now selected. The following sections discuss the methodologies and similarities and differences, advantages and disadvantages of various 3DCP technologies.

3.1 Extrusion-Based Layering

The extrusion-based technique is symmetrical to FDM technology which is also used for layer printing by layer structures using a cemented material extruded from nozzle mounted on a gantry, shutters to print a layer-by-layer of the structure. By addressing some of the construction site applications such as comprehensive building structural components with complex geometry, this technology can make an essential and useful contribution to the construction industry [13]. The Contour Crafting (CC), Concert Printing (CP), and CONPrint3D extrusion-based laying processes may be used to print concrete constructions using cemented materials or aggregates and fibre strengthening. Concrete printing and the manufacturing of contours are typically instances of additive manufacturing, both components of a comparable technology called inkjet and mixed material extruded via boxes to build up vertical components. Figure 1 shows the schedule for the powder-based approach in action.

3.1.1 Contour Crafting

The Contour Crafting (CC) technology was created by Dr. Behrokh Khoshnevis of University of Southern California and is a fully on-site technology. With the vertical extrusion of the layers this printing technology can be strengthened manually by strengthening bands to allow the final product to be strengthened. The vertical

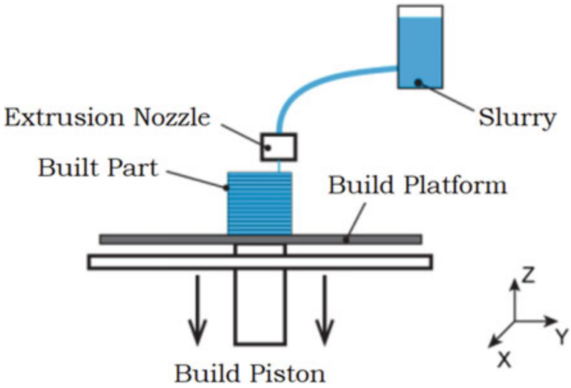

Fig. 1 Extrusion-based technique [13]

concrete form is constructed utilising an extrusion method which transforms two layers of a cemented mixture into a vertical concrete covering. A shape contour maker has a large printing area with a working surface of 5 m × 8 m × 3 m. This technology gives a good quality of the surface, is easy to produce and can be printed on a variety of materials [14]. It is quite difficult for the CC machine to insert the reinforcement links between layers manually. Smooth extruded surfaces with fins similar to Trowel-like fins are added to the printed head. Figure 2 depicts a CC machine-made concrete wall shape for a concrete foundation.

The major benefits of CC technology are higher surface smoothness and the much more rapid speed at which CC is manufactured. The ability to link with different robotics procedures for the installation of internal components like pipelines, electrical drivers and enhancer modules is the another essential characteristic of CC [15].

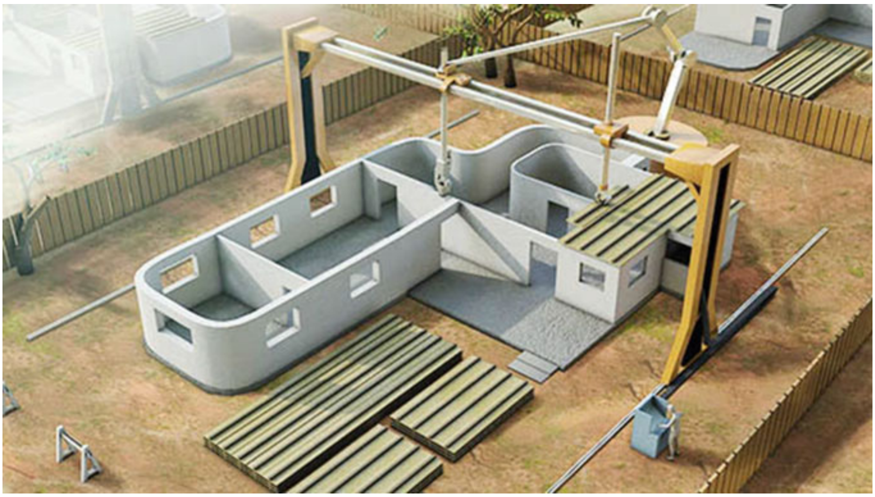

Fig. 2 Contour Crafting (CC) technology [15]

Vertical parts are currently mainly manufactured in CC compression. If you require a door or a window, a lintel is fitted to conceal the gap and allow the wall to be built above it. Hence, the problem is not large-scale. Due of this limitation, vertical extrusion is the only printing process of the CC type. The initial forming and trowel method might also be hard for manufacturing, depending on the size and shape of the printed object. A further advantage is that the sequential casting in form of the concrete is distorted because of hydro statistic pressure of the extruded concrete, making CC technologies very difficult to print.

3.1.2 Concrete Printing

Concrete printing at the University of Loughborough is invented by means of a 4 m × 1.6 m × 1.50 m dimension printing press with a printing area of roughly 132 m^2. This technology allows the use of high-performance ground and fibre-reinforced concrete, which offers improved mechanical performance in printed components. The study found that coarse aggregates up to 9.5 mm and concrete of C30 were used for printing concrete mixtures. Concrete Printing is a new construction material created by a United Kingdom team from the University of Loughborough. The technique is based on extrusion-based technology and is comparable to CC technology [16]. In contrast, concrete printing technique was designed to maintain 3D freedom whilst reducing deposit resolution in order to further regulate the internal and external geometries of the printed structures. Figure 3 displays the full bench which is typically made by means of the concrete printing technology. The bench is also provided with an example of a reinforcement strategy which is intended to plan voids as pipes for reinforcement following installation.

Concrete Printing permits freeform components and overhangs, but requires additional support. A second material is employed in a technique similar to the FDM process. This technique is detrimental since the second material requires an additional

Fig. 3 Full scale bench manufactured by the Concrete Printing [16]

deposition device, leading to a higher maintenance, cleaning and control instruction and the need to clean the secondary structure throughout the subsequent processing operations [17]. In comparison with the intended industrial application, the advantages of the concrete printer technology are that the trade-offs needed to preserve its dimensionality are quite slow.

3.1.3 CONPrint3D: Concrete On-Site 3D Printing

Contrary to their numerous technological advantages, the production of contours and concrete printing have certain intrinsic constraints such as the necessity for new and sophisticated technology and small sized mineral particles. This limitation is overcome by a novel on-site 3DCP technology developed by CONPrint3D, Technical University of Dresden, Germany. The high geometric flexibility of CONPrint3D is one of the technological benefits that makes it possible to use the standard equipment and rely little on a well-trained workplace [18]. CONPrint3D is majorly focused on creating a time and resource efficient building process but also on producing a commercially viable new process whilst gaining greater acceptance from existing industries' professionals. This is achieved by the utilisation of current construction and manufacturing processes by adapting a new methodology to the site restrictions. The key component of the project strategy is to autonomously and accurately adapt a concrete boom pump to transport material to certain locations using a custom printed head installed on the boom as shown in Fig. 4.

Moreover, as the contour-building and concrete printing methods are only confined to vertical extrusion and require original shape, one of the major problems such as hydrostatic pressure control, further operation and maintenance could result in complexity, depending on the structural geometry to be printed.

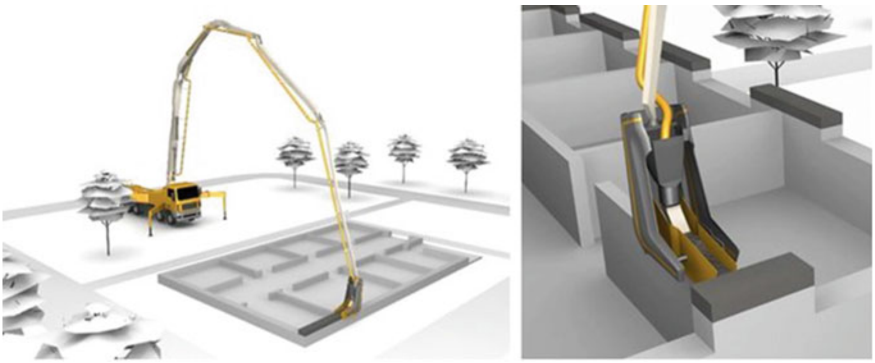

Fig. 4 CONPrint3D technology [18]

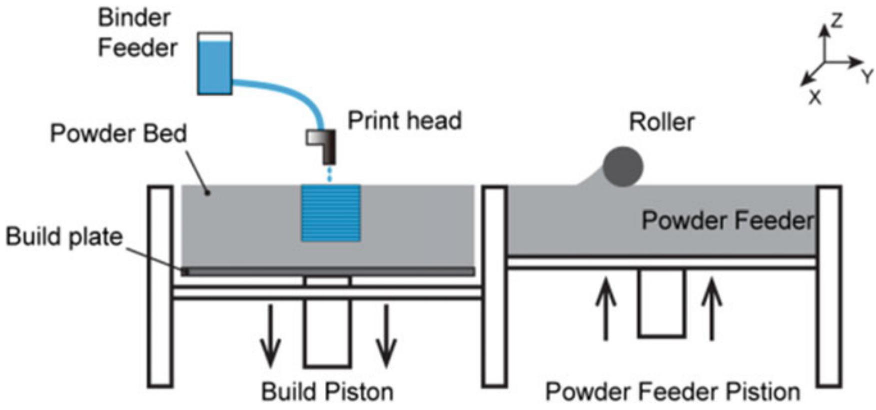

Fig. 5 Powder-based technique [19]

3.2 Powder-Based Methods

The powder-based approach is one more typical additive process in which precise structures of difficult geometry are produced by selectively depositing the liquid binder (or "ink") in the powder bed into a binding powder where the bed is struck to form a strong structure. This method is also well known as an off-site process which is majorly for precast concrete component fabrication. Powder-based technology is particularly suitable, according to the scientists, for tiny building components for example panels and on-site interior structures [19]. Figure 5 shows a diagram of the powder technique in action. Starting with the first powder layer (about 3 mm thick), a roller with the print head spreads out the powder which is required to cover the base of the building plate. The roller then disperses a thin layer of powder (approximately 0.1 mm in thickness) over the surface of the powder sheet, which is adjusted according to the setting of the thickness required for the 3D printer above the layer. The binder solution shall be transported from binder feeder towards the printed head, blasted into the powder layer by the help of nozzle, which makes it possible for polished particles to bind to each other and form a firm bond. Repeating the preceding techniques, the created item is finished and then it was removed after a specific period of drying and then loose powder shall be removed by using a blower.

3.2.1 D-shape

The D-shape approach has been explored by Enrico Dini. He had used a powder-based technology to harden a huge sand bed, similar to that used in concrete making, by depositing a binding agent. Sand is used as a construction material, whilst in the construction of the structure magnesium-oxychloride cement is used as a binding agent. Shiro Studio paired up with a D-shaped pavilion that sized 3 m by 3 m by 3 m

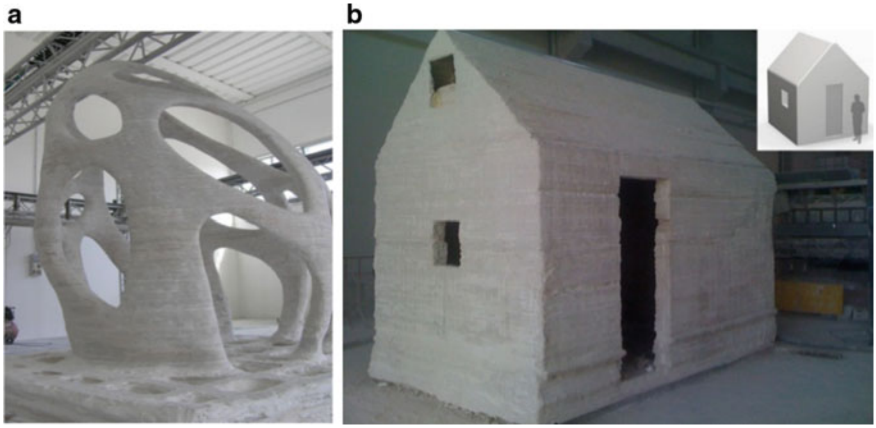

Fig. 6 **a** Radiolaria Pavilion, **b** Ferreri house printed by D-shape [20]

in 2008 [19]. The Radiolaria Pavilion was developed to demonstrate the capacities of D-shape technology by using sophisticated geometry (Fig. 6a). In 2010, D-shaped Ferreri house, measuring 2.4 m × 4 m has completed in one single procedure was also 3D printed (Fig. 6b). It took only three weeks for the house to be printed [20].

3.2.2 Powder-Based 3DCP Using Geopolymer

Construction components can be made utilising by a powder-based production process, with fine details and elaborate forms. When it comes to building components, there is a large demand for those that can only be created with costly coating using the existing building methods. To address this industrial demand, powder-based manufacturing techniques are capable of producing robust and durable parts at an acceptable speed [21]. Although this technology has a significant potential for use in the building industry, it does not fully meet its promise because of the extremely limited choice of cement-based printing materials accessible in commercially available 3D-based powder printers. In a study, the authors have recently succeeded in inventing a unique methodology for the adoption of geopolymer-based material (Fig. 7) in order to satisfy the demands and the need for widely existing powder-based 3D printers [22]. Geopolymer is an eco-friendly alternative material to OPC. Geopolymer provides greater mechanical, chemical and thermal characteristics compared with polypropylene whilst producing less carbon dioxide.

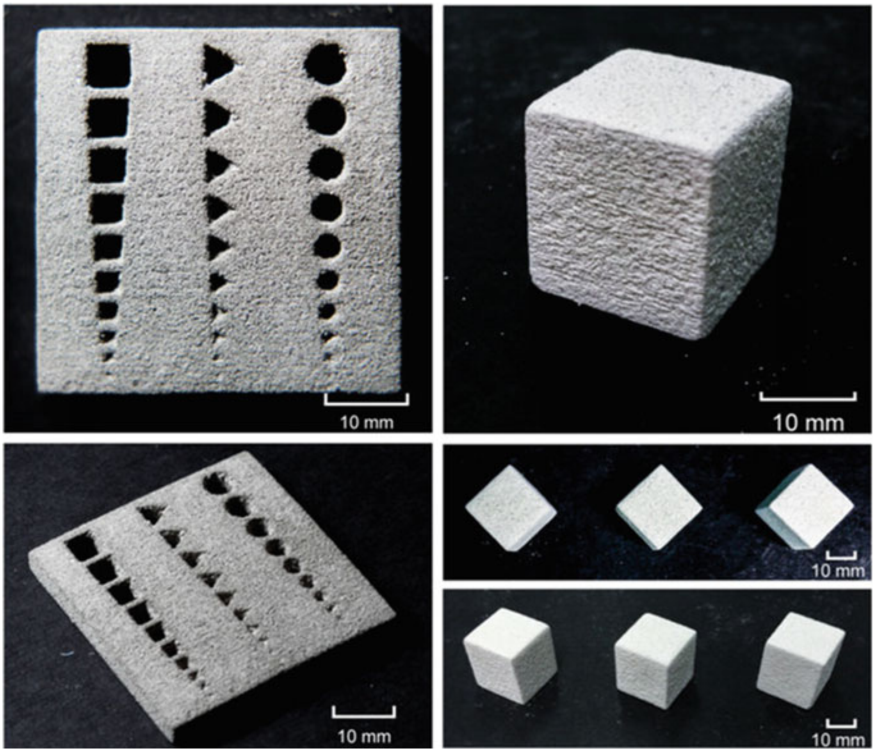

Fig. 7 3DP components by geopolymer-based material

4 Conclusion

Whilst additive printing is a relatively new notion for manufacturing components, it may give a new approach to develop architectural and structural components. The adoption of 3D printing technology by the construction sector can address various challenges such as time-consuming and inefficient construction procedures, amongst others. Whilst 3D printing is still in its early stages, many scholars think that it presents new chances for establishing new trends that ultimately lead to cost-effective, sustainable and time-efficient construction approaches. Worldwide researchers did studies to maximise capacity, bond strength and also the utilisation of 3D printed concrete reinforcement. Further attempts are being made to create 3D imprinted concrete standards and specifications in order to launch code-based designs of 3D imprinted concrete structures and to progress the technology further.

This research paper shall provide an overview of state-of-the-art 3D concrete (3DCP) technology, in particular extrusion and powder-based techniques in addition to already available 3DCP technology. We analyse the similitudes, differences and advantages of the different 3DCP technologies. The latest state-of-the-art extrusion, powder-based elements and structures were also discussed. Even though 3DCP is a relatively new technique, encouraging examples of this study demonstrate that the technology is rapidly evolving so that 3D printing of concrete structures is going to be a reality in the very near future. 3D printing will have to be deployed by a staff who are equipped with integrated knowledge about the materials to be used, structures, robotics systems, computer software and hardware in the building industry. To equip future personnel to address the difficulties arising from this new technology, an entirely new academic programme is required in institutions.

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