

3D Printing in Architecture, Engineering and Construction

(Concrete 3D printing)

Dr. Ahmed Saleh Abd Elfatah
Assistant Professor at Faculty of Engineering, Helwan University
engasa@hotmail.com

ABSTRACT

One of the new developments in construction and architecture is 3D Printing with a concrete-like material. This technique can create the opportunity for personalization of large-scale projects for the lower and middle class since it removes the restrictions on shape, that are present in the traditional way of building. The technology also has shown potential in a wide range of disciplines, but the building industry is still behind in the development of 3D printing.

The influence of 3D printing in building industry must not be underestimated as it can reduce various determining factors such as the construction process, material costs and the time span of the whole project. By studying new printable materials and optimizing shapes including the typical properties of 3D printed concrete, the potential of this promising technique can be realized in practice. This research focuses on the background of this new technique, potential applications and future of 3D Concrete Printing.

KEYWORDS: 3D Concrete Printing (3DCP), Additive manufacturing, Contour Crafting (CC), Architecture, Engineering and Construction (AEC).

1. INTRODUCTION

Additive manufacturing is the new method of creating products from materials such as plastic, sand, and other powdered materials. The process of Additive manufacturing has been used since the mid-1960s and there have been various improvements in terms of materials used in the process of additive manufacturing. Additive manufacturing that is commonly known as 3D printing nowadays has been very efficient in cost reduction of manufacturing and reduction of waste in the process of manufacturing.

In this research, the methods and types of 3D printing and their feasibility in using concrete as a material in the process of making 3D printed concrete products are analysed. 3D printing has been one of the fastest growing technologies in the world presently. The concept of 3D printing has evolved since the 1980s, but not many researches have focused on the concrete 3D printing technologies. The advantages of using concrete as a construction material are durability and it can withstand any natural disasters such as rain, snow and wind and provide shelter to live in. Dr. Behrokh Khoshnevis, a researcher from the University of Southern California, developed a system called Contour Crafting (CC) in mid-2000s that paved the way for the present day's 3D Concrete Printing (3DCP). This Contour crafting has been

adopted widely by various research institutes to produce massive 3D printed structures. The use of CC in building industry can reduce the amount of physical labour used for projects and reduce construction wastes as well. The efficiency of 3D printing concrete is described later in this research.

1.1. Research Aims

The main aim of this research is to evaluate the feasibility of concrete for 3D printing, to emphasise the impact of this new technology for future construction and to encourage the use of concrete in 3D printing thereby reducing costs of construction and increasing the rate of productivity in construction industry.

2. Additive Manufacturing

Additive Manufacturing (AM) is a process in which three-dimensional objects are made by adding layer-by-layer of material. The materials used can be plastic, metal, concrete etc. The commonly used AM technologies include the use of a computer, 3D modelling software (Computer Aided Design or CAD), machine equipment and layering material^[1]. Once a CAD sketch is produced, the file is then transferred to the AM equipment and the machine reads the data from the CAD file and starts to lay down the material in layers on top of each other forming the object in three dimensions. The materials used to create these objects can be powder, liquid or sheet metal. The term Additive Manufacturing includes several technologies that can produce similar objects rapidly such as Rapid Prototyping (RP), Direct Digital Manufacturing (DDM), Layered Manufacturing (LM) and 3D printing^[1].

2.1. 3D printing

3D printing is an additive manufacturing process of making three-dimensional solid objects from a digital file. The materials used to produce the object are different types of hard plastic, metal, concrete, carbon fibre, food ingredients etc. The use of 3D printing has evolved in the recent years with the technological advancement in engineering sector^[2].

2.2. 3D printing in Architecture and Construction

3D printing architecture models have become an interesting alternative. Typically, architectural models are made of cardboard, wood or other moldable materials. Architects need models to study the aspects of their design. It is often changed to get a perfect concept of their idea in both architectural design and interior design. 3D printing at a construction scale will have a wide variety of applications within the private, commercial, industrial and public sectors. Potential advantages of these technologies include faster construction, lower labor costs, increased complexity and/or accuracy, greater integration of function and less waste produced. Several different approaches have been demonstrated to date which include on-site and off-site fabrication of buildings and construction components, using industrial robots, gantry systems and tethered autonomous vehicles^[3]. Demonstrations of construction 3D printing technologies to date have included fabrication of housing, construction components (cladding and structural panels and columns), bridges and civil infrastructure, artificial reefs, follies and sculptures. It

might also enable construction to be undertaken in harsh or dangerous environments not suitable for a human workforce such as in places with special conditions^[4].

2.2.1. 3D printed buildings

A building consists of many parts, such as foundation, walls, windows and doors, ceiling, roof, plumbing and wiring and no company prints whole houses. In construction industry, 3D printing can be used to create construction components or to 'print' entire buildings, when we say, "to print a building," we only mean printing walls of a building, because the printer doesn't yet participate in other processes until now. Really, believe that 3D printing construction can heavily replace traditional construction. Now, traditional stone construction of blocks and bricks is the most threatened one. Materials used in printing buildings contain a mixture of cement and sand, so a printed house is not different from a concrete house^[5]. The printer is just a way of laying down the material. The only difference is that the printer is a machine or robot, an automated system that eliminates the human factor. Therefore, concerns about the durability of printed houses are not justified.

2.2.2. 3D Printing in Interior Design

Many architects and interior designers are extensively using 3D printing to create new and unique designs that give the overall ambience of a property with a truly modern and cosmopolitan look. With new design flexibilities with 3D printing, designers are now not constrained by any technical limitations for any object. They use 3D printed organic vessels made of salt polymers to indoor, while the exterior cladding is composed of polymer printed blocks (Fig. 1). They can unleash the best of their creativity and make unique designs that were not previously possible with conventional manufacturing techniques^[6].

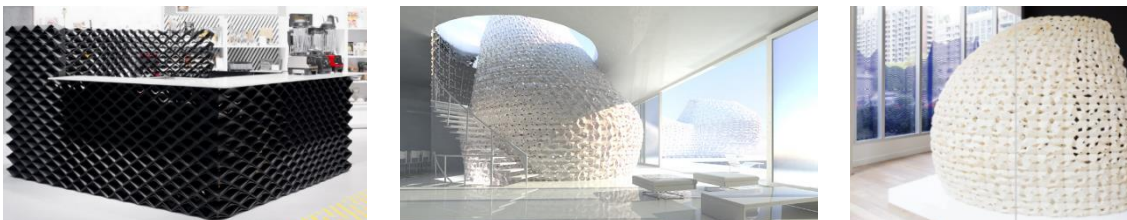


Fig. (1) Shows an interior space made of 3d printed mixture obtained by salt and glue constituting an efficient, translucent and inexpensive material <https://www.archdaily.com/890494/interior-design-and-3d->

In fact, 3D printing also saves a lot of time as manufacturing a single part can be done in a matter of hours against the days and weeks needed for traditional methods. They no longer need to solely depend on whatever is available in the market; these designers also have the freedom to let the clients choose the colour and size of the product while keeping the design the same^[5]. With easier access to 3D printing, architects and interior designers are not in need for searching for completing their designs because material selection is slowly but surely becoming an obligatory part of the interior designing process with using 3D printing.

2.2.3. 3D printed bridges

The first pedestrian bridge printed in 3D in the world is in Spain. The 3D printer used to build the footbridge was manufactured by D-Shape. The 3D printed bridge reflects the complexities of nature's forms. It was developed through parametric design and computational design, which allows to optimize the distribution of materials and allows to maximize the structural performance, being able to dispose the material only where it is needed, with total freedom of forms^[7]. The bridge has a total length of 12 meters and a width of 1.75 meters representing a milestone for the construction sector at international level, as large-scale 3D printing technology has been applied in this project for the first time in the field of civil engineering in a public space (Fig. 2).



Fig. (2) (a) 3D printed bridge with the D-Shape technology. The first structure of this type in the world^[7], (b) 3D-printed steel bridge in the heart of Amsterdam 3D-printed steel bridge in the heart of Amsterdam, (c) the first 3D-printed steel bridge. In 2015, Dutch 3D printing company MX3D^[8].

2.2.4. Extraterrestrial printed structures

The printing of buildings has been proposed as a particularly useful technology for constructing off-Earth habitats, such as habitats on the Moon or Mars. As of 2013, the European Space Agency was using regular 3D printing technology^[8].

The architectural firm proposed a building-construction 3D-printer technology in January 2013 that would use lunar regolith raw materials to produce lunar building structures while using enclosed inflatable habitats for housing the human occupants inside the hard shell printed lunar structures. Overall, these habitats would require only ten percent of the structure mass to be transported from Earth, while using local lunar materials for the other 90 percent of the structure mass^[9].

2.3. 3D printing technology and materials

There are varieties of 3D printing materials used at construction scale. These include the following main methods and materials: extrusion (concrete/cement, wax, foam, and polymers), powder bonding (polymer bond, reactive bond, sintering) and additive welding. Many different implementations, conditions and variants of buildings, in particular the specific conditions of the construction site should be taken into account. While designing a mortar mixture intended for use in 3D printing technology, it should be noted that this mixture meets the accepted criteria and design assumptions. It is possible to determine the principles, the composition of mortar mixtures and its required properties. (Fig. 3)^[10].

Material, designed and used in 3D printing technology for construction, depends on three interpenetrating factors: raw materials, methods of application and methods of production. While designing such a material, it is also necessary to pay attention to the properties that the manufactured object must fulfil and that it is possible to print by the given printer. The composition of the mixture is also influenced by climatic conditions at the place of object's production, as they affect its composition and maturing conditions^[7].

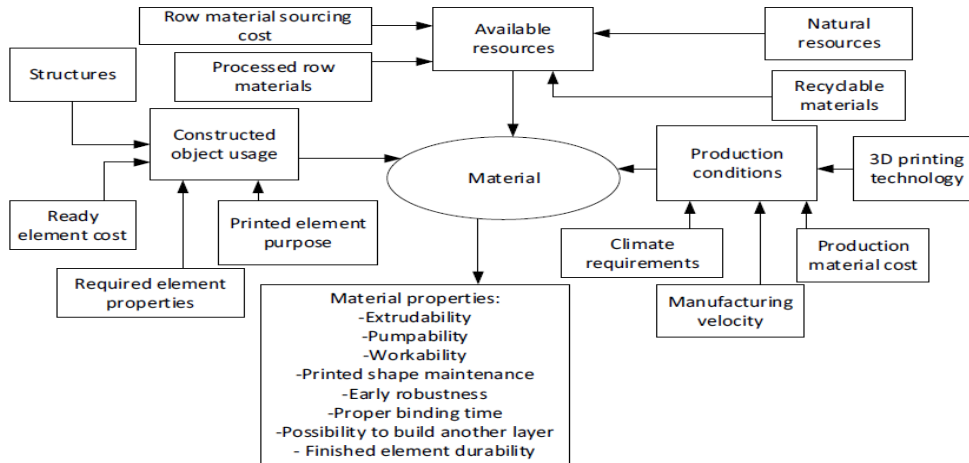


Fig. 3 Building material composition for 3D printing and properties requirements [10]

The time of achieving the given properties also affects the printing process; it also depends on the method of material delivery and the time of applying subsequent layers of building material [10]. Attention should be paid to such parameters as: flowability of the mixture, extrudability, stability of the printed shape, bonding time, and strength and shrinkage of concrete. The 3D printer concrete is now the most common and testing for maximum utilization in construction industry. So, the more materials used in construction industry are, the more common is a concrete composite. The 3D printing construction company CyBe uses a specially designed mortar that sets within three minutes of being printed and dries in one hour. Many companies currently use or are developing a concrete mix made with recycled materials. Construction company Cazza's mix is made from up to 80 percent recycled material [4].

3. Concrete 3D printing

The steps of 3D printing an object with concrete consists of three steps: preparation of data, preparation of concrete mix and printing of the object. In the data preparation stage, the spatial model of the object to be printed is created in CAD format. The object is then sliced into layers using one of the slicing softwares. The software creates a plan for the 3D printer for laying the concrete in layer-by-layer form. The next stage is the preparation of the concrete mix and management of feeding of concrete to the 3D printer (Fig. 4). (The mixture is automated and flows into the printer continuously) [11].

At the third stage, the concrete mixture is pressed out of the printer through

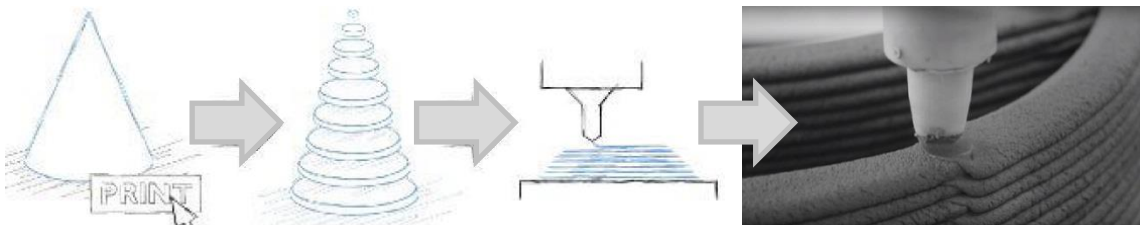


Fig. 4 Concrete 3D printing process & Concrete extrusion process [11]

the nozzle and placed in layers. The concrete flows through the nozzle of the printer on a prescribed path programmed by the user to the 3D printer. This path is programmed accordingly so that the printer lays the concrete in layer-by-layer fashion, forming a real three-dimensional object from the digital model [11]. The workability of the concrete plays a vital role in this stage of the printing. The workability is responsible for both the extrudability and buildability aspects of concrete.

3.1. Concrete 3D printers

Concrete 3D printing could be used in many ways in construction industry. One option is to print elements in the factory, and then they are transported to construction sites and assembled. Another option is to set up the printer on a construction site where the structure is printed in elements on the site and assembled together, or directly print the structure on site. Two types of printers are currently in use in the industry. The first type is a framed printer. This kind of printer would fit only in factories because it is very difficult to transport and assemble this kind of printers (Fig. 5). The disadvantage of this printer is that the frame of the printer must be larger than the structure itself. The larger frame makes the printer expensive and difficult to transport and assemble. [12]

The second type of printer is a non-framed concrete printer. It is a robotic printing arm mounted on a vehicle. This kind of printer can be easily transported and does not require flat ground, unlike the framed printer (Fig. 6). This kind of non-framed 3D printer is used by CyBe constructions in the Netherlands [13].



Fig. 5 Framed concrete 3D printers Source: <https://www.tue.nl/en/university/departments/built-environment/research/research-programs/structural-design/research/research-areas/concrete-research->

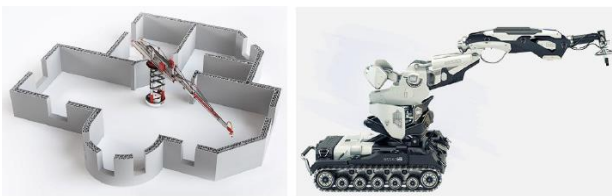


Fig. 6 Non-framed concrete 3D printers Source: <https://3dprint.com/189228/cazza-3d-print-construction-robots/>

Traditional methods vs 3D printing

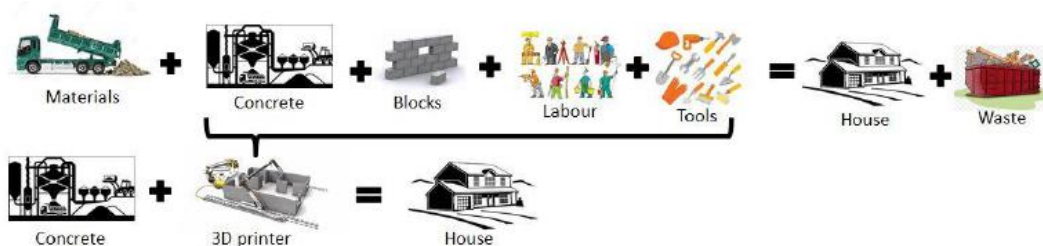


Fig. 7 Traditional production process vs 3D printing [4]

The illustration above shows clearly the various stages of construction of a structure according to the traditional techniques. They involve human resources in different locations of the structure. Thus, they are time-consuming and expensive. The 3D printer on the other hand shows how the printer is both a tool and a manufacturer [4]. The less involvement of the user in the printing process, the smoother the process is automated.

3.2. Parameters affecting 3DCP

As summarised in (Fig. 8), the printing process is affected by a multitude of parameters. The three main categories are the computer-aided design, printing process and material behaviour. These categories have a significant influence on one another [14].

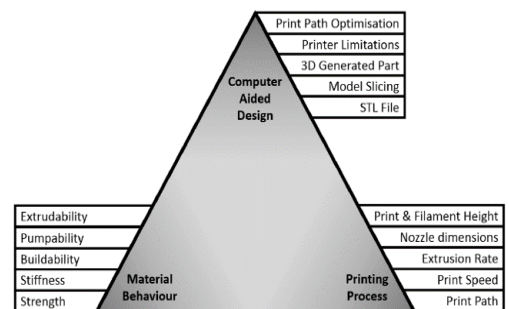


Fig. 8 Parameters affecting concrete printing [4]

3.2.1. Computer-aided design for 3D printing

The typical workflow of concrete 3D printing starts with CAD modelling of the object to be manufactured, as illustrated in (Fig. 9). Next, the CAD model is exported to a conventional 3D data format, typically a STL file format. The STL file is then sliced via software and converted to a machine-readable language before being input to the printer. The printer then proceeds to manufacture the desired 3D object. It is important to consider the physical process of 3D printing and its limitations, which are not evident during the computer-aided design process [15]. For example, the design process should also consider the printer speed, nozzle dimensions, layer thickness, material behaviour and the extrusion capacity of the

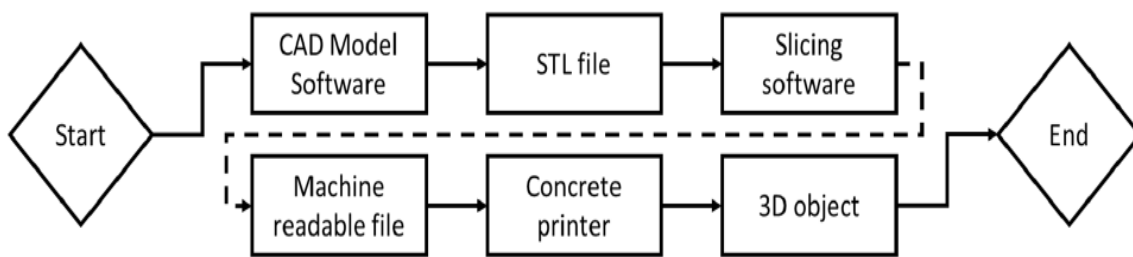


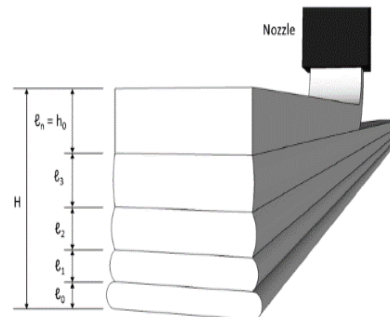
Fig. 9 Modelling workflow of concrete 3D printing [15].

pump.

3.2.2. Printing process

The physical printing process is subject to a multitude of parameters, namely the print speed, filament extrusion rate, nozzle dimensions, the printing path, filament height and print height.

The quality of the end product, produced through the concrete printing process, is strongly correlated to the effective control of these parameters [16].



Filament height (h_0), layer height (L_n) and print height (H) [16].

3.2.3. Material behaviour

The fresh state material behaviour of printable concrete influences its extrudability, buildability, pumpability, stiffness and strength. Figure no. 10 illustrates where these properties come into play throughout the concrete printing system [17]. The fresh state material behaviour is currently a focus point in concrete printing research. Various studies report a trial and error methodology to determine the optimum printable concrete mix composition. However, none report the use of coarse aggregate for printable concrete [14]. Typically, the particle sizes are limited to less than 2 mm.

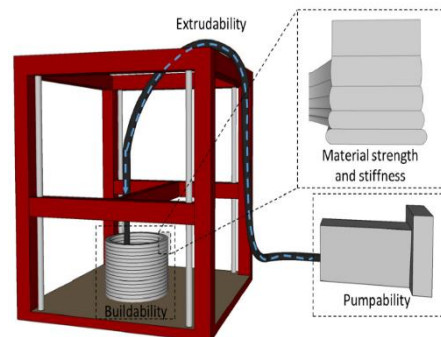


Fig. 10 Material behavior affecting concrete printing [14].

3.3.Challenges of concrete printing

Concrete printing and other AM processes still have a multitude of challenges to overcome, before they are adopted for widespread use. This includes accurate material delivery and placement, in addition to control and measurement of material phase transitioning, from its fresh state to hardened state. Furthermore, the layering of concrete could cause the formation of "cold joints" which refer to insufficient bonding between layers reducing structural strength, in turn. The inclusion of steel or fiber reinforcement is another matter requiring attention, as is the surface finish of the product [18]. Moreover, standardized requirements, benchmarks and testing procedures are yet to be developed to validate the safe and sustainable use of concrete printing as a construction method. The following key properties of concrete need improvement in order to successfully 3D print concrete structures:

- Extrudability.
- Flowability.
- Buildability.
- Open time and
- Contact between layers

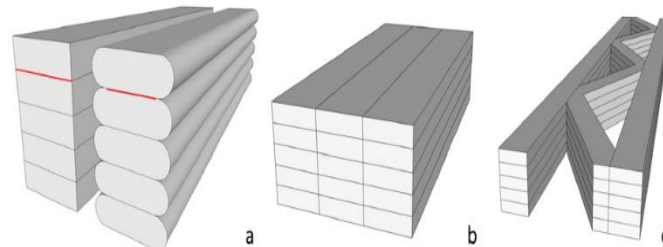


Fig. 11 (a) Increased surface area of rectangular nozzle compared to circular; (b) Increased number of adjacent layers; (c) Supporting cellular structure [18].

4. 3D Construction Printing: a worldwide overview

Several research groups of research organizations are involved in the development of large-scale 3D printers for the construction industry. The technologies developed differ in terms of printing techniques and materials. The Concept of three-dimensional (3D) printing of concrete has been experimented since the mid 1990's. The generically name 3D Concrete Printing varies with various research groups and enterprises around the world. The projects presented below are experimental and commercial projects that are ongoing on 3D Concrete Printing (3DCP) by various production units and academic institutions around the globe. Tables no. (1, 2, 3, and 4) show the above according to the following factors:

- ✓ Printer Type: Powder bed or layer by layer
- ✓ Movements: Typical movement systems for the printhead
- ✓ Location: In SITU or off site
- ✓ The Printed Object: Load bearing or Hollow
- ✓ Other printer types/technologies

Table. 1 3D Construction Printing a Worldwide overview (researcher)





		The 3D Printing Technologies Used in 3D Construction Printing			
		printer Type :Extrusion (FDM) – Layer by layer			
Printer Type	Powder bed or layer by layer				
		Concept		Pros & Cons	
		The building material is typically a concrete mixture deposited by a XYZ movable Nozzle system.		<ul style="list-style-type: none"> + Geometrical freedom in XY + Mechanically simple construction - Geometrical limitation In Z (now) - Visible and physical layer problems 	
		https://3dprint.com/137655/3d-printing-concrete-expand-2021/			
		printer Type : Printer Type :Powder bed			
Printer Type	Powder bed or layer by layer				
		Concept		Pros & Cons	
		Full layers of the building material is deposited as a powder bed. The powder is then infiltrated with a binder where the geometry has to be solid for the specific layer. Process is repeated.		<ul style="list-style-type: none"> + Geometrical freedom in XY and Z + Better Finish because of thin layers - Slow/ Long post processing time - The object has to be dug out 	
		https://3dprintingindustry.com/news/behind-3d-printed-bridge-exclusive-interview-catalonian-			
		Printer XYZ Movement :Gantry			
Movements:	Typical movement systems for the print head				
		Concept		Pros & Cons	
		The print head is moved in XY and Z with a gantry system. Printing occurs within the boundaries of the system		<ul style="list-style-type: none"> + Stable and secure construction + Simple and cheap construction - movability - Hard to move from place to place - Takes up a lot of space 	
		https://3dprintingindustry.com/tags/batiprint/			
		Printer XYZ Movement :Robotic arm / Crane			
Movements:	Typical movement systems for the print head				
		Concept		Pros & Cons	
		This platform is rooted in the centre of the print area in comparison to surrounding the object. The nozzle is fixed on a robotic arm or a computer driven crane system.		<ul style="list-style-type: none"> + Smaller mechanical system + Easy movable - higher Price - Print Area/limited reach (unless mounted on a moving platform) 	
		https://medium.com/@Nik_chen/what-is-construction-3d-printing-perspectives-and-challenges-5b57170c2a29			

Table. 2 3D Construction Printing a Worldwide overview (researcher)






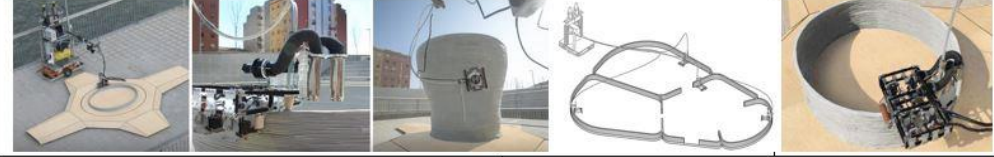


		The 3D Printing Technologies Used in 3D Construction Printing			
		Location :In Situ			
Location	In SITU or off site				
		Concept		Pros & Cons	
		The Construction is built on site. Either very close to where it has to stay or built right on the spot.		<ul style="list-style-type: none"> • + Full construction in one go • + Less freight of elements • - Varying weather parameters • - The 3D Printer has to be shipped and kept under roof 	
		https://archpaper.com/tag/3-d-printing/page/2/			
		Location :Off Site (Prefab Construction)			
Location	In SITU or off site				
		Concept		Pros & Cons	
		Prefabricated elements are 3D Printed in a production area where the 3D Printer is stationary. After production, the elements are shipped to the construction site.		<ul style="list-style-type: none"> • + stabilities in a stationary system • + Stable weather parameters (indoor) • - Shipping of elements • - More manual labour required on the construction site 	
		https://www.google.com.eg/search?biw=1366&bih=632&tbm=isch&sa=1&ei=117NXM--N8nBlwSm8YPIAw&q			
		Printed Object :Load Bearing Vs. Formwork			
The Printed Object	Load bearing or Hollow				
		Load Bearing		Formwork	
		Load bearing constructions or concepts only working in pressure. Limited load bearing capability		The outer shell of the construction is 3D Printed – when 3D Printing is done the construction is armed and cast in traditional way (with poured concrete) to increase load bearing capability.	
		https://www.google.com.eg/search?fbm=isch&sa=1&ei=O4LNXOLyDqOlwS8rKy4CQ&q			
		Other printer types/technologies: Branch Technology			
Other printer types	Typical movement systems for the print head				
		Concept		Pros & Cons	
		Freeform 3D Printing of grid-structure in plastics. After the print the insulation, concrete, plaster or other building materials can be added/sprayed on.		<ul style="list-style-type: none"> • + Freeform structures based on “prefab” method • + The extruded grid is easy to ship (lightweight) • - More manual labour on the site. 	
		https://www.branch.technology/			

Table. 3 3D Construction Printing: a Worldwide overview

The 3D Printing Technologies Used in 3D Construction Printing					
Other printer types/technologies :MIT & Nantes University					
Other printer types/technologies					
	<table border="1"> <tr> <td>Concept</td> <td>Pros & Cons</td> </tr> <tr> <td>Formworks 3D printing of insulation foam (EPS) – concrete poured in afterwards.</td> <td> <ul style="list-style-type: none"> + Fast printing + Integrated (and solved) insulation issue + On site - Complex connections required to interior part </td> </tr> </table>	Concept	Pros & Cons	Formworks 3D printing of insulation foam (EPS) – concrete poured in afterwards.	<ul style="list-style-type: none"> + Fast printing + Integrated (and solved) insulation issue + On site - Complex connections required to interior part
	Concept	Pros & Cons			
	Formworks 3D printing of insulation foam (EPS) – concrete poured in afterwards.	<ul style="list-style-type: none"> + Fast printing + Integrated (and solved) insulation issue + On site - Complex connections required to interior part 			
http://news.mit.edu/2017/3-d-printing-buildings-0426					
MiniBuilders The Institute for Advanced Architecture of Catalonia (IAAC)					
Research Center					
	<table border="1"> <tr> <td>Concept</td> <td>Pros & Cons</td> </tr> <tr> <td>SMALL ROBOTS PRINTING LARGE-SCALE STRUCTURES: <ul style="list-style-type: none"> • 3D Printing robots –runs and drives on the printed object. • Able to print big size without a big printer. • Different robots have different tasks. </td> <td> <ul style="list-style-type: none"> + small-scale construction robots, all mobile and capable of constructing objects far larger than the robot itself. - the objects they produce are linked to and constrained proportionally to the size of the machine. This methodology of production and construction is not scalable. </td> </tr> </table>	Concept	Pros & Cons	SMALL ROBOTS PRINTING LARGE-SCALE STRUCTURES: <ul style="list-style-type: none"> • 3D Printing robots –runs and drives on the printed object. • Able to print big size without a big printer. • Different robots have different tasks. 	<ul style="list-style-type: none"> + small-scale construction robots, all mobile and capable of constructing objects far larger than the robot itself. - the objects they produce are linked to and constrained proportionally to the size of the machine. This methodology of production and construction is not scalable.
	Concept	Pros & Cons			
SMALL ROBOTS PRINTING LARGE-SCALE STRUCTURES: <ul style="list-style-type: none"> • 3D Printing robots –runs and drives on the printed object. • Able to print big size without a big printer. • Different robots have different tasks. 	<ul style="list-style-type: none"> + small-scale construction robots, all mobile and capable of constructing objects far larger than the robot itself. - the objects they produce are linked to and constrained proportionally to the size of the machine. This methodology of production and construction is not scalable. 				
https://iaac.net/project/minibuilders/ / http://www.3dprintetbyggeri.dk/pdf/bes%C3%B8gsrapporter/Minibuilders.pdf					
Professor Berok Khoshnevis (UCSC,US), 2000; The “father” of the concept of 3D construction (Contour Crafting)					
Commercial Companies Contour Crafting					
	<table border="1"> <tr> <td>Concept</td> <td>Pros & Cons</td> </tr> <tr> <td>Mobile Gantry system where crane and robot can extrude not only the building material, But it can also include other elements directly on the building site. The concept are of gantry types that are removed after printing.</td> <td> <ul style="list-style-type: none"> + Theoretically well described projects Backed by 111 patents + Advanced print head designs with three extruders –outer wall and infill in one go. - Very little done in real life </td> </tr> </table>	Concept	Pros & Cons	Mobile Gantry system where crane and robot can extrude not only the building material, But it can also include other elements directly on the building site. The concept are of gantry types that are removed after printing.	<ul style="list-style-type: none"> + Theoretically well described projects Backed by 111 patents + Advanced print head designs with three extruders –outer wall and infill in one go. - Very little done in real life
Concept	Pros & Cons				
Mobile Gantry system where crane and robot can extrude not only the building material, But it can also include other elements directly on the building site. The concept are of gantry types that are removed after printing.	<ul style="list-style-type: none"> + Theoretically well described projects Backed by 111 patents + Advanced print head designs with three extruders –outer wall and infill in one go. - Very little done in real life 				
http://contourcrafting.com/					
D-Shape, Italy/UK, Enrico Dini, 2005 First commercial pioneer					
Commercial Companies D-Shape technology					
	<table border="1"> <tr> <td>Concept</td> <td>Pros & Cons</td> </tr> <tr> <td>The 3D printer was depositing layers of powder on top of each other spreading a binder selectively by an inkjet printer, according to the graphics file provided by a computer.</td> <td> <ul style="list-style-type: none"> + Unique technology Powder material (clay)The 3D printer injects a binder to solidify the powder + Complex forms The ability to build complex forms, difficult with conventional formwork construction </td> </tr> </table>	Concept	Pros & Cons	The 3D printer was depositing layers of powder on top of each other spreading a binder selectively by an inkjet printer, according to the graphics file provided by a computer.	<ul style="list-style-type: none"> + Unique technology Powder material (clay)The 3D printer injects a binder to solidify the powder + Complex forms The ability to build complex forms, difficult with conventional formwork construction
Concept	Pros & Cons				
The 3D printer was depositing layers of powder on top of each other spreading a binder selectively by an inkjet printer, according to the graphics file provided by a computer.	<ul style="list-style-type: none"> + Unique technology Powder material (clay)The 3D printer injects a binder to solidify the powder + Complex forms The ability to build complex forms, difficult with conventional formwork construction 				
https://d-shape.com/					

5. Costs and Benefits of Concrete 3D Printing in Construction Industry

5.1. 3D Construction Wall Printing Calculator

Since every 3D printing technology makes use of a different material, there are many categories and price ranges. It’s hard to give an exact price of a 3D printed building in 2018, as the price depends on the structure’s size and complexity. As time progresses, more and more companies will adopt 3D printed buildings. This, combined with developing technologies, will bring prices down and quality up. In addition, that’s great news if it means more access to safe, affordable shelter for those in need. Table.4 shows a formula that will calculate the cost, time and material usage for a 3D construction wall project, based on 12 input factors.

5.1.1. Cost calculation in 3D printing vs the Traditional methods (per m³ concrete)

The BOD, which is short for “Building on Demand” is named precisely so to underline that with 3D printing technology applied for building projects, the building process is automatized and the borders for what can be made are hereby expanded. Even if the BOD is less than a 50 sqm building, it is still large enough to illustrate some of the economic and architectural advantages of applying 3D printing technology to constructions. With traditional building techniques, any shape that is organic or not straight is a challenge, technically as well as with respect to costs. The BOD does not contain any straight walls, the only straight elements being the windows and doors.

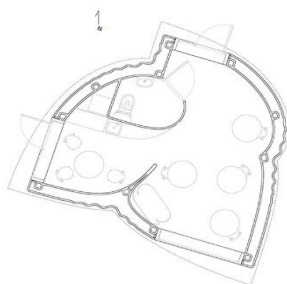


Fig. 12 The BOD is a small 3D printed office hotel of less than 50 square meters located in Copenhagen’s Nordhavn
<https://cobod.com/the-bod/>

Table.4 Excel sheet for cost calculator Concrete 3D printers

Cost Calculator: Input Variables are **RED BOLD (00)**, everything thing else is a calculation result.

1	BUILDING SPECIFICS			
	Total m2 of exterior wall *	00	Total m2 of interior wall *	00
	<i>The length of each wall times the height, all exterior walls</i>		<i>The length of each wall times the height, all interior walls</i>	
2	PRINT LAYER AND SPEED PARAMETER			
	Wall thickness (cm)*	00	Layer height (cm) *	00
	<i>The width of each print layer (5 cm is recommended)</i>	<i>The height of each print layer (2 cm is recommended)</i>	<i>30 cm/s is recommended. (Min 10 cm/s, printer can do max 100 cm/s, but materials for such speed will be a challenge)</i>	
3	ECONOMIC INPUT			
	Price of material per m3 *	00	Number of operators *	00
	<i>The price of 3D concrete is typically the price of normal concrete +20%</i>		<i>We recommend 2 operators, but it can be done with 1</i>	<i>Hourly rate for printer operators (local currency) *</i>
	<i>Will vary considerably from country to country</i>			
4	SETUP TIME AND RISC FACTOR			
	Safety factor (percentage, %) *	00	Setup time of printer on site (hours) *	00
	<i>Example: 50% increases number of print hours by 50% - let it reflect the amount of experience you have with 3D construction printing</i>		<i>First time setup will require 8 hours</i>	
	Take down time of printer on site (hours) *	00	No. of workers involved in setup/take down *	00
	<i>First time take down will require 4 hours</i>		<i>2 workers is recommended</i>	
5	TOTAL COST, TIME AND MATERIAL NEEDED			
	<i>Total cost of project</i>			

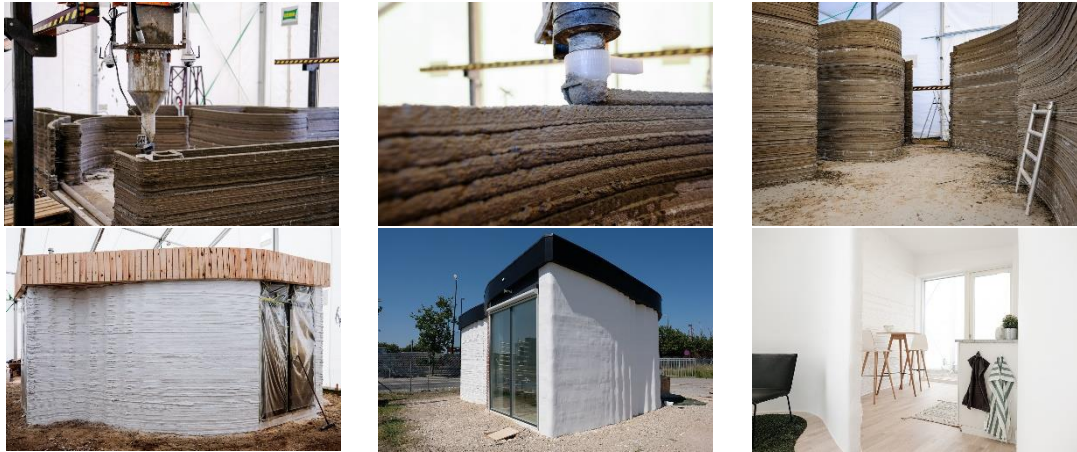


Fig. 12 A Stages of implementation of the BOD Project by COBOD for 3D construction printers and automated processes for the building site. <https://cobod.com/the-bod/>

Table. 5 3D Construction Printing: A Worldwide overview (researcher)

Cost calculation in 3D printing for BOD project		Traditional methods
Total m2 of exterior wall	35.00	
Double-sided exterior wall -> Total area of exterior walls (m2)	70	
Total m2 of interior wall	10.00	
Wall thickness (cm)	5.00	
Layer height (cm)	2.00	
Print speed (cm/s)	20.00	
Material printed per hour (m3/h)	0.72	
Price of material per m3	2,500.00	2600 L.E
Number of operators	3.00	
Hourly rate (local currency)	100.00	
Safety factor (percentage, %)	50.00	
Setup time of printer on site (hours)	8.00	
Take down time of printer on site (hours)	4.00	
No. of people involved in setup/take down	2.00	
Total m2 of walls (m2)	45	
Total m2 of walls to be printed (m2)	80	
Total material use (m3)	4.0	4 m ³
Hours of print time - theoretical (hours)	5.56	
Hours of print time needed - including safety factor (hours)	8.34	
7 hours of printing = 1 hour of preparation	1.19	
Total operator hours for printing (hours)	26.1	
Total operation hours for project (hours)	50.1	
Total cost of operators (local currency)	5,010.00	2200 LE.
Total cost per m2 of wall (local currency)	333.56	
Total cost of concrete (local currency)	10,000.00	10400 LE.
Total cost of project (local currency)	15,010.00	12600 LE.

Table (5) illustrates that the cost of BOD project increases by 20% vs. Traditional methods. This increase represented at the trained labor rather than materials used. As 3d printing needs double the cost of labor used in traditional method. This percentage varies according to standards, concrete, the height of the building, and quantities of concrete (the last 2 elements represents the main elements affecting the cost)

N.B: This illustration concerns the application of 3D Printing in Egypt; Given that although labors numbers are reduced, but their costs increase because they are specialized technical workers

5.2. Advantages and Disadvantages of 3D Printing Technology

3D printed buildings can easily lay structures using curvilinear forms instead of typical rectilinear forms which makes them a lot more durable. Structures walls are normally hollowed out to allow for utility lines to pass-through and reduce the amount of materials used. Less material not only adds to the durability but also saves a ton of money on the construction costs for the architects and contractors using 3D printing. While the benefits are endless there are still quite a few hurdles holding back this technology. Let's get into the Advantages and Disadvantages of 3D printed construction ^[19].

5.2.1. Advantages of 3D Printed Construction

Reduced Construction Waste. Using 3D printed construction for architectural projects is more environmentally friendly. While using very little energy the printed construction will only generate about 30% of the waste that a normal construction project produces ^[20].

Increased Design Shapes. 3D printing can create design shapes and customization that isn't possible or would be super expensive if done by regular construction. Printers can precisely place small amounts of concrete exactly where needed for complex shapes greatly enhancing an architect's design possibilities.

Reduced Construction Time. Using a 3D printer to complete a building project can massively reduce the construction period.

Lower Construction Costs. 3D printed buildings have much lower building costs than those built with traditional methods because of the reductions in raw material and more importantly labour. An architectural projects labour costs can be reduced by up to 80% by having most construction completed by 3D printers.

5.2.2. Disadvantages of 3D Printed Construction

Building Codes. There are no regulations or processes to get 3D printed buildings approved for residential or commercial use. The government would first need to come up with standards that must be followed as far as electrical, plumbing, structural integrity and public safety codes.

Material Types. The material that can be delivered from the printer head is pretty much limited to just concrete and plastics.

Engineering Compatibility. Very few architects and engineers have took interest in 3D printed buildings. The additional capabilities that come with the new technology are not being used during the design phase. Traditional blueprints are not compatible for use with a 3D printer, so the entire design process needs to be handled differently.

3D Printing Technology is Expensive. 3D printing equipment and materials cost make the technology expensive. Industrial grade 3D printers are still expensive costing hundreds of thousands of dollars, which makes the initial expenses of using

the technology very high. For a single machine, capital investment starts in the tens of thousands of dollars and can increase to as high as hundreds of thousands of dollars

3D Printers Aren't that User-friendly. Because of the excitement and potential around 3D printing technology, 3D printers have come across as easy to use and sound more useful than they really are.

Manufacturing Job Losses. 3D printing technology can make product designs and prototypes in a matter of hours as it uses only one single step. It eliminates a lot of stages that are used in subtractive manufacturing. As a result, it doesn't require a lot of labor cost. As such, adopting 3D printing may decrease manufacturing jobs. For countries that rely on many low skill jobs, the decline in manufacturing jobs could dramatically affect the economy.

5.3. applying three-dimensional concrete wall printing technology in Egypt

The traditional construction approach in Egypt has numerous drawbacks. This is evident in the lengthy time frame, the large number of used labour, a high percentage of error and long-distance transportation. All these issues lead to adverse environmental impact and increased construction cost. Such downsides can be addressed efficiently by the rising new technology of Three-dimensional printing. Therefore, it will be used SWOT analysis for the application of the 3DP technology in Egypt, and its impact on the Egyptian market with identify the problems and challenges of applying this technology to the Egyptian domestic market.

5.3.1. Possibilities

Discussions suggest that the efficiency of construction time may be key to the emergence of this technology in the Egyptian context, but the type and size of the building are important factors to be considered. Thus, it can be argued that 3DP technology may succeed in mass production projects as well as large buildings with limited floors. Has the potential for rapid production and quality, which may compensate for the low quality of work currently experienced among working labor. In addition, the application of this technology will provide an opportunity to regain control in the hands of certified architects, resulting in better internal environmental quality and energy performance in the construction industry in Egypt. Moreover, changing the current building standard in Egypt may improve architectural identity and enhance the final roles of architects in the construction industry.

5.3.2.Challenges

The expected challenges to the application of this technology are associated with the cost; noting that comparing brick price (used for typical wall construction) to the cost of reinforced concrete could reach $\frac{1}{4}$ and $\frac{1}{2}$ if compared to plain concrete (which should be used for 3DP). More challenges are related to the lack of practical knowledge, lack of scientific knowledge, industry/ society rejection of the norm changing methods as well as the lack of stakeholders' interest, trained workforce and cost of importing. as well challenges facing the automated construction systems

in Egypt, such as lift slab, slip forms ...etc. An additional consideration is related to modification limitations because the design flexibility is limited because of working according to predefined models. It is also impossible to accept any change orders during construction; hence design modifications are not possible. Also, modifications during operation are not possible. Other considerations are related to the costly expenses of durability and maintenance procedures. Moreover, the main concern is that 3Dp technology is imported rather than capacity-building, which

Table. 6 SWOT analysis for the application of the 3DP technology in Egypt

Internal factors	
Strengths (S)	Weaknesses (W)
<ul style="list-style-type: none"> ▪ Time reduction ▪ Increased precision ▪ Longer operational schedule ▪ Reduces construction waste ▪ Minimizes transportation cost ▪ Better control of the construction ▪ Design freedom (complexity is free) ▪ Lower cost/higher productivity ▪ Zero mistakes ▪ Better safety ▪ No added cost for complexity 	<ul style="list-style-type: none"> ▪ High capital cost ▪ Expertise needed ▪ Risk factor elevated ▪ Less awareness ▪ Less incentives ▪ difficult to find skilled labour ▪ 3D Printing Technology is Expensive ▪ Building Codes ▪ not printing horizontal structures ▪ Limited height and large size buildings
External factors	
Opportunities (o)	Threats (T)
<ul style="list-style-type: none"> ▪ Applying BIM integrated technologies ▪ workshops and seminars to prepare workers to cope with the changes in work routine and learn new skills. 	<ul style="list-style-type: none"> ▪ Reducing job opportunities ▪ use of this advanced technology might lead to small companies diminishing. ▪ I believe that clients would be reluctant to use this technology ▪ current workforce would oppose such paradigm shift in construction

will greatly increase cost.

Accordingly, a SWOT analysis is developed to define external and internal factors that affect the widespread application of this technology in the national context. The former factors are attributed to strengths and weakness of the technology itself, while the latter represent external factors that may be considered as opportunities or threats of applying this technology in the local construction market.

As a result, 3D printing technology has opened new possibilities for industries by enabling faster product design, customization, cost reduction, tangible product testing, and more. However, 3D printing technology has a dark side and is not always the right choice for product development for your development project. 3D machines are still potentially hazardous and wasteful. Moreover, their economic, political, societal, and environmental impacts have not been extensively studied.

6. Conclusion

The 3D printing technology has rapidly changed the views on using concrete as a 3D printable material alone. The requirements and challenges in adopting concrete to 3D printing have been discussed. 3D printing technique for cementitious material is a promising method that may revolutionize the traditional building and construction processes in terms of apparent benefits in low-cost, high-efficient automatic construction, architectural design freedom, and reduction of labor requirements and risks during construction. This paper has discussed the different types of 3D printing system that are available commercially in terms of their general benefits and drawbacks. The types of 3D printing concrete technologies, research and commercial projects that have practiced the technologies have been listed. The various possibilities of using concrete as a 3D printable material and future of this technology has been analyzed. Large-scale 3D printing processes of cementitious materials are reviewed. They have the potential to reshape the way we think about architectural buildings. However, 3D printing technology still faces certain challenges associated with mechanical strength, reinforcement, curing, durability and correlation properties like flowability, extrudability and buildability. It is a great challenge to study printable cementitious materials compatible with 3D printers.

However, the technology needs more resources to develop faster. The truth behind the 3D construction printing projects is that none of the completed projects has been competitive so far. There might have been some saving in labor costs and materials, but overall it has not been competitive to the traditional methods of construction. It is evident that many companies and academia are interested in the 3D concrete printing technology, but there is a lot to be learned on this subject in the near future. The phase of scientific advancement in technology has risen in the past few decades from mobile phones to artificial intelligence. Therefore, the future holds good promises for 3D Concrete Printing.

6.1. Recommendations

- Increased cooperation with academia for insights in new and improved 3D concrete printing technologies.
- Increased cooperation with conventional suppliers to support the development of concrete 3D printing.
- Capital and Investments in concrete 3D printing projects should increase with rising popularity of this technology.
- Integrating reinforcements in the 3D printed structure to build high-rise buildings in the future.
- Usage of recycled materials should be increased to build environmentally friendly structures.
- The trends of using concrete 3D printing will increase in the field of architecture for its versatile nature for complex designs.
- through BIM software. This could allow a greater control over all phases of the project, from concept to engineering, with tighter control of time and cost, as well as fewer unforeseen and varied workloads.
- Strategic Implications for Stakeholders As this evolution proceeds, the construction industry will be transformed.
- Companies and governments would do well to prepare for this transformation and to influence it as far as possible to their own.

- [1] Chang, S. H. (Shawn H. (2016), '**Exploring the evolution of additive manufacturing industry: a study of stakeholder requirements and architectural analysis of Desktop three-dimensional printing Segment**', Massachusetts Institute of Technology. Available at: <https://dspace.mit.edu/handle/1721.1/106243> (Accessed: 15 January 2018).
- [2] Dana Goldberg (no date) '**History of 3D Printing: It's Older Than You Think**, Available at: <https://www.autodesk.com/redshift/history-of-3d-printing/> (Accessed: 15 January 2018).
- [3] Paul, S. C. et al. (2018), '**A review of 3D concrete printing systems and materials properties: current status and future research prospects**', Rapid Prototyping Journal, p. 0. doi: 10.1108/RPJ-09-2016-0154.
- [4] Nithesh N. (2018), '**Development of concrete 3D printing**, masters in Building Technology at Aalto University, 2018.
- [5] Chen, D. et al. (2015), '**Direct digital manufacturing: definition, evolution, and sustainability implications**', Journal of Cleaner Production. Elsevier, 107, pp. 615–625.
- [6] Roberto Naboni and Ingrid Paoletti. (2015) '**Advanced Customization in Architectural Design and Construction**', Springer Cham Heidelberg New York, ISBN 978-3-319-04423-1 (eBook).
- [7] '**Spain unveils world's first 3D printed pedestrian bridge made of concrete**', 3ders.org. Retrieved 2019-04-16.
- [8] [Building a lunar base with 3D printing / Technology / Our Activities / ESA](#), Esa.int. 2013-01-31. Retrieved 2019-04-30.
- [9] Diaz, Jesus (2013-01-31). '**This Is What the First Lunar Base Could Really Look Like**', Gizmodo. Retrieved 2013-02-01.
- [10] Wolfs, R. J. M., Bos, F. P. and Salet, T. A. M. (2018) '**Correlation between destructive compression tests and non-destructive ultrasonic measurements on early age 3D printed concrete**', Construction and Building Materials. Elsevier Ltd, 181, pp. 447– 454.
- [11] Bos, F. et al. (2016), '**Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing**', Virtual and Physical Prototyping. Taylor & Francis, 11(3).
- [12] Nathan Ingraham (2017), '**TU Eindhoven's 3D-printed concrete bicycle bridge first of its kind**', Available at: <https://www.designboom.com/technology/tu-eindhoven-3d-printed-concrete-bicycle-bridge-gemert-09-08-2017/> (Accessed: 22 December 2017).
- [13] Marlon A (2015), '**How 3D Printing is Affecting the Construction Industry**', Available at: <https://www.forconstructionpros.com/blogs/construction-toolbox/blog/12059477/how-3d-printing-is-affecting-the-construction-industry> (Accessed: 22 December 2017).
- [14] Paul, S. C. et al. (2018) '**A review of 3D concrete printing systems and materials properties: Current status and future research prospects**', Rapid Prototyping Journal.
- [15] Hager, I., Golonka, A. and Putanowicz, R. (2016) '**3D Printing of Buildings and Building Components as the Future of Sustainable Construction?**', Procedia Engineering, 151, pp. 292–299.
- [16] Roussel, N. (2018) '**Rheological requirements for printable concretes**', Cement and Concrete Research. Elsevier, (January), pp. 1–10.
- [17] Li, Z., Wang, L. and Ma, G. (2018) '**Method for the Enhancement of Buildability and Bending Resistance of 3D Printable Tailing Mortar**', International Journal of Concrete Structures and Materials. Springer Singapore, 12(1). doi: 10.1186/s40069-018-0269-0.
- [18] Wangler, T. et al. (2016) '**Digital Concrete: Opportunities and Challenges**', RILEM Technical Letters, 1, p. 67. doi: 10.21809/rilemtechlett.2016.16.
- [19] Wolfs, R. J. M., Bos, F. P. and Salet, T. A. M. (2018) '**Early age mechanical behavior of 3D printed concrete: Numerical modelling and experimental testing**', Cement and Concrete Research. Elsevier, 106(May 2017), pp. 103–116. doi: 10.1016/j.cemconres.2018.02.001.
- [20] Wolfs, R. J. M., Bos, F. P. and Salet, T. A. M. (2018) '**Early age mechanical behavior of 3D printed concrete: Numerical modelling and experimental testing**', Cement and Concrete Research. Elsevier, 106(May 2017), pp. 103–116. doi: 10.1016/j.cemconres.2018.02.001.