DEVELOPMENTS OF 3D CONCRETE PRINTING PROCESS

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Abstract

The 3D Printer is a device which is designed to produce scanned 3-D models on a computer by using various materials, without - need for an extra mold. 3D production is also known as a production method for desktop manufacturing or "additive manufacturing (AM)". In this technology which is known as rapid prototyping, 3D computer design is transformed into a real object. By the 3D printer technology, low material usage, light weight products and design of multi-function components are made available. This technology-3D printer- which has been adopted in the manufacturing industry for decades, has recently been used in the construction industry for rapid and practical production of houses and villas. This technology can provide significant benefits to the construction industry in terms of building construction, reduced construction time, workforce and construction cost. In other words, 3D concrete printer technology provides the opportunity to use a wide range of materials, providing more freedom in both architectural and structural design and allowing the production of low cost structures and building elements due to high speed of production without moulds or scaffolding. Compared to traditional building construction techniques, 3D printing technology should be considered as an environment friendly product that offers virtually unlimited possibilities to implement structures that involve geometric complexity. However, in industrial applications of 3D concrete, there are disadvantages in using this technology, such as material-mixture formulation, lack of standard and interfacial connection quality between overlapping layers. For the production of 3D concrete, a multidisciplinary effort is required such as material science, architecture/design, engineering- and robotics knowledge. Despite of the comprehensive work on this technology by several leading and different companies and institutions all over the world, it was noticed that the construction industry has not been fully successful in the development of the 3D layered production technique. In spite of continuing efforts in overall the world, this technology is still inadequate. 3D concrete technology is a promising technique that can make huge changes in the construction industry. 3D concrete production method, which is the future concrete technology, should be developed rapidly with the scientific studies and R & D studies of the firms in the production sector and a worldwide awareness should be taken into consideration. In this study, the development of 3D concrete printing from its beginning until the present is discussed.

Keywords: Additive manufacturing; Construction cost; Environmental effects; Mass customization; 3D concrete printing technology

1. Introduction

Concrete, which is obtained by mixing aggregate, water and cement in certain proportions is one of the most consumed materials commercially. Portland cement is the most important component of concrete which make a significant revolution in the last century. In 2013, world cement production was approximately 4 billion tons. Relating to the previous situation, approximately 26.7 billion tons of aggregate and 2.7 billion tons of water were consumed, which makes it clear that 33.4 billion tons of concrete have been consumed in 2013 (Justnes and Hammer 2016; Tangüler et al. 2015). Roads, bridges, tunnels, dams, power plants, harbors, airports, ditches, sea walls, waste and freshwater power plants and networks, all these buildings and their infrastructures are based on the widespread usage of concrete. The developments in the energy sector and the continually climate change will lead to an increasing demand for concrete. Significant amounts of concrete which are required for renewable energy installations, such as wind farms and the rise of the ocean level will probably require the construction of thousands of kilometers of dam (Damme 2018).

Nowadays, 3D printer technology is used in many fields and it has different usage areas every day; like industrial manufacturing, medicine and health, aerospace, architecture and construction, military applications, textiles, food, and education. By comparing all these areas, the construction industry is still behind the development of 3D printing production. The positive impact of 3D printing on the construction industry should not be underestimated, as it will reduce the various determinants of the entire project, such as construction, material, costs and time. For the first time in 1984, by Charles (Chuck) Hull, a 3-dimensional object production using numerical information was realized (Nadarajah 2018). The 3D digital model is converted to STL (Stereolithography) format and sent to the 3D printer. The 3D printing creates a concrete object by building it layer by layer. Previously it was known as Rapid Prototyping. The 3-D printing technology uses a small amount of material, thus, introduces lightness into the products and makes it possible to design multi-functional components.

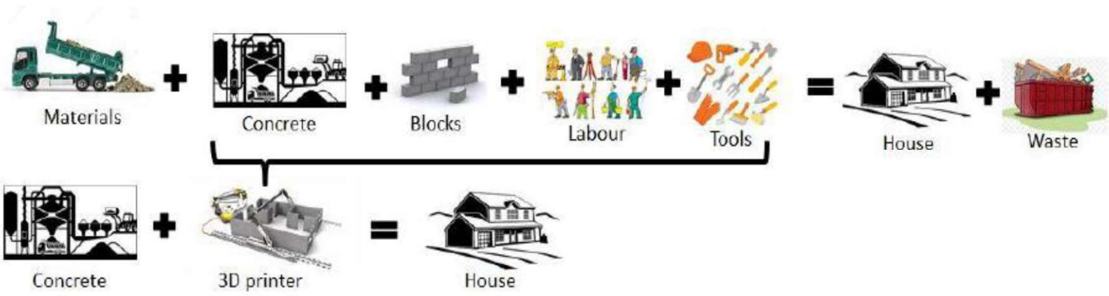


Figure 1. Comparison of traditional construction and 3D printing construction process (Nadarajah 2018)

Some advantages of production by using 3D concrete printing are listed as follows;

• Since the production of complex geometries can be made easier with concrete printing, it will be possible to produce complex and limitless possibilities of new architectural designs.
• 3D printing, which is an economic production method, limits concrete consumption by using concrete only where it is needed.
• There is no need to use the vibration method when using this robotic technology.
• Productivity may increase by using printers which can work 7/24 without needing moulds.
• The digital production type can work with a digital design type that perfectly matches the Building Information Model.
• Produced elements can be used many times without a significant increase in production costs or duration (Özalp et al. 2018).

There are several methods of discovering products with 3D printing. Almost all of these methods are based on layering method. This means that the main concept of these technologies is Additive Manufacturing (AM)

1.1. Additive manufacturing

Additive manufacturing is defined as a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies by the ASTM. The synonymous usages are: Additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication (ASTM F2792-10). Usually, AM technologies includes use of a computer, 3D modeling software (Computer Aided Design (CAD)), machine equipment, and layering material all together as presented in Figure 2. After a CAD draft is generated, the file is transferred to the AM equipment and the machine reads the data from the CAD file. After that the object is created in its three-dimensional shape by placing the material in layers one on top of the other. To create the object different materials like: powder, liquid and metal plates (Chang 2016) can be used.

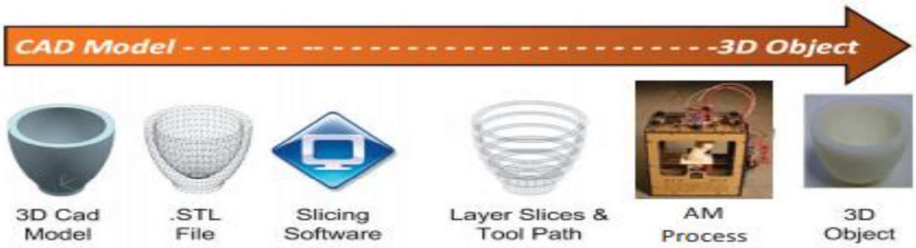


Figure 2. Generalized Additive Manufacturing Process (Campbell et al. 2011).

The layered production process has being used since the mid 1960s, and there have several developments in the material usage. Since the mid of the 1990s, this process has been used in concrete production (Bos et al. 2016). The term layered production includes several technologies that can rapidly generate similar objects, such as Rapid Prototyping (RP), Direct Digital Manufacturing (DDM), Layered Manufacturing (LM) and 3D printing. Layered production, today commonly known as 3D printing, which has been very effective in reducing the production cost process duration (Nadarajah 2018). AM has significant advantages in the construction industry. For example, AM provides reduction inwaste materials up to 30 % and energy consumption, in situ production, reduction in use of raw materials and CO2 emissions and still more architectural/design and other advantages as compared with general techniques (Gebler et al. 2014; Bos et al. 2016). However, AM processes often include disadvantages to conventional construction and manufacturing processes, such as slow print speed, high precision, surface quality, the need for careful selection of materials and low mechanical properties (Hopkinson et al. 2006). AM processes are used in design production in the aerospace and automotive industries, the manufacture of small parts are used in medical applications and architectural modeling. Research in free-form structures began in 1997. Pegna (1997) showed that the complexity of the construction process could be simplified by restructuring with a number of basic operations and that three-dimensional form could be obtained by layered production by leaving a layer of reactive material (Portland cement) on a sheet. After this initiative, large-scale construction sector started adopting AM techniques.

The use of AM may be changed according to the designer's working method and design processes. In this regard, there are currently three large-scale AM processes worldwide; i- Contour Crafting (America), ii- D-shape (Italy), and iii-Concrete Printing (UK).

All these three methods have proven that components of considerable size can be successfully produced and are suitable for construction and/or architectural applications and have begun to replace traditional construction processes.

1.1.1. Contour crafting (CC)

One of the major developments in AM technologies related to the construction industry is Contour Crafting (Lim et al. 2012), a layered production technology using robotic arms and extrusion nozzles. The first usage of the Contour Crafting (CC) technique, which is one of the origins of 3D concrete printing and is still used, can be seen in the early publications by Khoshnevis and Bekey (1998) (University of Southern California). The development of that technique from that time until now has shown serious development. Polymer, ceramic paste, cement, and various other materials and mixtures were used in the layered production method used to create large-scale objects with a smooth finished surface (Wolfs 2015). The CC process is a process that simulates the traditional construction process but is carried out with some automation. The CC process is an interesting concept, the mould is not disposed of and becomes a part of the wall, it requires three separate steps as molding, reinforcement and placement, the height of building layer is around to 20 mm. In the CC method, various materials such as coarse aggregates, reinforcing fibers, additives can also be used, and may also deflect the nozzle to form non-orthogonal surfaces such as domes and vaults. With Contour Crafting, NASA has also been interested in space research management. From the experiments on the CC, it was observed that the method was also promising in possible constructions on the moon (Khoshnevis and Zhang 2012; Cesaretti et al. 2014; Özalp et al. 2018).

1.1.2. D-shape

Enrico Dini, an Italian civil engineer invented a 3D printer called D-shape. It was created in 2004 claiming the world’s first construction scale 3D printing technology that consolidates crushed dolomitic limestone into a solid-stone material. Enrico's aim was to use locally available materials to form 3D printed structures. The binder was a natural one that was tested successfully against a wide variety of crushed stone aggregates, such as volcanic rock and marble (Nadarajah 2018; Anonymous 2019(a)). The D-shape process is based on injecting a binder into the material layer. The process aims to print architectural works using an inorganic binder with sand in 5-10 mm layers. The method uses a powder deposition process that is very similar to the ink-jet powder printing process in which the binder is used, so that the desired layers of the printing materials are shaped (Cesaretti et al. 2014). The disadvantage of such processes is that they require more maintenance, cleaning and control, and the final structure must be cleaned from the remaining dust to form the post-treatment shape. Part of the post-processing process involves removing the unused building dust and grinding and polishing the surface (Lim et al. 2009). The D-Shape is a huge 3D printing process that is designed and built digitally from the basement floor to the roof, including foundations, partitions, ceilings, staircases, gaps.

1.1.3. Concrete printing (CP)

Concrete Printing is another large-scale 3D construction process. it is similar to ContourCrafting with concrete printing because the print head used for the cement mortar extrusion is also mounted on a top crane. The printing nozzle moves along a pre-programmed path and continuously extrudes the concrete materials. Compared to Contour crafting, the 3D CP method has less deposition resolution, which allows better control of complex geometries. CP has the potential to produce highly customized construction components (Ma et al. 2018). Unlike D-Shape, CP uses a single spool nozzle, which means that only the required volume of material is stored for the structure; however, the single nozzle approach inevitably limits the deposition rate, because the nozzle must circulate around the entire structure area (Lim et al. 2012). As in most AM processes, the process is based on extrusion by using a cement based mortar that provides data preparation, material preparation, mechanical and other properties (Lim et al. 2011). In the Department of Civil and Structural Engineering at Loughborough University, the technique of concrete printing (CP) has been developed for using in extrusion-based construction processes in a manner similar to CC. In addition to achieve 100 MPa of compressive strength and a bending strength of 10 MPa in 28 days, a high-performance printing concrete has been developed based on workability, extrudability and buildability requirements (Le et al. 2012 (a); Le et al. 2012 (b)). Figure 3. shows the elements in which CC, D-shape and CP methods are produced.

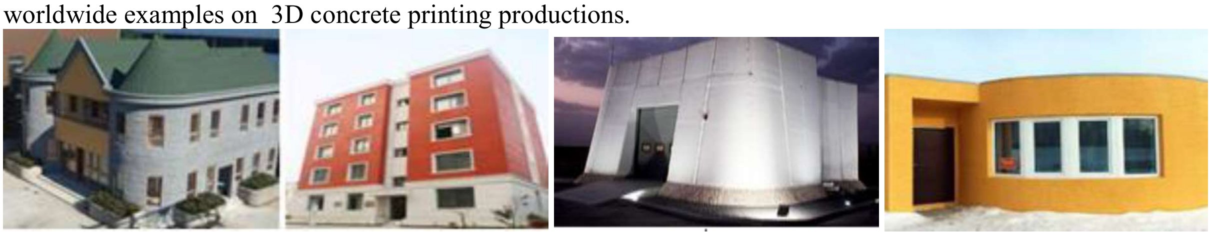
a b c

Figure 3. a: Schematic representation of Detached Houses produced by CC (Anonymous 2019(b)), b: Radiolaria designed by Andrea Morgante and printed with D-shape (Anonymous 2019(a)), c: Wonder Bench (2 m×0.9 m×0.8 m) produced by CP (Loughborough University, Lim et. al. 2011).

2. Developments and Requirements

2.1. Developments in the 3D concrete printing technology

In the last few years, 3D printing concrete concept has been developed around the world. The use of concrete and cement-based materials in combination with 3D printing continues to grow with time. In this context, the process, which started with small non-structural applications, started to produce large scale structures with the increase of large-scale companies that adopt and develop the 3D printing method. Below is a list of some of the worldwide examples on 3D concrete printing productions.



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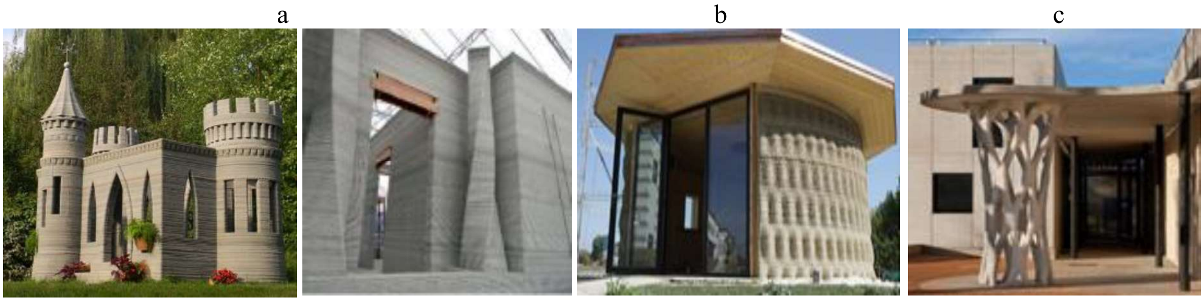

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Figure 4. a: Multi-storey houses produced in China by Winsun (Anonymous 2019(c)), b: 3D Dubai R & D Laboratory by CyBe (Anonymous 209(d)), c: 3D concrete printing house produced in Russia by Apis Cor (Anonymous 2019(e)) , d: Castle in Minnesota, USA and Hotel suite interior in the Philippines by Total Kustom (Anonymous 2019(f)), e: Gaia is a sample home by WASP (Anonymous 2019(g)), f: Post In Aıx-En-Provence by XtreE (Anonymous 2019(h)), g: Office building in Dubai by Winsun (Anonymous 2019(i)), h: The first 3D printed pedestrian bridge in China by Tsinghua University (Anonymous 2019(j)), i: Bridge produced by 3D concrete for cyclists in 2017 by Eindhoven University of Technology (Anonymous 2019(k)) , j: Urban furniture by İSTON (Anonymous 2019(l)).

2.2. Requirements of concrete for 3D printing

In the last few years, 3D printing concrete concept has been developed around the world. The use of concrete and cement-based materials in combination with 3D printing continues to grow with time. In this context, the process, which started with small non-structural applications, started to produce large scale structures with the increase of large-scale companies that adopt and develop the 3D printing method. Below is a list of some of the worldwide examples on 3D concrete printing productions.

The following key properties of concrete needs improvement in order to successfully 3D print concrete structures:

- Extrudability: Extrusion process is the ability of concrete to pass through a concrete pump, transmission pipe and spray nozzle without any change in its physical properties. Good extrudability is achieved by co-application of Self-Compacting Concrete and Shotcrete principles to the mixture design (Le et al. 2012 (a)). The concrete must have a smooth flow rate to allow the printer to pour into layers on top of each other. If the structure has a lot of architectural detail, the printing speed must be adjusted accordingly, so the system does not waste the extrusion material and the quality of the concrete printed material is flawless. Excessive build-up of concrete during printing results in poor surface coating resulting from incorrect control of the system (Nadarajah 2018). The construction of concrete layers with extrusion and the fresh concrete properties of 3D concrete is mentioned in many studies, but a suitable test method has not been defined to evaluate this concrete property.

- Buildability: Buildability can be defined as the ability of the underlying concrete layer to harden and carry the other layers before the next concrete layer is placed on the printed layer. In that way, a suitable platform is provided for the construction of the concrete on each floor. Extrudability and Buildability are the most important features of concrete in 3D printing. The requirements of both of them are related to the workability of concrete (Le et al. (2012) (a)). Bos et al. (2016) found that in the 3D production method, the sub-layers should not deform by the weight of the top-layer, but also the interlayers must adhere and they have to be well connected with the upper layers to be able to form. Factors that affect Buildability are: Chemical admixtures, temperature and using of less gypsum cement.

- Workability: The quality of the final printed structure is significantly influenced by the properties of the fresh concrete after being poured, remain intact and have sufficient workability (can be extruded)and does not collapse under a load of successive layers. Conventional methods for evaluating workability include the slump, compression factor and flow tests for which various national standards are available. The workability of 3D printing concrete is affected by small changes in environmental conditions (temperature, humidity, raw material moisture etc.) (Papachristoforou et al. 2018). To increase the workability of the 3D concrete mixture viscosity modifying agent should be added and the mixture must have a small particle size to suit the nozzle diameter. The adjustment of the workability of 3D concrete for pumpability and extrudability is similar to the wet process production of the Shotcrete Concrete (Lim et al. 2011). It is essential that viscosity modifying agents are used in 3D concrete printing. Because, these agents change the rheology by adding thixotropic properties to the concrete. By this way, the viscosity of the concrete decreases when the force is applied provides comfortable workability and good pumpability, and when the application of power stops, the viscosity increases so that a good skid resistance is obtained in the concrete (Özalp et al. 2018).

- Open time: The workability time of a cement material is generally associated with the setting time, measured by a Vicat. This equipment is designed to determine the start and end time of the setting, and cannot be used to characterize the change in the workability of fresh concrete over time. Several studies have been carried out to monitor the change in workability over time using the crash test. However, it is not appropriate to perform a crash test to determine the open time duration. Measuring the sliding force over time gives more informative results in terms of measuring workability. The Open time period is determined as the period of time when the workability of fresh concrete for 3D concrete is sufficient to maintain extrudability (Le et al. 2012 (a)). This means that the open time is the time during which the 3D concrete's Pumpability, Printability and Buildability are consistent within acceptable tolerances.

- Contact strength between layers: In placing the concrete on top of each other, the interfacial adherence must be strong in order to obtain a solid structure. Therefore, the concrete should not be in a hardened condition, but instead of hydrating the concrete, the preceding layer should continue when concrete is placed on the surface. In other words, the cold joint must not occur. To ensure this, some researchers have emphasized the importance of the shape of the layers. The shape of layers can be modified by varying the printing nozzle's shapes (Bos et al. 2016). Besides the size and shape of nozzles, the printer should rotate 90 degrees around the corners in order to shape the corners accurately for the structure. To provide corners of 90 degrees, the versatility of the 3D concrete printer is taken into consideration and tested many times before actual printing (Wolfs 2015).

- Aggregates: Aggregates play a very important role in the process of 3D concrete. The type and size of aggregate used in the concrete mixture have an effect on the load-bearing capacity of the structure. Nozzle sizes change between 20 mm and 40 mm. Accordingly, the size of the aggregates should be greater than 4-6 mm in order to prevent the nozzle from blocking. The use of coarse aggregates also leads to instability in the printing structure, causing collapse of the structure formation (Nadarajah 2018).

- Water-cement ratio: The water-cement ratios have been experimented from 0.25-0.44 by various researchers. The use of the minimum amount of water with superplasticizers is important for the better adhesion of concrete. In addition, it was determined that the addition of materials such as fly ash, silica fume and slag could be beneficial to the mixture if it is added by 5 to 30% of the total binder volume (Nadarajah 2018).

Since till now there are very few articles about the material composition and properties for 3D concrete, but there is a known fact that 3D concrete should be designed to be extruded from a nozzle to form the top-layer structural components. The result of this mixture requires a plasticizer to increase the workability and the use of material with fine particle sizes so that it can flow freely from the nozzle diameter.

3. Challenges and Opportunities

In recent years, an automatic layer by layer production process, 3D concrete printing technology, has started to attract attention in the construction industry. Moreover, the development of AM is described as a new revolution in the construction industry. 3D concrete printing technology is not yet an isolated solution that can solve all problems in the construction industry because it is still under development. Although several studies have been carried out in the construction sector but still now there is a need to continue working on this technology to understand its role in the construction industry and reach its maximum potential. With developing in the field of robotics 3D printing technology will be developed in order to overcome these limitations at the same time (Wu et al. 2016; Camacho et al. 2018; De Schutter et al. 2018).

In the early studies, it was thought that 3D printing technologies may not be suitable to create large-scale models or structures (Gibson et al. 2002). These claims were doubled because of using the small size of 3D printers in the initial phase of technology. On the other hand, with the development of new 3D printers in recent years, many large-scale models or structures have been created using these large-scale 3D printers (Wu et al. 2016). Samples are presented in Figure 4.

In addition to the size of the printers, the materials play a very important role in 3D printing. In the construction industry, almost all of the AM production work is focused on concrete. This has led to very limited availability of the currently owned material palette. The durability and mechanical characteristics of the printed products using the latest printing materials must be high performance for the use of 3D technology in large scale models and structures. However, due to the difficulty of having high-strength printing materials, it is thought that 3D printing cannot be used in large scale models and structures. But it has been proven that it may be as effective as various materials modified and high-strength printing materials. Also, the strength of the conventional concrete can be obtained in large-scale structures from printing concrete

Looking at the current state of the 3D printing materials, it is seen that there is still not enough focusing on material properties. The studies on concrete are mainly related to the initial strength and long-term strength, mainly the load-bearing capacity parameter. Although the materials used for 3D printing technology are examined in terms of their load resistance capacity, they are rarely examined for their fire resistance, durability and thermal properties. When material performance is checked in detail, some mechanical and physical properties may be poorly observed. According to the information obtained from the studies, an appropriate mixture design and effective curing measures should be developed to ensure the expected performance. Although there are some developments for the production of 3D concrete, the mixtures are very sensitive due to their physic-chemical structure. This means a change in the nature of cement or aggregate may require a new adaptation of the concrete mix design or additive type. In addition, Materials must have some basic properties, such as fast curing, for use as 3D printing material. And if the concrete is used as a printing material, it should be able to be extruded to an acceptable degree so that it can be removed from the nozzle of the printer. In order to form each layer, concrete layers must adhere, while casting concrete must have sufficient workability features and must have buildability feature to carry the top layers and prevent collapsing (Labonnote et al. 2016; Wu et al. 2016; De Schutter et al. 2018).

Interface zones which are formed between the layers will significantly affect the mechanical performance, bond behavior, bearing and durability of the product of 3D printed structures/elements. Current structural and durability design standards consider concrete as a homogeneous material. However, this is not acceptable for the case of 3D printed concrete elements with anisotropic behavior, because of the layered structure and weaker interface. The layered system structure that requires new design models, such as the shear load at the structural design stage will need to be considered (De Schutter et al. 2018).

Concrete current standards need to be revised to be used in 3D printed concrete, having anisotropic behavior. Lack of appropriate standards and performance testing protocols are obstacles to the development and enhancing of digital production in the concrete industry. Moreover, this situation makes it difficult to compare the applications and studies in the literature. RILEM is supporting digital concrete technology. In addition to several groups of researchers, companies and universities are working on developing standards for AM technologies (Camacho et al. 2018; De Schutter et al. 2018).

The construction industry is responsible for high environmental impacts worldwide. Innovative construction processes need to emerge to reduce the high environmental impacts caused by the traditional construction process, which is increased by the fact that communities are more concerned about sustainability. The process of additive manufacturing, which reduces energy use, resource demands, and CO2 emissions, is a cost-effective construction process (De Schutter et al. 2018).

The results of environmental assessment have confirmed that digital production for highly complex geometry structures provides high environmental benefits compared to conventional construction. As seen in the figure below, the environmental impact of digital production does not change with increasing complexity of the structure. In the conventional construction process, as the complexity of geometry increases, more resources will be needed and more waste construction material will emerge and the construction process will be extended. AM is a construction method that works in harmony with the environment, which produces less waste and enables recycling by reusing most of the wastes in the future for different works. It can only be thought that complex geometries are not always advantageous in shape. However, as the complexity of the structural geometry to be obtained by the optimization means increases, the material utilization can be significantly reduced by utilizing the material used in maximum performance. For the construction of this structure, digital production seems to be quite advantageous compared to conventional construction with limited environmental impact and cost. It is also expected that additive production will provide significant benefits for the construction of structures in hard environments where human access is difficult, impossible or dangerous. In this way, possible accidents can be prevented in such applications (Labonnote et al. 2016; De Schutter et al. 2018).

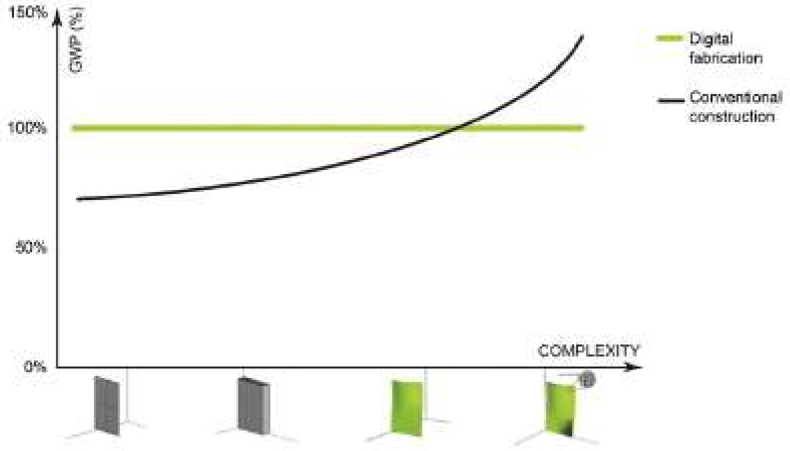

Figure 5. Comparison of environmental impacts of conventional construction and digital production, depending on building complexity (Agusti-Juan et al. 2017; De Schutter et al. 2018).

With the increased of use of complex geometry moulds, the difficulty of construction increases, the time and labor force required for the design and production of the mould also increase, and as a result, the total construction process is extended. The advantage of this technology is that it does not require molds, reduces the need for labor, and enables the production of large-scale structures in a short time. In addition, it is expected that the technology will significantly reduce the weight of the building and the cost of the construction materials used by significantly reducing the amount of material used, thanks to the advantages of the construction process and the high degree of optimization of the components. In particular, the construction of complex structures is expected to decrease in cost compared to conventional methods. Moreover, the cost of the structures produced by 3D printing is expected to become independent from the increase in the complexity of the structure. Also, this situation was studied by Agusti-Juan et al (2017). On his study of Potential benefits of digital fabrication for complex structures: Environmental assessment of a robotically fabricated concrete wall as seen in figure (Labonnote et al. 2016; De Schutter et al. 2018; Camacho et al. 2018).

The 3D printing technology offers a great deal of mass customization alternatives to the construction industry, which is always known to be an industry with limited mass customization. Contrary to the conventional methods of limiting the imagination of architects, the construction sector can be opened to a wide variety of mass customizations. The success of 3D printing in the construction industry depends on two factors; the uniqueness of the customer's needs and the degree of customer's desires. For example, in the construction industry in Korea for the last 30 years, mass customization in the house building sector is the core marketing strategy. Researchers agree that construction applications using 3D printing technology will increase gradually in the near future (Labonnote et al. 2016; Wu et al. 2016).

Furthermore, a complex geometry structure which is difficult and expensive to construct by conventional methods using standard construction procedures can easily be produced by means of 3D printing technology. 3D printing technology will accelerate the development of innovative construction that is not technologically and economically available a few years ago. New structural forms need to be explored, which will increase the potential of 3D printing technology in the construction sector and reveal its benefits (Labonnote et al. 2016; Camacho et al. 2018). This brings many advantages such as reducing material consumption and environmental impact, achieving aesthetic appearance and limitless designs. It should be kept in mind that the constructions made with 3D technology must comply with the mechanical rules and must ensure the safety and reliability levels expected by the current construction standards. The method will encourage more innovative designs, but these designs will have to be more rational.

4. Conclusion and Recommendations

The 3D printing technique for cement materials is a promising method, which can revolutionize the obvious benefits of low cost, high-efficiency, automatic construction, architectural design freedom, construction requirements and the reduction of risks during construction in conventional building and construction processes.

This paper discuss 3D concrete technology by taking the 3D concrete printing system in terms of its general opportunities and challenging which are summarized as follows;

- 3D printing technology needs to be developed in the directions of mechanical strength, reinforcement, curing, and durability. There is a few research on the durability of 3D concrete printing. Curing conditions should be investigated for 3D concrete printing, especially on in-situ applications.
- 3D concrete has some viable properties like flowability, extrudability and buildability. These properties are different from conventional concrete. For this reason, the design of 3D concrete should be made more carefully by taking into consideration these properties.
- One of the basic challenges is to obtain printable cement materials compatible with 3D printers. Currently available high-performance and very durable cement-based materials cannot be directly processed in a printing technique, because of inadequate rheological and stiffening properties. Cement's rheological properties, setting time and hydration temperature should be suitable with open time 3D concrete.
- Still, there isn't any standard about 3D concrete printing technology around the world. Basic and unified standards are needed to be established for effective and accurate evaluation for the mechanical behavior of specimen, components and structures manufactured with cement material by means of 3D printing.
- The initial cost of 3D concrete printing technology is high due to the high cost of 3D printer devices. Considering the different cost elements (labor, machinery, material, design and planning costs), 3D concrete printing presents many potential opportunities to increase the cost-effectiveness of construction processes in comparison to conventional construction methods.
- When the impact on environment is considered, design optimization in 3D technology increases shape complexity, but also reduces using of material. As a result, it is expected that for structures with the same functionality, 3D technology performs environmentally better over the entire service life in.

In order to solve these problems, ongoing research should focus on interdisciplinary works involving materials science, manufacturing methods, robotics, architecture and design. If the problems of 3D concrete printing technology are solved, 3D printing can reach its maximum potential in the construction field. The following steps are recommended for the more development of 3D concrete printing in the future

- Cooperation with academia should be increased for insights in new and improved 3D concrete printing technologies and cooperation with conventional suppliers should be increased to support the development of concrete 3D printing.
- Reinforcements should be integrated into the 3D printed structure to build high-rise buildings in the future.
- Usage of recycled materials in 3D concrete processes should be increased to build environmentally friendly structures.
- The using 3D concrete printing should be increased in the field of architecture for its versatile nature for complex designs.
- In the future, the compatibility between 3D concrete printing and hybrid technologies for more efficient construction should be increased.

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