Low-Carbon 3D Printed Concrete: A General Review of the Technology and Method

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***Abstract*— During the last decades, there has been an increase in interest in news about technologies and application methods to turn concrete into a less polluting material. 3-D Printed Concrete technology is an innovation in this direction. The main purpose of this paper is to address the pollution issue in construction in general and in the concrete industry in particular. To achieve this aim, this paper is divided into three sections. The first section, the construction industry and concrete contamination is explained. The second section introduces 3D Printed Concrete technologies as a possible solution to the contamination issue, describing its composition, properties and elaboration process. Finally, the last section delves into the main economic, technological and environmental benefits of this technology. It is expected that this work can motivate the incorporation of new building technologies in the construction industry to address the contamination issue and contribute to environmental improvement.**

Keywords: 3D printing, concrete, cement, construction industry

***Resumen*— Durante la última década ha habido un incremento en el interés en nuevas sobre tecnologías y métodos de aplicación para convertir el hormigón en un material menos contaminante. La tecnología del hormigón impreso en 3-D es una innovación en esta dirección. El principal propósito de este informe es atender los problemas de contaminación en las industrias de la construcción en general y el hormigón en particular y su posible soluciones con la tecnología 3DPC. Este reporte está divido en tres secciones. En la primera sección, la contaminación de la industria de la construcción y el hormigón es explicada. En la segunda sección se introduce la tecnología de impresión de hormigón en 3D como una posible solución a los problemas de la contaminación describiendo su composición, propiedades y proceso de elaboración. Para finalizar, en la última sección se profundizará en los principales beneficios económicos, tecnológicos y medioambientales de esta tecnología. La expectativa de este trabajo es la motivar la adopción de nuevas tecnologías de construcción para la industria así como en la dirección de los problemas de la contaminación, contribuyendo a mejorar el medio ambiente.**

Palabras clave: impresión 3D, hormigón, cemento, industria de la construcción

I. Introduction

During the last decades, there has been an increase in interest in news about technologies and application methods to turn concrete into a less polluting material. These solutions are divided into new application methods and the replacement of highly polluting materials in the composition of concrete. The construction industry is still the main cause of CO2 emissions and consumes large reservoirs of non-renewable materials such as sand, water in an uncontrolled way [1, p.2].

This topic is closely connected with the United Nations' 2030 Sustainability Agenda. It is more specifically connected with Sustainable Development Goal (SDG) #9, "Build resilient infrastructure, promote inclusive e and sustainable industrialization and foster innovation"; #11, "Make cities and human settlements inclusive, safe, resilient and sustainable"; #12, "Ensure sustainable consumption and production patterns"; and #13, "Take urgent action to combat climate change and its impacts" [2, p.3]. A change in the way the most widely available material in construction is used directly impacts on all these goals.

3D Printed Concrete (3DPC) can be used to produce various types of structures, such as user-customized and atypical designs with high complexity, but also to produce massive and fast structures. However, 3DPC is still in its early stage and its application is limited to certain areas due to technical weaknesses as mentioned by [3, p.1]. These technical constraints include rising production costs and energy-consuming construction methods.

While a simple manufacturing and production system is possible without going through lengthy and unnecessary building stages, these changes ensure a new building paradigm that allows users to build based on their own ideas through production and manufacturing systems. This simple method may bring many benefits to reduce environmental impacts due to its characteristics.

The main purpose of this paper is to address the pollution problems in the field of construction in general and concrete in particular and its possible solution with 3DPC technology. In order to achieve this objective, this paper is divided into three sections. Firstly, the problem connected with the construction industry and concrete contamination is explained. The next section introduces 3D Printed Concrete as a possible solution to the contamination issue, describing its composition, properties and elaboration process. Finally, the last section delves into the main economic, technological and environmental benefits of this technology. It is expected that this work can motivate the incorporation of new building technologies in the construction industry so as to address the

contamination issue and contribute to environmental improvement.

II. Contamination in the Construction Industry

The excellent results the construction industry produces is not without a negative impact on the environment. This includes water and noise contamination, generation of greenhouse gases, which all cause climate change and generation of large waste.

The pollution from the construction industry covers all stages of the construction process and it produces a large amount of carbon emissions according to [3, p.1]. The construction process ranges from manufacturing construction materials to transportation and on-site construction, machinery, among others. Many of these processes have high-energy requirements.

In this section of the paper, the contamination of cementitious materials, concrete and on-site construction will be studied and analyzed.

A. Cement Manufacturing Pollution

The manufacturing process of Ordinary Portland Cement (OPC), which consumes large quantities of resources and energy, and generates massive amounts of greenhouse gases, results in a substantial burden on our living environment [4, p.5]. As well as this, over time, people and workers in the cement industry inhale toxic byproducts of the manufacturing process that are carried into the bloodstream, causing health problems as well [4, p.1].

B. Construction Production Pollution

In addition to releasing carbon dioxide, construction projects also release many other pollutants into the atmosphere. These pollutants mainly contain traces of cement, wood and stone. Construction and demolition debris enters the air and drinking water sources in construction sites at and around those places reducing air quality [5, p.]. Water pollution is a negative environmental impact of construction where demolition toxic chemicals, cement, adhesives, paint, sand debris from construction influences water in the local environment like lakes, rivers [5].

Construction sites produce a lot of noise during their activities because construction workers use heavy machines and equipment. The noise affects construction workers more because they are around the noise for long hours. It can lead to a total or partial loss of hearing.

Any form of debris from building, renovation, or demolition done in construction sites produces waste products that range from large sizes to minuscule volumes. This waste should focus on recycling some valuable materials instead of turning them into landfill waste according to [5 p. 2].

III. 3D printed concrete: composition, properties and elaboration

The 3DPC process consists of the extrusion of filaments of cementitious materials that are deposited on the plate of the 3D printing machine that uses the data of the 3D model to form components without a previous shape. That is the basis of the principle that transforms three-dimensional digital drawings into three-dimensional shapes desired by users through a 3D printer.

Partial substitution of ordinary Portland cement (OPC) is a key aspect to reduce contamination. The OPC manufacturing process consumes a lot of quantities energy, and generates massive amounts of greenhouse gases. Using supplementary cementations materials (SCM) is the way to improve the sustainability of 3DPC, especially in the context of the use of low OPC SCM-based binders in printable cement.

A. Composition

Most of the available 3D printable cementitious materials are designed in the form of printable mortars containing mainly three components: binder, fine aggregate and water. The main component of the mortar is the binder. The SCM is substitute for OPC, and the SCM may be composed of fly ash (silica), silica fume, granulated blast furnace slag, limestone and calcined clay. The other material is fine aggregate like fine sand and this must not contain chemical substances that harm the mixture. In relation to the water used, it must not contain substances such as chlorine and sulfates.

B. Properties

1. *Flowability*

The flowability test is a common assessment for studying the rheology on fresh state concrete. However, the slump flow might be the most appropriate test to effectively indicate the printability of the studied mixtures.

In addition to the mix ingredients discussed above, there are external factors contributing to the flowability of printable materials although adequate flowability enables smooth transportation of the materials from the mixer to the printing nozzle, which influences the properties such as buildability, extrudability, rheological evolution and open time.

2. *Extrudability*

Extrudability can be defined as the property of a fresh paste to pass through the printing nozzle as a continuous and intact filament. Additionally, the extrusion process of flowable material is proposed as a superior characteristic for 3DPC. The material exhibits exceptionally high fluidity, requiring significantly lower pump pressure and energy input than the stiff material, such as hardened mortar, during the mixing, pumping, and extrusion processes.

3. Buildability

The buildability property is used to evaluate material quality due to the shape-retaining of the deposited material and final form. It is characterized as the maximum number of layers that can be built using a fresh mix.

4. Open time

Open time is the time between the moment the dry mixture is in contact with water and the printing moment. An increase in the time interval between the printable layers could generate air voids that can harm the adhesion of the layers thus having detrimental impact on the structure.

5. Rheometry Evolution

The evolution of rheometry has a strong relationship with other properties such as fluidity, extrusion, buildability and open time of 3DPC. Therefore, beyond those properties, the evolution of rheometry affects important steps in pumping, extrusion, deposition phases, and hardened state properties such as elastic modulus.

During the printing process, the gravity-induced stress on the layers gradually increases and may cause problems in the printing process and with the finished material. Although the stress must be low enough to ensure sufficient fluidity, it is expected to increase with rest time to prevent material deformation and control the geometry.

C. Elaboration Process

The 3DPC systems are composed of three pieces of equipment: a deposition facility, unit control settings and a material transport system. The deposition facility is the place where the materials are stored while the unit control settings are controlled and programmed by the user. A 3D model is converted to G-files by a laminator program for 3D printing.

In general, there is a material transport system for parts that do not require as much precision and accuracy. These systems use 3D printers with at least 3 translational degrees of freedom (DOF) (i.e. x-axis, y-axis and z-axis) and a fourth DOF is connected in the z-axis to provide rotation as shown in Fig.1. But a material transport system is used for more complex cases of higher-precision uses. For such purposes, industrial robotic arms can exhibit up to six rotational degrees of freedom, which can help with more complex printing.

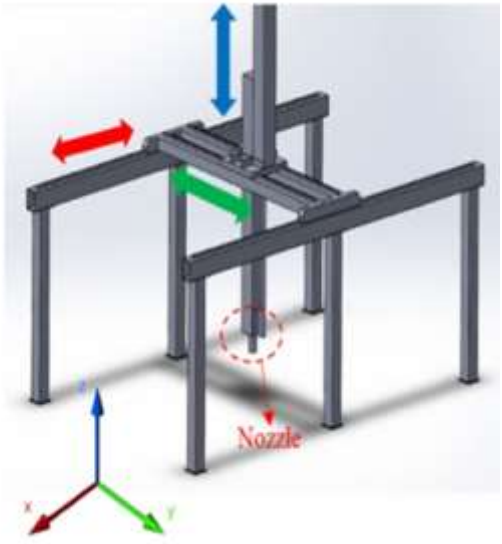

Fig 1. Basic schematic of the 3D printed machine [3]

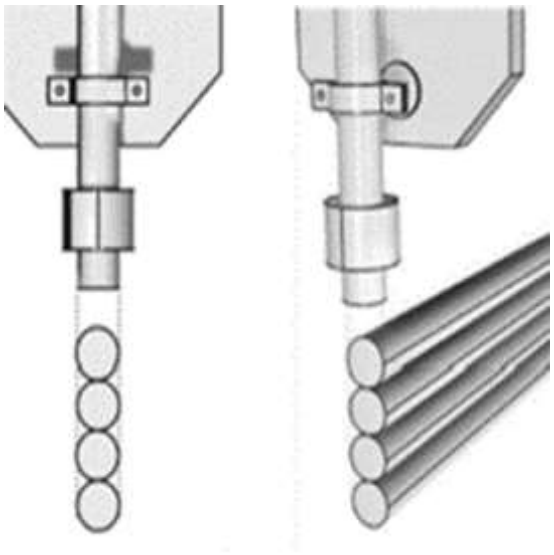

Fig 2. Schematic illustration of vertical filaments deposited [4]

3D Construction is divided into preparation materials and printing process. In the preparation of materials step, in a small scale application, the focus is on mixing the fresh mix in multiple batches and delivering to the material conveying pump hopper as shown in Fig.2.

The printing process~~,~~ the mixed materials are placed in the hopper to provide concrete to the pump and the nozzle constantly. In this way, the process is optimized and possible defects are avoided. Less cement is used reducing carbon dioxide emissions.

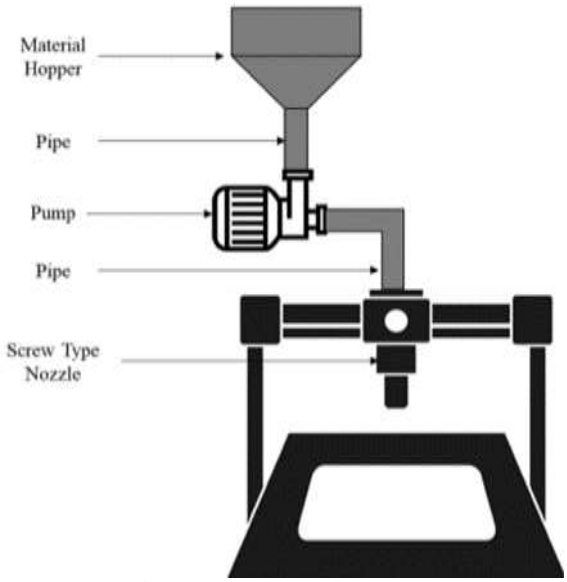

Fig 3. Scheme of a 3D printed machine

IV. Benefits of 3D Printed Concrete

The use of 3DPC can bring many benefits such as economic, technological and environmental aspects combined with more specific ones the elimination of formwork, and reduction in construction time, cost, material and waste generation. These benefits are discussed below.

A. Economic benefits

The economic benefits of 3DPC technology are connected with no need for formwork, less construction time, material and labor requirements. The costs for these items are reduced and the product becomes less expensive while with the introduction of computer tools, 3DPC becomes a semi-autonomous process.

B. Technological benefits

This method only uses concrete where necessary and is combined with advances in other fields, such as the electronics and robotics industry.

The construction method is optimized using 3DPC technology, which will reduce the amount of concrete used in construction and, at the same time, reduce CO2 emissions, making it more sustainable. This process is called topology optimization.

This method offers the opportunity to create additional functionality through complex geometry, and some experts suggest it could be used to integrate and automate services within structures in an efficient way. Integration of services is an appealing thought, especially as a solution to reduce the material layering in architectural structures and simplify and speed up the construction process.

C. Environmental benefits

If we do away with OPC and traditional concrete, pollution coming from materials like OPC and chemicals that are harmful to humans and animals are avoided. Since there is a decrease in the amount of material used, concrete becomes a more sustainable material. Additionally, this method can eliminate waste and pollution caused to the environment by the stages of the building process. Because of all this, 3DPC becomes a more than acceptable option to replace old concrete technologies.

V. Conclusion

All in all, this article develops the ideas connected with changes in the construction industry. In recent times, this technology has begun to be studied to replace traditional construction. In fact, 3D printed concrete is a viable alternative.

This new technology proposes new pathways to reduce CO2 emissions in the construction industry due to the fact that this material does away with ordinary Portland cement (OPC), which is replaced by Supplementary Cementitious Materials (SCM). At present, OPC is one of the biggest pollution producers.

One objective in this paper was to study this new technology in relation to its proprieties: flowability, extrudability, buildability, open time and rheometry evolution. As stated in this work, this construction method can bring economic, technological and environmental benefits.

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