ARCHIVES OF CIVIL AND MECHANICAL ENGINEERING 18 (2018) 311–319

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: http://www.elsevier.com/locate/acme

Original Research Article

Fresh and hardened properties of 3D printable cementitious materials for building and construction

Suvash Chandra Paul *, Yi Wei Daniel Tay, Biranchi Panda, Ming Jen Tan

Singapore Centre for 3D Printing, School of Mechanical & Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 22 February 2017
Accepted 25 February 2017
Available online 30 August 2017

Keywords:
3D concrete printing
3D printing process
Printing direction
Rheology
Mechanical strengths

ABSTRACT

The main advantage of 3D concrete printing (3DCP) is that it can manufacture complex, non-standard geometries and details rapidly using a printer integrated with a pump, hosepipe and nozzle. Sufficient speed is required for efficient and fast construction. The selected printing speed is a function of the size and geometrical complexity of the element to be printed, linked to the pump speed and quality of the extruded concrete material. Since the printing process requires a continuous, high degree of control of the material during printing, high performance building materials are preferred. Also, as no supporting form-work is used for 3DCP, traditional concrete cannot be directly used. From the above discussion, it is postulated that in 3DCP, the fresh properties of the material, printing direction and printing time may have significant effect on the overall load bearing capacity of the printed objects. The layered concrete may create weak joints in the specimens and reduce the load bearing capacity under compressive, tensile and flexural action that requires stress transfer across or along these joints. In this research, the 3D printed specimens are collected in different orientations from large 3DCP objects and tested for mechanical properties. For the materials tested, it is found that the mechanical properties such as compressive and flexural strength of 3D printed specimen are governed by its printing directions.

1. Introduction

In the last two decades, the traditional way of mixing and casting of concrete on site has been replaced, significantly by pre-casting or pre-fabrication in several developed countries. However, the construction sector can still benefit from automation toward reducing labor and construction time, improved quality and reduced environmental impact. In this regard, 3 dimensional (3D) printing was first introduced in 1986 as a means of rapid prototyping [1]. Today, there are different techniques, but the basic principle remains that of additive manufacturing (AM), meaning that material is added layer by

* Corresponding author.
E-mail addresses: suvashpl@ntu.edu.sg (S.C. Paul), danieltay@ntu.edu.sg (Y.W.D. Tay), BIRANCHI001@e.ntu.edu.sg (B. Panda), mmjtan@ntu.edu.sg (M.J. Tan).
http://dx.doi.org/10.1016/j.acme.2017.02.008
1644-9665/

layer [2]. 3D printing or AM enables 3D solid objects to be "printed" from a digital model by laying down successive layers of material. 3D printers were initially used in industrial environments to produce and refine prototypes also known as rapid prototyping. With reductions in cost and improvements in technology, 3D printing is quickly finding new applications, particularly for short-run manufacturing where customization is important. 3D printing is very useful in the manufacturing of complex geometries, precisely customized parts, parts in a variety of slight variations, or parts that need to be adapted frequently in their manufacturing lifecycle [3,4].

More recently, in a bid to raise construction productivity and to fundamentally change design and construction processes, many countries such as Singapore and Hong Kong are embracing the concept of Design for Manufacturing and Assembly (DfMA) in the construction industry. DfMA is designed for significant amount of work to be done off-site in a controlled manufacturing environment. As a result, Prefabricated Prefinished Volumetric Construction (PPVC) is getting more attention in the construction industry. PPVC is a method whereby free-standing volumetric modules (complete with finishes on walls, floors and ceilings) are either constructed and assembled or manufactured and assembled in an accredited fabrication facility, in accordance with any accredited fabrication method, and then installed in a building under building works. PPVC is one of the game changing technologies that support the DfMA concept to significantly speed up construction. It can potentially achieve a productivity improvement in terms of manpower and time savings, depending on the complexity of the projects. Furthermore, dust and noise pollution can be minimized as more activities are done off-site. With the bulk of the installation activities and manpower moved off-site to a factory controlled environment, site safety will also improve.

The government of Singapore plans to build the city's future public housing by integrating the technology of PPVC strategy for assembly. The idea is to use large-scale 3D printers to build one story at a time before transporting and stacking each floor [5]. Different materials and processes can be used for 3D printing, and printers can range greatly in size, from briefcase sized to those large enough to print houses. The level of definition and the strength qualities of final printed parts can also vary considerably. Successful application of 3D printing in the construction industry can have a huge impact on the total cost of construction. Fig. 1 shows that for a new concrete construction project, more than 50% of the total cost

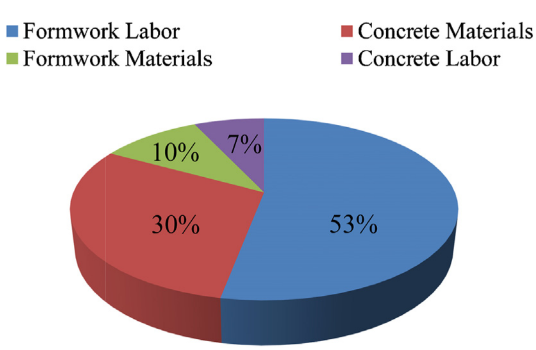

Fig. 1 – Typical cost distribution for new concrete construction project [6].

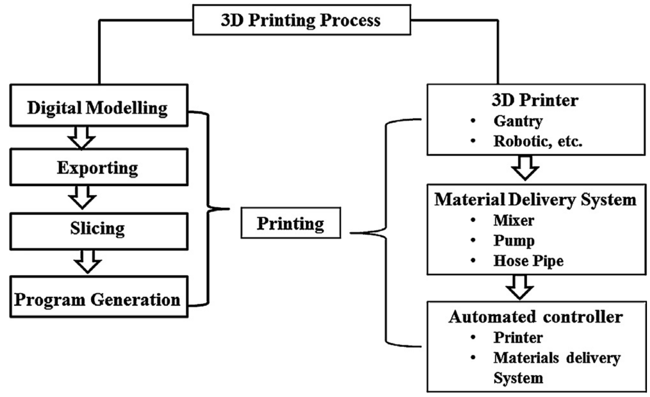

Fig. 2 – The process of 3D printing for construction industry.

is spent for the formwork and labor [6]. Since in 3D printing, no formwork is required and a short project time is required due to continuous work done by the printer, a dramatic reduction in the project cost can be achieved by adopting 3D printing technique in construction industry.

The typical 3D concrete printing (3DCP) process for the construction industry is shown in Fig. 2. The whole 3D printing process can be described in two ways. Firstly, the software segment (left side of Fig. 2) and secondly, hardware segment (right side of Fig. 2). At first, a 3D software such as AutoCAD or Solid Works is used to model the objects, then it is exported to another software for slicing (define the layer dimension). Thereafter, a program file in the form of G-code is generated for the whole object for the printer to read and perform the job as shown in Fig. 2. In the hardware segment, an integrated printer (either gantry or robotic) with material delivery system that is connected with a pump and hose pipe are required to deliver the material to the nozzle orifice/head, which is connected at the end part of the hosepipe to deposit the material in layer by layer. A controller is also required to control the printer and pump according to the design (shape, size, etc.) of the printed object. The whole process of 3DCP is already discussed in details by the several researchers [7–10].

While the interest on 3D printing is growing rapidly, however, there are still some concerns about the properties of 3D printed objects, as the manufacturing process is different from the conventional method. In traditional construction, the desire shape of the structure is achieved by pouring concrete in a predefined formwork, while in 3D printing, it is achieved by extruding concrete in layer by layer manner. Therefore, the fresh properties of concrete as well as printing parameters such as printing time, speed, etc. play an important role in the hardened properties of 3D printed objects. Since in 3DCP, no formwork is required to support the concrete layers and material needs to be pumped to the nozzle head for extrusion, the rheology of the fresh properties of printable material becomes very important.

Since no supporting formwork is used for 3D printing, traditional concrete cannot be directly used. For ensuring little or no deformation in the bead layers, an almost zero slump but pumpable concrete is required. However, the production of low slump concrete needs special attention to the granulometric properties of the aggregates. Another important