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Effect of surface moisture on inter-layer strength of 3D printed concrete

Jay G. Sanjayan *, Behzad Nematollahi, Ming Xia, Taylor Marchment

Department of Civil and Construction Engineering, Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, Victoria, Australia

HIGHLIGHTS

- Factors influencing the inter-layer strength in concrete 3D printing are studied.
- The moisture level at the surface is identified as an important factor.
- Low moisture level is linked to low inter-layer strength in 3D concrete printing.
- The surface moisture level is affected by bleeding and evaporation rates.
- Strengths of 3D printed concrete were different in x, y and z directions.

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ABSTRACT

The extrusion-based 3D concrete printing is a new technology under development for construction of buildings and structures of complex geometries without the use of expensive formwork. The weak inter-layer strength between printed layers is one of the limitations of this technology when compared with cast-in-the-mold concrete. This study investigates effects of print-time interval on the inter-layer strength, along with compressive and flexural strengths of extrusion-based 3D printed concrete in different directions. Specimens were printed with 10, 20 and 30 min delay times (print-time intervals). Compressive, flexural and inter-layer strengths of the 3D printed concretes were measured. The inter-layer strengths of the specimens printed with 10 and 30 min delay times were comparable but higher than that of the specimens printed with 20 min delay time. A correlation was found between the results of inter-layer strength and the surface moisture content at the interface of the layers. The surface moisture content, in turn, depends on the bleed rate of the concrete and the rate of drying of moisture from the surface among other factors. The results also indicated that the compressive and flexural strengths of 3D printed concrete depended on the testing direction. The orthotropic phenomenon was more pronounced in compressive than flexural strength.

1. Introduction

Additive manufacturing (AM), commonly known as three-dimensional (3D) printing is a group of emerging techniques for fabricating 3D structures directly from a digital model in successive layers. The American Society for Testing and Materials (ASTM) defines AM as "the process of joining materials to make objects from 3D model data, usually layer upon layer" [1]. The AM technologies have been initially developed in the 1980s and have already been successfully applied in a wide range of industries including aerospace and automotive manufacturing, biomedical, consumer and food [2]. Currently, AM techniques have become an integral part of modern product development.

3D printing technology is recently gaining popularity in construction industry. Unlike the conventional approach of casting concrete into a formwork, 3D concrete printing (3DCP) will combine digital technology and new insights from materials technology to allow freeform construction without the use of expensive formwork. The freeform construction would enhance architectural expression, where the cost of producing a structural component will be independent of the shape, providing the much-needed freedom from the rectilinear designs [3].

When compared to conventional construction processes, the application of 3D printing techniques in construction industry may offer excellent advantages including: (1) reduction of construction costs by eliminating expensive formwork [3,4], (2) reduction of injury rates by eliminating dangerous jobs (e.g. working at heights), which would result in an increased level of safety in construction [3], (3) creation of high-end-technology-based jobs [3],

* Corresponding author.
E-mail address: jsanjayan@swin.edu.au (J.G. Sanjayan).

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(4) reduction of on-site construction time by operating at a constant rate [3,4], (5) minimizing the chance of errors by highly precise material deposition [3], (6) increasing sustainability in construction by reducing wastages of formwork [3,4], (7) increasing architectural freedom, which would enable more sophisticated designs for structural and aesthetic purposes [3,4], and (8) enabling potential of multifunctionality for structural/architectural elements by taking advantage of the complex geometry [5].

In the last few years, different 3DCP technologies have been developed to adopt AM in concrete construction. These technologies are mainly based on two techniques, namely extrusion-based and powder-based techniques. The powder-based technique is a typical AM process that is capable of making structures with fine details and intricate shapes by jetting binder liquid selectively through nozzle(s) on the powder layer, causing powder particles to bind to each other. Examples of 3DCP technologies developed based on powder-based technique include D-shape technique [6] and Emerging Objects [7]. The powder-based technique is an off-site process, which is suitable for manufacturing building components with complex geometries such as panels, permanent formworks and interior structures, which can be later assembled on-site. There is a demand in construction industry for such components, which currently can only be manufactured with the use of expensive formworks using the available construction systems. Powder-based technique has the potential to make robust and durable building components at a reasonable speed to satisfy this industrial demand. However, the very limited scope of cement-based printing materials that can be used in commercially available powder-based 3D printers prevent this technique from performing at its maximum potential for application in construction industry. To tackle this limitation, recently the authors of this study developed an innovative methodology to adopt geopolymer-based material for the requirement and demand of commercially available powder-based 3D printers [8,9].

The extrusion-based technique is similar to the fused deposition modelling (FDM) method, which extrudes cementitious material from a nozzle mounted on a gantry, crane or a 6-axes robotic arm to print a structure layer by layer. This technique has been aimed at on-site construction applications such as large-scale building components with complex geometries. Examples of 3DCP technologies developed based on extrusion-based technique include Contour Crafting [10–12], Concrete Printing [13,14] and CONPrint3D [15]. Although extrusion-based 3DCP has a great potential to make a significant and positive contribution to the construction industry, there are several technological challenges that need to be overcome before this technology can be used in construction industry.

One of the main challenges is the weak inter-layer strength of printed concrete. The inter-layer strength is seen as a major weakness of printed concrete in the extrusion-based 3D printing process, as potential flaws can be created between extruded layers, which induce stress concentration [14]. In conventional cast-in-the-mold concrete, bond strength between existing and new concretes typically depends on surface and moisture conditions of the existing concrete surface [16]. According to Gillette [17], free water on the existing concrete surface decreases the bond strength. However, Pigeon and Saucier [18] concluded that the moisture condition of the existing concrete surface does not influence the bond strength. Austin et al. [19] reported that higher bond strength could be obtained when the existing concrete surface is in saturated surface dry (SSD) condition. These controversies in the reported results may be due to different materials used for existing and new concretes, along with different environmental conditions and test methods adopted in each research. In 3DCP, unlike conventional cast-in-the-mold concrete, the extruded layers are still in the fresh state. Therefore, there is a need to investigate the parameters influencing the bond strength between two subsequent layers in the fresh state. The inter-layer strength depends on the adhesion between extruded layers, which is a function of print-time interval between layers, referred to as delay time. There is a need to optimize the delay time, which on the one hand should be long enough so the printed layers can gain adequate green strength to support the upper layers without significant deformation or collapsing. On the other hand, the delay time should be short enough to guarantee adequate bond strength between printed layers and to provide an economically feasible rate of construction. Therefore, the delay time becomes a critical parameter in the extrusion-based 3DCP process. Le et al. [14] recently investigated the effect of delay time (in increments of 15, 30 min, 1, 2, 4, 8, 18 h and 1, 3, 7 days) on the inter-layer strength of a printed high-performance fiber-reinforced mortar using direct tension tests on cylindrical cored specimens. It was concluded that the inter-layer strength reduced as the delay time increased. The researchers stated that "this reduction with increasing gap in printing time was expected as the adhesion reduced" [14], but they did not investigate the factors such as surface moisture affecting the adhesion between the layers. Therefore, this study aims to fill this knowledge gap. This study investigates the effect of delay time on the strength properties of extrusion-based 3D printed concrete including compressive, flexural and inter-layer strengths.

2. Experimental procedures

2.1. Materials and mix proportions

Ordinary Portland cement (OPC) conforming to the Australian Standard, AS 3972 [20] general purpose cement (Type GP) was used in this study. Table 1 presents the chemical composition and loss on ignition (LOI) of the OPC determined by X-ray Fluorescence (XRF). The total does not sum up to 100% because of rounding-off of the percentages. The percentages of C3S, C2S, C3A and C4AF as the main constituents of OPC were 57.59%, 14.87%, 4.10% and 13.94%, respectively, calculated from the chemical composition shown in Table 1 using Bogue formula [21]. Sieve graded high silica purity sands with two different particle sizes were used in this study. The finer silica sand denoted as "FS" with maximum particle size of 300 μm was supplied by TGS Industrial Sand Ltd., Australia. The coarser silica sand denoted as "CS" with maximum particle size of 500 μm was supplied by Building Products Supplies Pty Ltd., Australia. Fig. 1 presents the particle size distribution of the OPC and silica sands used in this study determined by using a CILAS particle size analyzer model 1190.

Table 2 presents the mix proportions of the 3D printable concrete used in this study. According to Le et al. [13], the most critical fresh properties of a 3D printable concrete mixture are

Table 1
Chemical composition of the OPC.

Chemical	Component (wt.%)
Al_2O_3	4.47
SiO_2	20.34
CaO	62.91
Fe_2O_3	4.58
K_2O	0.29
MgO	1.24
Na_2O	0.31
P_2O_5	–
TiO_2	–
MnO	–
SO_3	2.58
LOI[1]	3.27

[1] Loss on ignition.