Effect of Delay Time on the Mechanical Properties of Extrusion-based 3D Printed Concrete

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Abstract

The extrusion-based 3D printing method is one of the main additive manufacturing techniques used in the construction industry which is capable of producing large-scale building components with complex geometries without the use of the expensive formwork. The mechanical properties of the printed concrete component are very much unlike the conventionally cast concrete. Therefore, the properties of these are important for the design of structures built with 3D printing process.

In this study, a custom-made apparatus was used to simulate extrusion-based 3D printing process. Layered specimens with 10, 20 and 30 minutes delay time (i.e. the printing time interval between layers) have been printed using tailored conventional concrete mixture. Mechanical properties including compressive, flexural and inter-layer bonding strengths have been measured and the effect of delay time on the mechanical properties has been investigated.

All printed specimens exhibited an anisotropic phenomenon in both compressive and flexural strengths. A significant inverted bell curve pattern emerged in the inter-layer bonding strength. The inter-layer bonding strength of the specimens with 10 minutes and 30 minutes delay time was similar, but higher than that of specimen with 20 minutes delay time. The major finding is that the surface moisture content plays a major role in the inter-layer bonding strength.

Keywords –

Concrete; Additive Manufacturing; 3D Printing; Mechanical Properties

1 Introduction

Nowadays, in the manufacturing industry, one of the most technological trends of manufacturing is Additive Manufacturing (AM), also referred to as three-dimensional (3D) printing. AM is a group of techniques for producing 3D objects directly from a digital model. Until recently, AM techniques have gained popularity in a wide range of high value adding industries such as military, aerospace, automotive and biomedical [1]. In general, the construction industry is labor intensive and has issues with safety and sustainability. Compared with other industries, the construction industry is viewed as a low-tech industry with low levels of innovation [2]. The image of the construction industry may be changed by the adoption of AM techniques.

Unlike conventional manufacturing processes such as subtractive method, AM techniques build a finished part in successive layers with less waste material. The adoption of AM techniques in the construction industry may (1) reduce the labor requirements which would result in a decreased construction cost and an increased level of safety, (2) reduce on-site construction time by operating at a constant rate, (3) minimize the chance of errors by highly precise material deposition, and (4) increase architectural freedom which would enable more sophisticated designs for structural and aesthetic purposes [3-4]. The application of AM techniques in the construction industry is still in its early stage. Two forms of AM techniques have been so far explored for application in concrete construction: (1) the extrusion printing technique and (2) powder printing technique.

The extrusion printing technique is analogous to the Fused Deposition Modelling (FDM) method but uses a variety of slurry-like materials to create structures. The extrusion printing technique has been aimed at on-site construction applications such as large-scale building components with complex geometries. Additionally, this technique allows the usage of traditional construction materials such as cement, geopolymer, clays and plasters.

Briefly, in the extrusion-based 3D printing process, a cementitious material is extruded from a nozzle mounted on a gantry, crane or a 6-axes robotic arm to print a structure layer by layer. The cementitious material must be thoroughly considered in this approach as there are many requirements including the viscosity of the mixture, time of setting, the time interval between old and new layers and the mechanical properties after hardening. Other considerations include the size/shape of the nozzle, the size of the tank that is practicable for the printer, the size of the printer and other variables [5].

One of the most important challenges of the extrusion-based 3D printing is that conventional steel reinforcements are difficult to be incorporated in 3D printing [6], which makes it difficult to compensate for inherently weak tensile strength of concrete. For this reason, the bonding strength between the printed layers is a critical mechanical property in the extrusion-based 3D printing process [7]. In the extrusion-based 3D printing process, the printed layer needs to be strong enough to support the next upper layer without deforming or collapsing [8], and also needs to be soft enough to allow a good bond between the old and new layers. Thus the printing time interval between layers, referred to as delay time, becomes a significant factor. Currently, there is a very limited research work available regarding the effect of delay time on mechanical properties of extrusion-based 3D printed concrete.

As discussed above, the inter-layer bonding strength is a particular area of weakness correlating to overall specimen strength in the extrusion-based 3D printing process and is greatly affected by the delay time. This paper investigates the mechanical properties of 3D printed concrete with varied delay time.

2 Materials and Methods

2.1 Materials

An ordinary Portland cement (OPC) conforms to AS 3972 general purpose (Type GP) was supplied from Geelong Cement, Australia.

Two types of sands were used as the aggregates in the mixtures. Sand Type I was washed sand (supplied by Building Products Supplies Pty Ltd., Australia) with a particle size less than 500 μm and sand Type II (supplied by TGS Industrial Sands Pty Ltd., Australia) was a high silica purity fine sand with a particle size less than 300 μm.

2.2 Mix proportions

The mix design aimed to meet the requirements of the extrusion-based 3D printing process, including extrudability, workability and buildability.

Initially, a baseline trial mixture was proportioned using traditional concrete ingredients and a normal mixing process. The starting point selected was a mix with a cement: sand (Type I) ratio of 1:3. The water to cement ratio for the baseline mix was 0.5. The mixture was prepared and loaded into the 3D printing apparatus, but the baseline mix was too stiff to be extruded out from the nozzle for printing.

The mix optimization process includes reducing the amount of sand Type I, increasing the amount of sand Type II and reducing the amount of water, which resulting an optimum mix with a cement : sand (Type I) : sand (Type II) ratio of 1:0.97:0.33. The water to cement ratio of the optimum mix was 0.38.

2.3 Extrusion-based 3D printing process

2.3.1 3D printing apparatus

A custom-made apparatus was used to simulate extrusion-based 3D printing process (see Figure 1-a). A 45 °angle extrusion nozzle (see Figure 1-b) with a 15 mm × 25 mm opening was used.

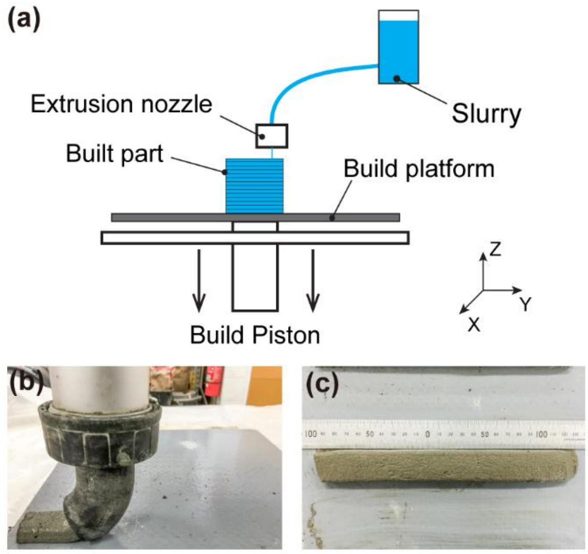

Figure 1. (a) Schematic illustration of the extrusion-based 3D printing process, (b) 45 °angle extrusion nozzle, (c) One layer of extruded concrete (250 mm (L) ×25 mm (W) ×15 mm (H))

2.3.2 Specimen preparation

The optimum mixture was loaded into the 3D printing apparatus and extruded through the nozzle by manually moving the extruder with a constant speed of 12 mm/s.

A single base layer (approximately at 250 mm length) (see Figure 1-c) was extruded for each specimen. Then, after the given time interval, another layer was deposited on top of the previous layer. Specimens prepared for compressive and flexural strengths testing consisted of 4 printed layers, while the specimens made for inter-layer bonding test consisted of 2 printed layers. All the specimens were cured in the laboratory environment at room temperature (23 ± 3^{o}C) until the day of testing (i.e. 7 days after casting).

2.4 Mechanical properties testing

2.4.1 Compressive strength

The compressive strength was measured in a universal testing machine under load control at the rate of 20 MPa/min. For the compressive strength test, the printed specimens were cut into smaller sizes with approximate dimensions of 50 mm (L) × 25 mm (W) × 60 mm (H) and loaded in one of the two directions: perpendicular to the printed layers (testing direction Top) and parallel to the printed layers (testing direction Front), as shown in Figure 3-a. At least three specimens were tested for each testing direction.

2.4.2 Flexural strength

The flexural strength was measured in a universal testing machine under displacement control at the rate of 1 mm/min. For flexural strength test, the specimen dimensions were 250 mm (L) × 25 mm (W) × 60 mm (H). All specimens were tested under 3-point bending test setup with a span of 150 mm. The flexural strength test was also conducted in two directions, perpendicular to the printed layers (testing direction Top) and parallel to the printed layers (testing direction Front), as shown in Figure 4-a. At least three specimens were tested for each testing direction.

2.4.3 Inter-layer bonding strength

The schematic illustration of the inter-layer bonding strength test setup is shown in Figure 2.

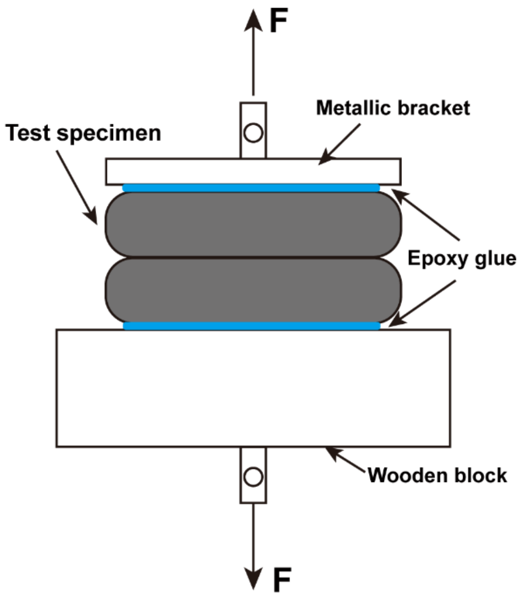

Figure 2. Schematic illustration of the inter-layer bonding strength test setup

For the inter-layer bonding strength test, the specimen dimensions were 50 mm (L) × 25 mm (W) × 30 mm (H). A metallic bracket and a wooden block were epoxy glued on the top and bottom of the printed specimen, respectively. The inter-layer bonding strength test was conducted in a universal testing machine under displacement control at the rate of 1 mm/min. Care was taken to align the specimen in the machine to avoid any eccentricity. At least 3 specimens were tested.

3 Results and Discussions

3.1 Compressive strength

Figure 3 presents the compressive strength results for different delay time. As can be seen, the anisotropic phenomenon was observed in the compressive strength of the printed concrete. The compressive strength in the direction of perpendicular to the printed layers (testing direction Top) was higher than that in the direction of parallel to the printed layers (testing direction Front), irrespective of the delay time. The compressive strength in the direction of perpendicular to the printed layers (testing direction Top) was 30%, 35% and 37% higher than that in the direction of parallel to the printed layers (testing direction Front) for 10, 20 and 30 min delay time, respectively.

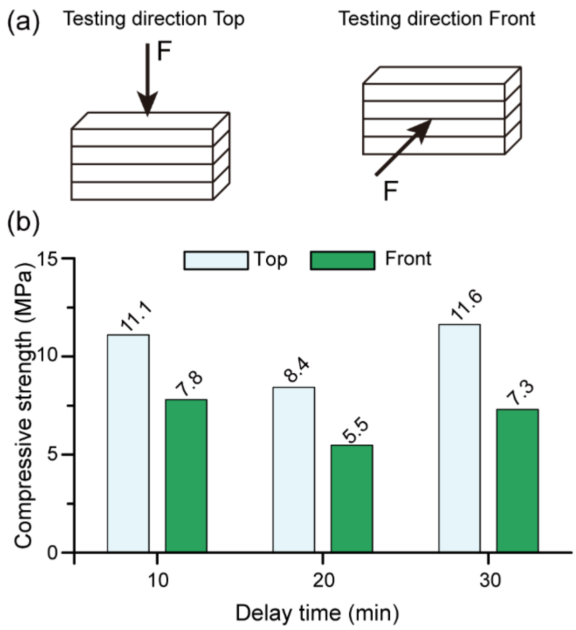

Figure 3. (a) Testing directions of the specimens, (b) Compressive strength results

As can be seen in Figure 3, an inverted bell curve pattern was observed for compressive strength results in both testing directions. The specimen printed with 20 min delay time had an average compressive strength of 8.4

MPa in the Top loading direction and 5.5 MPa in the Front loading direction, which were lower than those of the corresponding specimens with 10 min and 30 min delay time.

3.2 Flexural strength

Figure 4 presents the flexural strength results for different delay time. Similar to the compressive strength results, the anisotropic phenomenon was also observed in the flexural strength of the printed concrete. The flexural strength in perpendicular to the printed layers (testing direction Top) was also higher than that in parallel to the printed layers (testing direction Front), irrespective of the delay time. This results is consistent with the compressive strength results. The flexural strength in the direction of perpendicular to the printed layers (testing direction Top) was 55%, 13% and 34% higher than that in the direction of parallel to the printed layers (testing direction Front) for 10, 20 and 30 min delay time, respectively.

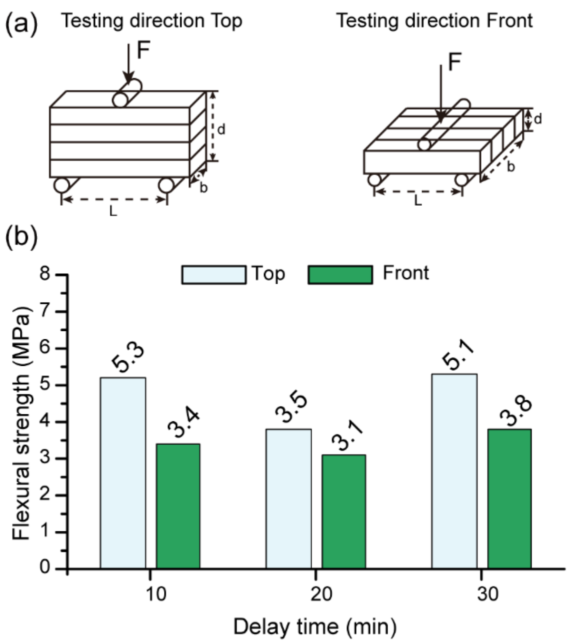

Figure 4. (a) Testing directions of the specimens, (b) Flexural strength results

Similar inverted bell curve pattern was also observed for the flexural strength of the printed concrete. The specimen printed with 20 min delay time had an average flexural strength of 3.5 MPa in the Top loading direction and 3.1 MPa in the Front loading direction, which were lower than those of the corresponding specimens with 10 min and 30 min delay time.

3.3 Inter-layer bonding strength

The inter-layer bonding strength test was conducted to indicate the true inter-layer bonding strength and failure mode between layers. As can bee seen in Figure 5, a similar inverted bell curve pattern was also observed for the inter-layer bonding strength of the printed concrete. The inter-layer bonding strength of the specimens with 10 min and 30 min delay time was similar, but higher than that of specimen with 20-min delay time. It should be noted that all specimens failed between the printed layers.

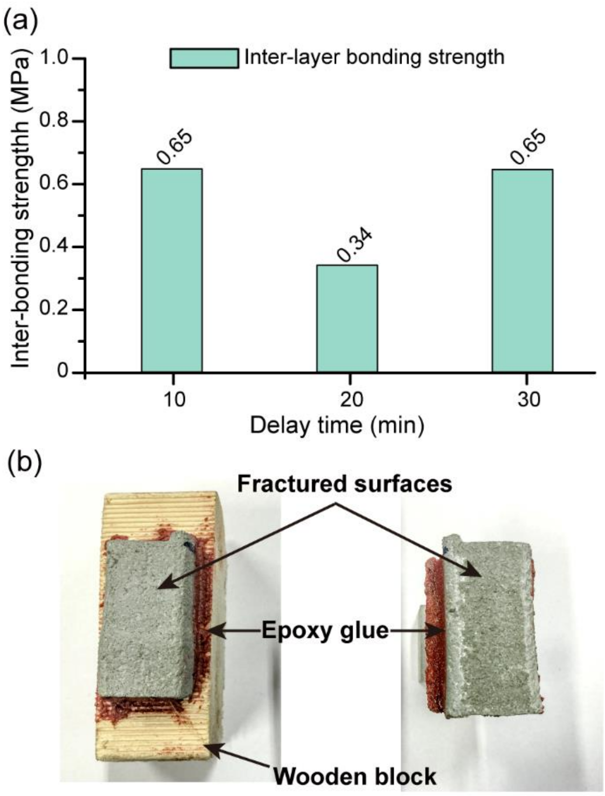

Figure 5. (a) Inter-layer bonding strength result of printed specimens, (b) Fractured surfaces between layers

Le et al. [9] reported that with increasing delay time the inter-layer bonding strength decreases as the adhesion between old and new layers reduces. However, a different inverted bell curve pattern was observed in this study. This could be due to the different surface moisture contents of printed specimens with different delay time.

Therefore, as a preliminary study the surface moisture content of the specimens were measured using a paper towel. The experiment setup and results are presented in Figure 6. Three single base layers (approximately 250 mm long) were extruded for each delay time. After the deposition, a cut-to-size paper towel measuring 250 mm in length and 15 mm in width was placed on the surface of extruded layer for 20 seconds. The mass change of the paper towel was measured as the surface moisture content. The temperature and relative humidity in the laboratory were maintained at 24℃ and 65%, respectively during the measurement. For each delay time, three measurements were recorded.

As can be seen in Figure 6, the surface moisture contents varied with delay time, and an inverted bell curve pattern was observed similar to the inter-layer bonding strength result. The average surface moisture content of 20 min delay time specimens was 0.16 g which was lower than the specimens with 10 min delay time (0.28 g) and 30 min delay time (0.30 g).

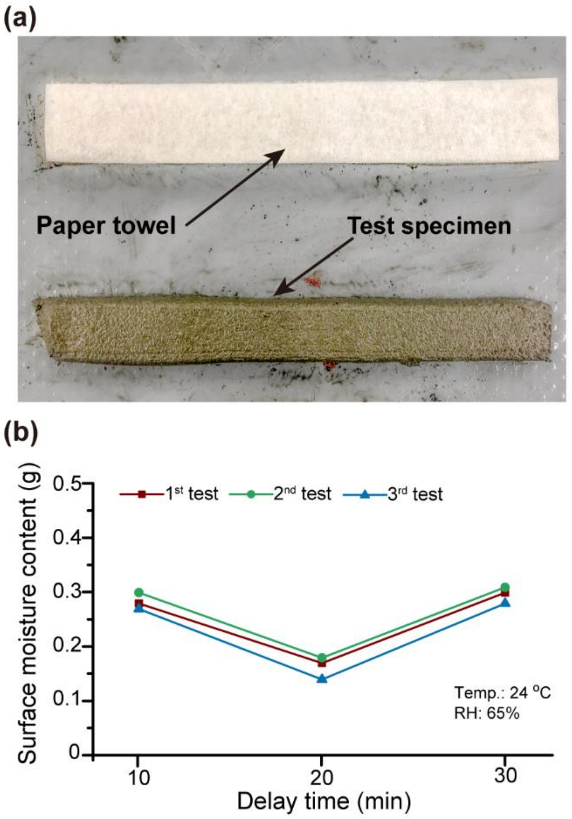

Figure 6. (a) Experimental setup for surface moisture content measurement, (b) Surface moisture content result

The higher surface moisture contents of the 10 min and 30 min delay time specimen provided a better aqueous medium for the fresh concrete mixture in the old and new layers to bond together, resulting in superior inter-layer bonding strength.

The surface moisture content is affected by several factors including instrument condition (e.g., type, size and material of the extruder, pressure) and material condition (such as mix composition and bleeding). Thus, further research is currently being conducted in order to clearly understand the underlying reasons of inverted bell pattern of the surface moisture content of different delay time.

4 Conclusions

The effects of different delay time on the mechanical properties of the extrusion-based 3D printed concrete were investigated in this study. Specimens with different delay times were printed and the mechanical properties including compressive, flexural and inter-layer bonding strengths were measured. The following conclusions can be drawn from this study:

(1) The anisotropic phenomenon was observed in the compressive and flexural strengths of the printed concrete. The compressive and flexural strengths in the direction of perpendicular to the printed layers (testing direction Top) was higher than that in the direction of parallel to the printed layers (testing direction Front), irrespective of the delay time.

(2) A significant inverted bell curve pattern was observed for the inter-layer bonding strength result. The inter-layer bonding strength of the specimens with 10 min and 30 min delay time was similar, but higher than that of specimen with 20-min delay time. A clear correlation was found between the results of inter-layer bonding strength and the surface moisture content.

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