

# BOND STRENGTH OF 3D PRINTED CONCRETE

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**ABSTRACT:** 3D concrete printing is an innovative additive manufacturing process where the material is extruded through a nozzle to print structure layer-by-layer. In this paper, the authors investigate the possibility of improving the interface bond strength of this layer by layer construction technique. Many factors affect the bond strength between the two layers such as time gap, surface contact area and surface moisture. The nozzle requires a specific amount of time for it to complete one cycle (time gap). Four different time-gap on the bond strength of individual layer was studied and is found that the bond of a shorter time gap yields better strength. A proposed method to improve the strength of the bond at the interface is to increase the contact surface area. Increasing the contact surface area of the layers could improve the bond strength.

**KEYWORDS:** Building and Construction; Additive Manufacturing; 3D printing; bond strength; Time-gap

## INTRODUCTION

The interest both in academia and in construction practice towards large-scale three-dimensional (3D) printing technologies has been ever increasing in the past few decades (Tay et al., 2017). This manufacturing process extrudes layer upon another layer until the whole structure is completed and inevitably create a structure that has anisotropic property. The strength of this anisotropic structure depends on the inter-bond layer. Le et al. (2012) show that the inter-bonding layer in the layer-wise structure has great influence on the overall structural performance. 11 groups of specimens with varying time gap were tested and their bond strength was found to reduce exponentially with increasing time gap. Higher travel speed is preferred to achieve better mechanical properties. The quality of the bond depends on both the preparation and placement of the subsequent layer (Granju et al., 2011). Wolfs (2015) created an algorithm for optimization which included printing time gap in relation to the bond strength to improve the overall structural strength.

Panda et al. (2018) tested the bond strength with geopolymer as the material of study. He obtained similar material behavior as Le et al. However, for the 35-minutes time gap, the strength was found to be higher because a new batch of material was used, it is able to bind with the old geopolymer (Panda et al., 2018). The state of interface material is crucial which relates to the tensile-bond strength and the interface is affected by printing parameters such as print speed and printing time gap between layers (Panda et al., 2018).

### Load rate

The printing speed is inter-related with the loading capacity of the material. Although printing at higher speed is recommended to reduce the time-gap in-between layers, if the printing speed is faster than the loading capacity of the material, the fresh material may not be able to sustain the load of the subsequent layer and will cause the whole structure to fail (Figure 1a). It is necessary to

maintain a balance between the load rate and the material stiffness to prevent the material from slumping (Perrot, Rängeard, & Pierre, 2016).

### Time-Gap

A crucial characteristic of this 3D extrusion printing process is the bond interface between layers (Y. W. Tay et al., 2016). It influences the overall structure performance, as time-gap increases, the moisture condition of the substrate with the exposed surface will reduce due to evaporation and hydration of concrete. When a fresh layer is placed on a dry layer, the moisture of the former will flow and penetrate the latter (Chorinsky, 1986). The rate of movement of water from the newly deposited layer to the existing layer will be determined by the imbalance moisture condition of the substrate between the two layers (Austin, Robins, & Pan, 1995).

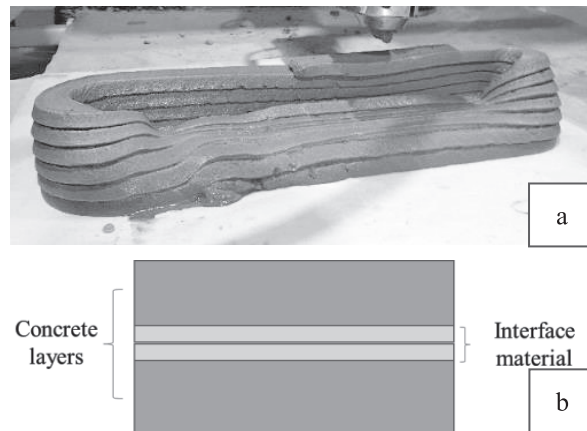


Figure 1: (a) Structure collapse because the loading rate is faster than the material stiffening  
(b) Bonding mechanism in layered concrete (Panda et al., 2018)

This paper examines the effect of the printing time-gap parameter on the interface bond layer. the outcome of this is to improve the overall bond-strength of the structure. Although there have been a few papers discussing on the difference of time gap on the strength of the concrete (Le et al., 2012; Panda et al., 2018; Paul et al., 2018; Wolfs, 2015), on macroscopic-scale, the cross-section of the material after deposition was never examined. By examining the cross-section of the printed filament, it is possible to understand how layers are stacked on top of the others and could provide an insight into ways to improve the printing parameters.

## METHODOLOGY

### Materials

The mix design was aimed to meet the requirement of pumpability during delivery through the hose and shape retention after extrusion. The material need to be delivered by means of pumping through a hose with a diameter of 2.54mm and the maximum allowable particle size by the pump is 2mm. Table 1 shows the mix design composition. No additives were incorporated in this study as the main objective is to improve the inter-bonding layer and addition of additives may increase the complexity of this study. A Hobart mixer was used to prepare the material. Dry components were dry-mixed at 59rpm for 5 minutes. Water is then added to the mixture for mixing at slow-speed (59rpm) for 1-minute and follow by 7-minutes of high-speed mixing (198rpm).

Table 1: Material mix design composition

Cement to binder ratio	Fly ash to binder ratio	Silica fume to binder ratio	Sand to binder ratio	Water to binder ratio
0.7	0.2	0.1	1.2	0.46

### Printing Parameters

A rectangular nozzle with dimension 30mm by 15mm was chosen to print rectangular cross-section filament for stability. Rectangle filament can achieve higher contact area in-between two filaments as compared to round nozzle. Interval of 1-minute, 5-minute, 10-minute and 20-minute were chosen as the printing time gap in-between layers. Some other printing parameters are shown in Table 2.

Table 2: Printing parameters used for the experiment

Travel speed	Flow rate	Layer height	Area of nozzle orifice
80mm/s	0.039 ℓ/s	15mm	450mm <sup>2</sup>

### Bond Test

Instron 5960 dual column tensile test machine was used to investigate the bond strength of the material. Four specimens with a length of 30mm were extracted from the concrete block by sawing in a diamond cutter. Both side of the samples were then glued to two mild steel plates using rapid hardening adhesive (X60) supplied by HBM showed in figure 2 and the tensile testing was carried out at a rate of  $0.035 \pm 0.015$  MPa/s proposed by ASTM standards (ASTM C1583, 2013). The effective area of bonding and failure load were then used to calculate the bond strength for each specimen and the average bond strengths were reported and discussed in the following section.

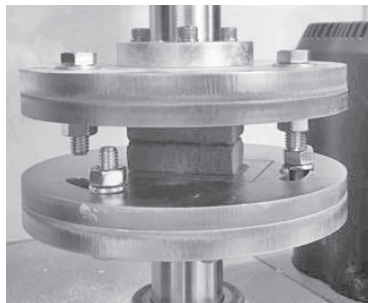


Figure 2: Preparation of specimen for the tensile test.

## RESULTS AND DISCUSSION

### Influence of time gap on bond strength

Preliminary results (Figure 3) show a similar trend to other researchers work. The strength reduces logarithmically as the time gap increases. The results in figure 3a shows that there is a huge reduction in the strength of bond from 1-minute to 10-minutes. However, after 10-minutes, the strength reduced is insignificant.

Further investigation on the bond from its cross-section shows that there is almost no obvious line in-between the layers for 1-minute as compared to the 20-minutes time gap (Figure 4). The concrete extruded on the top layer when printed at 1-minute time gap binds well with the bottom

layer. Water from the bottom substrate evaporates more for a 20 minutes time gap as compared to a 1-minute time gap. The interface of the new concrete that is printed on top is not bonding well with the interface at the bottom substrate for the 20-minutes specimen could be due to moisture loss where evaporation happens at the surface of the bottom substrate.

At when the printer is printing at 1-minute time gap, the bottom layer as is sensitive to disturbance. When a new layer is deposited on top, the interface layer at the bottom substrate may rearrange its orientation to accommodate to the stresses brought by deposition of new layers. However, at 20-minutes time gap, the material at the bottom substrate is stiff. As new layer is deposited on top, the energy caused by the deposition is not sufficient for the interface layer to rearrange its orientation thus voids appear at the bond (Figure 4b).

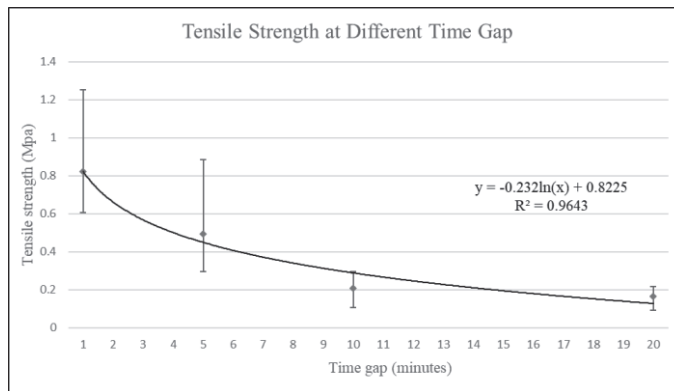


Figure 3: Tensile strength of samples at different time gap

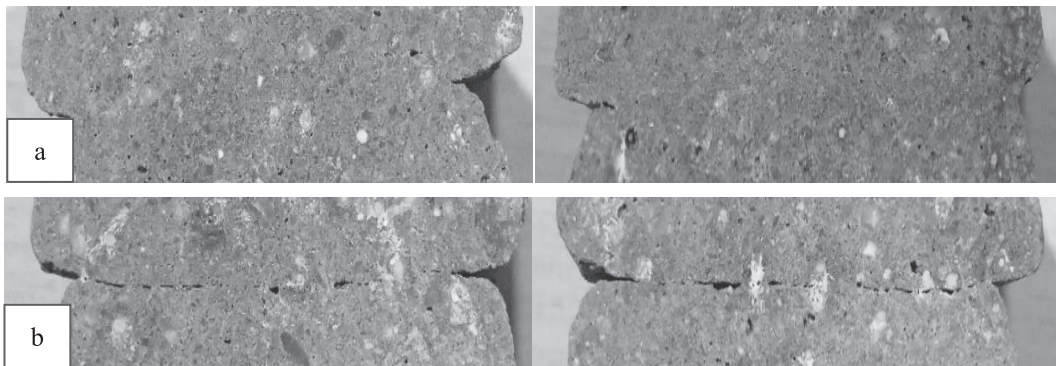


Figure 4: (a) sample printed at 1-minute time gap (b) specimen printed at 20 minutes time gap

### Deformity appearing on the interface

Close observation shows that at all time gaps, there is deformity across the filament at the interface forming a mild U-shape (Figure 5). The deformity (arc drawn in figure 5b and 5d) is more obvious when compared to the top surface of the 2<sup>nd</sup> layer in figure 5a and 5c. This deformity could be caused by the weight of the top filament during printing process where it is extruded and lay on the existing substrate. The weight and the force during contact may disturb the interface material and could have deformed it. When the material is still moist and has a short time-gap, this disturbance will help the material at the interface (Figure 1b) to interact and bond well. However, if the time-

gap is long, the material at the interface does not interact well thus only deforming it without interaction creating all the voids at the bond interface.

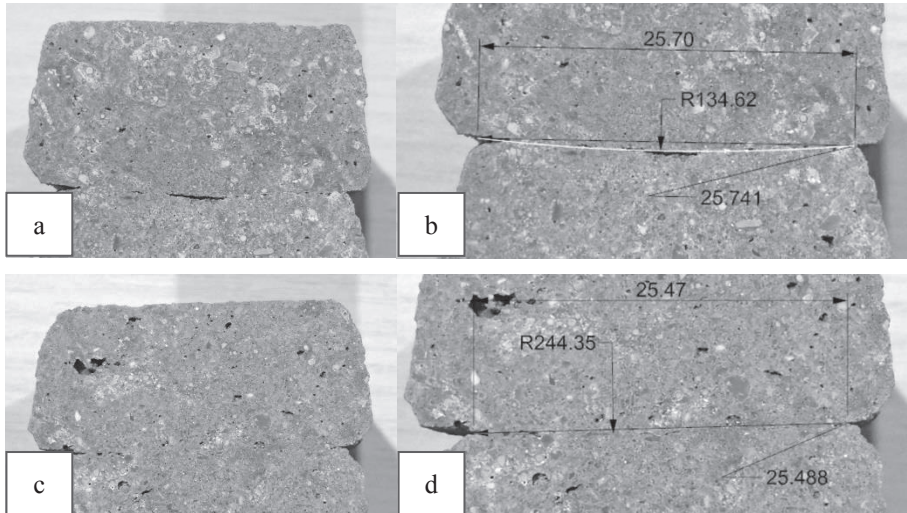


Figure 5: (a) 10-minutes specimen (b) Arc draw on the interface of the 10-minutes specimen (c) 1-minute specimens (d) Arc draw on the interface of the 1-minute specimen.

### **Printing load rate**

In concrete printing, due to the manufacturing process, the first layer at the bottom takes the most loads as subsequent layers are added above. Sufficient time is required for it to mature and stiffen to prevent deformation. This stiffening rate should be faster than the load rate to maintain overall structural integrity. Load rate ( $r$ ) is defined as the rate of material that is placed above the existing layer.

$$r = \frac{wgV}{x} \text{ (N/s)} \quad (1)$$

where  $w$  is the weight of the specimen for each layer,  $g$  is the gravity,  $V$  is the nozzle travel speed and  $x$  is the distance travel by the nozzle for each layer.

Printing should occur at the fastest load rate possible to help reduce the time-gap between layers. A proposed approach to decrease the time gap between layers while keeping the load rate constant is to reduce the height of each layer. This helps to increase the nozzle travel speed and decrease the time-gap between layers which will eventually improve the overall mechanical strength of the structure without increasing the load rate.

### **CONCLUSION**

The time gap in-between layers are unavoidable due to the layer-wise manufacturing method. Material properties between two layers will differ due to the difference in moisture caused by the time-gap. The lack of interaction at the interface material reduces the material bond strength.

Time gap in-between layers affect the overall mechanical property. Increasing the travel speed alone without caution on the loading rate will cause the fresh concrete to fail and buckle which eventually leads to structural failure. The load rate should coincide with the material stiffening

process. A proposed approach to keep the load-rate constant and increase the travel speed is to reduce the layer thickness. This helps reduce the time-gap which will improve the strength at the inter-bonding layer.

Future work includes the use of a modified nozzle to increase the interface area which may improve the bond strength without changing the filament width.

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