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TIME GAP EFFECT ON BOND STRENGTH OF 3D PRINTED CONCRETE

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Abstract

An advancing technology that combines the concrete extrusion with a motion control to create structures with complex geometrical shapes without the need for formwork is known as 3D concrete printing. Since this technique prints layer by layer, the time taken to reach the same position in the subsequent layer is important as it will create an anisotropic property that has a weaker tensile strength at the bond interface of the two printed filaments. Through rheological measurement, which reveals the material deformation and flow behaviour, it is possible to examine the material structural build-up due to time-gap effect by measuring at different time delay. This paper focuses on investigating the time-gap effect on the printed filament with rheological and observation at macroscopic-scale to understand the material behaviour of the initial and subsequent printed layer during its fresh phase. Rheological experiment findings reveal that the tensile strength of the printed specimen is correlated to the material modulus at the initial layer.

Keywords: 3D concrete printing; additive manufacturing; rheology; time-gap; tensile bond strength

1 Introduction

1.1 Background

Concrete is usually poured into a formwork that provides a temporary structure support as well as performing as a mould that shaped the freshly placed concrete to the desired configuration and size. In most cases, a vibrating rod is used together with the formwork. Since the concrete has a shear-thinning effect, the stress induced by this vibrating motion of the rod removes air bubble which increases compaction and would cause the material to flow in the formwork. This construction process produces homogenous material where the strength is the same throughout the material [1].

The extrusion-based 3D (three-dimension) concrete printing is an uprising construction method that does not require a formwork [2]. It is an additive manufacturing technique that combines concrete extrusion with a motion control. The material used with this technique has to possess no-slump, self-compacting and pumpable capability [3]. With the material capability as mentioned (such as no-slump and pumpable), it can be extruded from a nozzle and builds in a layer-wise manner. This allows a concrete structure that has a complex geometrical shape to be built without the need for formwork.

As the nozzle travel to trace out the two-dimensional profile to print a layer, the time it needs to reach the same location on the subsequent layer is called “time-gap”. The time-gap is dependent on the travel speed of the nozzle and the distance that it needs to cover for a single layer. This layering effect and the time-gap caused the material to possess a weak bonding at the interface between the two layers [3], [4].

1.2 Bond strength of concrete layers

The bond interface adhesion characteristic of two concrete layers can be divided into mechanical interaction and chemical bonding [5]. In concrete repair research, which analyses on the bonding and fracture mechanics of a hardened and fresh concrete reveals that a clean and rough surface on the substrate is required for the repair material to bond well [5]. The bond between old and fresh concrete has been widely investigated. On the contrary, there is little research on the bond interface between two fresh concrete before the emergence of 3D concrete printing due to its limited application [6].

The material parameter and printing parameter such as the aggregates size, material composition, printing flow rate, printing travel speed and printing time-gap can have a significant influence on the final 3D printed objects [6], [7]. It is reported by Zareiyan and Khoshnevis that using smaller aggregate size and lower aggregate to cement ratio yields higher tensile strength [6]. According to Paul et al, the strength of printed concrete has anisotropic properties and the tensile strength is stronger in the direction parallel to its printed direction than the strength perpendicular to its printed direction [3]. The low strength is usually caused by the weak bonds in-between the printed filament at the interfacial material shown in Figure 1 [8]. Studies that have been carried out in relation

to this anisotropic phenomenon revolves mainly around the mechanical properties of the printed concrete in its hardened state [3], [4], [6], [8], [9].

Figure 1: Cross-section of the printed filament

1.3 Rheological behaviour of cement paste

Rheology is the science behind the material deformation and flow, which emphasis on the relationship between the stress, strain and time [10]. The rheology of mortar, containing a range of particle size, is more complicated than one of its constituent material which is cement paste [11]. Banfill [12] mention that the flow properties of suspensions are governed by the interface of the solid-water and the dominant contribution is the cement-water interface. Presence of aggregates will only dilute this flow behaviour. Therefore, in this study, the rheological testing only focusses on the paste instead of the mortar.

Fresh cement paste is concentrated suspension that exhibit a complex viscoelastic behaviour [13]. Understanding the viscoelastic behaviour of cement paste can be helpful to better understand the behaviour of concrete [14]. Viscoelastic behaviour of a material is often modelled by a system of dashpot and springs. The dashpot represents the viscous behaviour of the material and when a load is applied, the deformation will increase with time. The viscous behaviour is usually represented by the loss modulus G'' . The spring represents the elastic response of the material. This spring elasticity behaviour of the material is defined by the storage modulus G' [15]. The dynamic test can be used to distinguish the elastic and viscous properties of the material [16].

Research done by Roussel and Cussigh [17] has shown that in distinct-layer casting (casting two layers of self-compacting concrete) the initial layer has a short amount of time to rest and rebuild structure before the second layer of SCC is cast above it. If the initial SCC layer rebuilds too much,

above a critical yield stress value, the two layers do not mix well thus creating a weak interface between the concrete layers. Furthermore, this weak interface may increase porosity locally and could cause permeability to aggressive substance. The time-gap in-between the two layers should be as small as possible to eliminate this weak interface.

This paper focuses on investigating the effect of time-gap on the material in its fresh states and its correlation with the tensile strength. Rheological experiments were conducted to examine the effect of time on the paste material behaviour in its fresh states under high shear which mimics the pumping process, as well as the effect of time on the structural rebuild of the paste material in its fresh state which mimics the material at rest after extrusion. In addition to the rheology test, the observation at macroscopic-scale of the cross-sectional inter-bond layer will be examined to understand how layers are stacked on top of another which could provide insights on the bonding affected by the time-gap.

2 Methodology

2.1 Materials preparation

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. Ordinary Portland cement (OPC, ASTM Type 1, Grade 42.5), Silica Fume (Undensified, Elkem), Fly Ash (Class F) and river sand were used in this experiment. Table 1 shows the mix design composition. The gradation of the materials used were illustrated in Figure 2 and 3. 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

Figure 2: Cumulative percentage passing by volume for all particles

Figure 3: Individual percentage retain by volume for all particles

After printing, to prevent evaporation of the water from the fresh concrete, the samples were covered with a plastic wrap. Samples were then cut into smaller size (30mm cube) 24 ± 1 hour after printing. These smaller cubes were then wrapped back with the plastic wrap and were cured in the laboratory environment for 28 days under the temperature of 23 ± 2 °C and relative humidity at 60%.

2.2 Rheological measurement protocol

A rheometer (MCR102, Anton Paar, Germany) equipped with a measuring stirrer with two hollow blades (Stirrer model: ST59-2V-44.3/120) and a cup was used. The cup of the rheometer has a modular insert cage with serrations as shown in Figure 4(a) to prevent wall slippages. Figure 4(b) illustrates the schematic drawing of the measuring system. Two protocols were conducted: amplitude oscillatory sweep test and oscillatory time sweep test.

An amplitude sweep was carried out to measure the critical strain of the material. Using a value below the critical strain allows the material to rebuild its structure without destroying its internal bond. The rheometer oscillates at a linear increment shear strain from 0.01% to 1%. The frequency is held constant at 1Hz. A strain value within the linear viscoelastic region (LVR) will be used in the structural rebuild test.

Oscillatory time sweep test was carried out to determine the viscoelastic behaviour of the paste. In the first interval, the rheometer destroys the microstructure with a constant rotational shear rate $\dot{\gamma}$ of 10 s^{-1} for the duration of 50 seconds. In the second interval, the material is allowed to recover and the stirrer oscillates within its LVR with a shear strain γ of 0.1% at 1Hz for the duration of 300 second. This test was carried out at a different time interval after mixing (0-minute delay, 10-minutes delay and 20-minutes delay) to simulate the time gap printing.

Figure 4: (a) Rheometer measuring system [18] (b) schematic drawing of the measuring system

2.3 Printing parameters

A gantry printer is coupled with a rectangular nozzle orifice with a dimension of 30mm by 15mm (See Figure 5). The schematic drawing of the printing parameters such as concrete flow direction, printing directions and nozzle orientation were shown in Figure 5. A rectangular nozzle was chosen because it provides a large surface contact area between the layers which contribute to the stability during printing. Interval of 1-minute, 5-minute, 10-minute and 20-minute was chosen as the printing time-gap in-between layers. Some other printing parameters are shown in Table 2.

Figure 5: Schematic drawing of flow of concrete

Table 2: Printing parameters used for the experiment

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

The initial layer is denoted by 0-minute and the subsequent layer of the printed filament is denoted by 1-minute, 5-minutes, 10-minutes and 20-minutes depending on the time-gap in-between the filament as illustrated in Figure 6.

Figure 6: Labeling of different layers for this study

2.4 Bond test

Instron 5960 dual column tensile test machine was used to measure the tensile bond strength of between the two layers on the 28th day after printing. In this study, the direct tensile bonding tests were conducted only on 3D printed samples with interfaces. Four cube specimens at each time-gap with a length of 30mm were extracted from the concrete block with a diamond cutter. It is noted that the height of the sample is relatively small compared with the width, which might induce not only tensile stress but also shear stress during the fracture.

Both sides of the samples were glued to two mild steel plates using rapid hardening adhesive (X60) supplied by HBM showed in Figure 7. The tensile test was carried out at a rate of 0.035 ± 0.015 MPa/s according to ASTM C1583/C1583M-13 [19]. It is noted that after extrusion, the filament exhibits slump behaviour. The cross-section of the filament shows an isosceles trapezoid shape where the bottom length is longer than the top length. The effective area of bonding and failure load were then used to calculate the bond strength for each specimen and the average bond strengths out of the four samples were reported and discussed in the following section.

Figure 7: Preparation of specimen for the tensile test.
(a) Actual experiment setup (b) Schematic drawing of the bond test

3 Results

3.1 Rheological measurement result

The amplitude oscillatory sweep test result used to determine the critical strain is shown in Figure 8. This critical strain was measured to be above 0.2%. Below the critical strain, the structural integrity of the network is maintained during measurement [20] and behaves solid-like. The material behaviour is dominant by the storage modulus (G') indicating that the material is highly structured [21]. Above this critical strain, the bond between the particles no longer have an attractive interaction

and the flocculated network loses its structural integrity [22]. The material behaves more fluid-like and the storage modulus (G') will eventually be exceeded by the loss modulus (G''). Only the paste portion of the material was used in the rheological experiment (which includes only cement, fly ash, silica fume and water as shown in Table 1). Since the change in the material stiffness behaviour due to time effect is caused only by the paste portion, to reduce the complexity of the material, the inert aggregates were not included in the rheological testing.

Figure 8: Critical strain of paste material with strain sweep measurement

After the LVR is defined by the strain sweep, the effect of time on the material structural rebuild can be further characterized using the oscillatory time sweep test. The LVR is below the critical strain value of 0.2% as measured by the amplitude sweep test (See Figure 8) [23]. To ensure the strain is well within the LVR, 0.1% strain was chosen to be used for measurement. The oscillatory time sweep test in the second interval will oscillate within the material LVR which will not destroy the microstructure [24]. 1-minute and 5-minutes samples were not included in the rheological experiment because of the proximity of the time difference and the difference was thought to be insignificant as compared to 10-minutes and 20-minutes samples.

The first interval of the protocol rotates the material at a constant shear rate of 10s^{-1} . In this interval, the microstructure bond within the material is broken down which simulates the action of the pumping process where the material is delivered from the reservoir to the print-bed [25]. The rheological breakdown measurement is shown in Figure 9. The calcium silicate hydrate (C-S-H) is the product of hydration that is responsible for the strength gain in the material. As time increases, more

C-S-H are formed between the cement particles, which increases the strength of the material [26]. When a constant shear rate is applied to the material, the bond breaks down in a logarithmic manner for all time-gap samples as presented in Figure 9. It requires more effort to pump a 20-minutes sample because more C-S-H bond was formed as compared to a 0-minute sample.

Figure 9: Results of the first interval for structural rebuild test

Figure 10 shows the oscillation result for the second interval. This second interval oscillatory result mimics the structural build-up of the subsequent layer material after extrusion in the printing process. Although there is a time difference between the samples (10-minutes and 20-minutes time difference), this time-gap does not affect the stiffness and structural build-up rate which imply that the material behaves the same for all time-gap specimen (0-minute, 10-minutes and 20-minutes) after extrusion as shown in Figure 10.

Figure 10: Oscillatory results of the specimen at a different time interval

The structural build-up of the initial layer increases logarithmically as presented in Figure 11. This increment behaviour of the material structural build-up is inversely proportional to the tensile

strength of the material. The forces acting on the initial layer caused by the layering of the subsequent layer above will induce certain shear stress on the interfacial material on the initial layer. This shear stress is the same for all time-gap, considering that the subsequent filament size, shape, height and material properties remain unchanged. As the material increase in stiffness in the initial layer, it will require a higher stress to achieve the same shear strain for the 20-minutes sample as compared to the 0-minute sample.

Figure 11: The structural build-up of the initial layer

3.2 Time-gap effect on bond strength

The direct tensile test result as shown in Figure 12 show decrease in strength as the time-gap increase. The strength reduced logarithmically, it is more significant initially between 1-minute and 5-minutes time-gap and the reduction in strength is insignificant after 10-minutes time-gap. This material behaviour is similar to the material structural build-up rate. As time increases, more C-S-H nucleation occur between the cement grain which improves the overall stiffness of the material [27]. Since the stresses acting on the initial layer by the deposition of the subsequent layer is the same for all time-gap. This increase in stiffness at the initial layer will cause less disruption on the interfacial material as time-gap increase, thus producing a weaker bond due to insufficient interaction between the two layers.

Figure 12: Tensile strength of samples at different time-gap

Further investigation on the bond from its cross-section shows that there are almost no obvious voids in-between the layers for 1-minute specimen (See Figure 13(a)). However, as time-gap increases, the void in-between the layers is increasingly obvious (See Figure 13(b), 13(c) and 13(d)). The interfacial material at the initial layer and the subsequent layer are sensitive to disturbance when the time-gap is short. As 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 the deposition of new layers. However, the material stiffness at the initial layer increases logarithmically with time. As a subsequent 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 as shown in Figure 13.

Figure 13: Samples printed at (a) 1-minute time-gap (b) 5 minutes time-gap (c) 10 minutes time-gap (d) 20 minutes time-gap

Close observation shows that at longer time-gaps, there is a deformity across the filament at the interface forming a mild U-shape (See Figure 13(b), 13(c) and 13(d)). This deformity may be caused by the weight of the subsequent layer and the stresses during the printing process which may disturb the interface material. When the material has a short time-gap, this disturbance will help the material at the interface 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 voids at the bond interface.

4 Discussion

It could be seen in Figure 9 that during the pre-shear process, which corresponds to the pumping process during 3D printing, the longer the resting time, the higher the initial shear stress in the beginning. It could be related to the structural building up process due to colloidal flocculation [28]. However, after a strong shear over 50-seconds, the equilibrium shear stress becomes much closer between various resting times. Moreover, after extrusion, as shown in Figure 10, the storage modulus between various resting times show little difference. It could be assumed that the pumping process is strong enough to break down the microstructure and eliminate the effect of resting time on the shear stress or modulus within 20-minutes.

After extrusion of the initial layer, the modulus of the initial layer will increase with time shown in Figure 11. Longer time-gap will result in higher modulus of the initial layer. The increase in modulus of the initial layer could make the interface too stiff to mix well with the subsequent layer. For the actual printing process, since the second layer shows similar performance, the difference in tensile bonding under various time-gap could be related to the modulus of the first layer. Some researcher attributed it to the surface moisture of the first layer [29].

In the meantime, in this study, it was found that the pores at the interface could play another big role. It is clearly seen in Figure 13 that with increasing resting time, the amount of voids at the interface is increasing and the pores become bigger. To prove that adhesion at the interface is greatly affecting the tensile strength, further study to modify the contact area of the interface is ongoing.

Although the printed material shows anisotropic property, this manufacturing technique is not the direct cause of it. If the material has high workability and is able to interlock with the previous layer caused by the printing process, the bond strength would remain the same, regardless of the time gap. However, since the stiffness of the material increases with time and in-order to retain the shape retention capability there is a limit in the workability of the material which makes the time-gap important.

5 Conclusion

3D concrete extrusion-based printing has a printing time-gap in-between layers, due to the layer-wise manufacturing method, which has a considerable influence on the bond strength between the filaments.

Rheological properties of the initial layer will have an impact on the bond with the subsequent layer and the adhesion at the interface between these two layers is the key to the tensile strength of the structure. The modulus of the subsequent layer is not affected by the time-gap, however, the modulus of the initial layer increases with the time-gap. It is reasoned that high modulus of the initial layer prevented the good contact and mix at the interface. As the time-gap increases, voids were increasingly induced at the interface which weakens the bond strength logarithmically.

In the meanwhile, the high modulus of the initial layer is necessary to support the subsequent layers and keep structural stability. Further work is ongoing to improve the bond strength while keeping high modulus, such as increasing the surface contact area of the interface.

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