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Investigation into the effect of delays between printed layers on the mechanical strength of inkjet 3DP mortar

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ABSTRACT

Currently, additive manufacturing have enabled to fabricate the three-dimensional models. 3D-Printing technique is a multipurpose process for producing structural members using a sequential layering approach. The "feature quality" of 3DP specimens can be improved by optimising the build constraints. In this paper, a mortar mix powder-base has been prepared that consists of cementitious materials. Experiments are conducted to investigate the effects of different delays in printing time on the mechanical properties of the scaffolds. It has been shown that the compressive stress and strength of printed specimens with a delay of 200 ms were greater than specimens with other delay values.

1. Introduction

Additive manufacturing technology, generally recognized as 3D printing (3DP), is becoming increasingly important in construction applications [1,11]. Complicated geometry is difficult to produce with either cast in-situ or conventional casting in formwork type construction. However, the powder-based 3DP method is ideal for producing building members with complex details. Similarly to precast members, 3DP can be used to print members off-site and assemble the members on-site. In the previous work [2], a creative methodology is developed for formulating cement powder materials for inkjet 3DP. The cement powder material has been verified to exhibit sufficient flow and deposition characteristics through the feeder bin to the build chamber of the 3DP.

Following the successful 3DP of a mortar specimen, the process of depowdering is applied in which the unbounded powder is detached by blowing air. The printed part is called a green part and is known to have a weak bond between powder particles. The green part is commonly porous and weak. The porosity and strength characteristics can be improved by a post-processing cure, so as to create a solid part with accurate dimensions [3,4]. In earlier work [2], the cubic geometry has been printed, and the maximum compressive strength was observed to be 8.26 MPa. However, this compression strength is relatively small for structural members and additional enhancements must be applied, such as heating cure [3] and delays in printing time. Adjustments in the time of delay between printed layers has been shown to affect the formation of the microstructure and porosity between particles [5].

In this paper, the ideal delay time between layers is explored and the corresponding highest compressive strength is shown. Additionally, the effect of layer printing delays and different curing mediums on the printed mortar parts by means of inkjet 3DP technology is assessed and discussed.

2. Materials and methods

2.1. Materials

The 3DP cement mortar structures were successfully printed in a way which can be applied for construction purposes. The prepared mix consists of Calcium Aluminate Cement (CAC), Ordinary Portland Cement (OPC) and fine sand, named CP. A CAC sieve range is between (75–150 μm). The reason for using the CAC with OPC is that it assists to accelerate the setting time of the mortar. The mix is 67.8% of CAC, 32.2% of OPC and 5% of fine sand, as a percentage of the total weight. Fig. 1 shows the cumulative distribution curve for the modified mix powder (CP) and original powder (ZP 151) versus the particle size. The binder solution (Zb 63) consists of water and humectants [6].

The modified powder (CP), which replaces the printer powder (ZP 151), has been mixed properly using a Hobart mixer [2]. The similarity and consistency of the powder materials are vital factors that must be controlled when in pursuit of superior resolutions and results. Therefore, the speed of the mixer and the time of mixing are carefully controlled to ensure a homogeneous powder and to produce better quality 3DP specimens.

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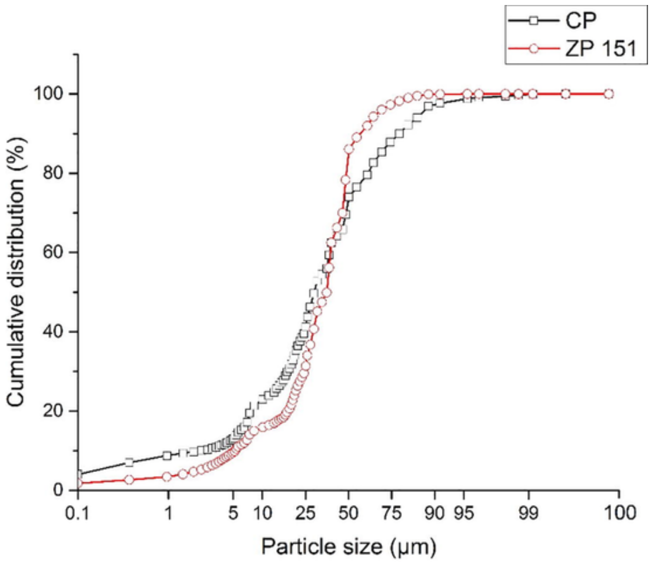

Fig. 1. The distribution curve of particle size for (a) ZP 151 powder and (b) CP powder.

2.2. Methods

Inkjet 3DP is a layer-on-layer procedure to create an entire scaffold using the powder-based materials and an activator such as water. The default pause time between layers can be changed, so as to introduce a short delay after each layer is finished and before the next layer is started.

The CP powders were put into an inkjet 3DP instead of the original powder ZP151. The ProJet360 uses a binder liquid that passes through the HP 11 printhead into a powder, one layer upon another layer, from the bottom of the build chamber to the highest until the object is complete. Table 1 shows the scaffold specifications of the printed specimens designed by CAD software and the 3DP parts. Five cubes for each type of delay in printing with dimensions (20 × 20 × 20)mm are used to examine the mechanical properties. The printing process is prepared using a binder/volume ratios of 0.415 (shell) and 0.415 (core). The binder/volume ratio values for shell and core regions are assumed to be constant. After completing a print, the printed object is dried in the build chamber for approximately 90 min before being removed from the powder bed. Then compressed air is used to remove any unbound powders from the printed specimens.

Moreover, the printed cubic specimens (20 mm) are prepared by the inkjet 3DP as explained in [2]. In the current study, after removing specimens from the printer they are post-processed, firstly in an oven to dry the specimens for 3 h at 60 °C. Then, as shown in Table (1), the specimens are cured in the tap water medium for either 3-days or 7-days. Once the specimens are out of the water medium, they are dried in the oven for 3 h at 60 °C. This procedure has been applied to all specimens. Curing in the oven has a significant effect on the mechanical strength of specimens [3].

In this study, three different speeds were used to find the optimum speed for cement mortar materials. These speeds have been selected based on previous studies, which were performed for plaster materials [5].

Table 1
Features and different time delays in layer printing of specimens.

Name of specimens	V_b/V_p	Number of samples		Delay in layer printing (ms)	Specimen size (CAD) dimensions (mm)
		3-days	7-days		
S100	0.415	5	5	100	(20 × 20 × 20)
S200		5	5	200	
S300		5	5	300	

3. Results and discussions

A compressive strength test is commonly used to confirm that the concrete mixture meets the required strength of the construction application. The compressive strength of the 3D printed samples was calculated and compared in different delay time to find the optimum delay time in printing. All samples were tested with similar parameters and setup conditions.

Fig. 2 shows the average values ± standard deviation values for all five measurements, for each of the three delay times for 3-days and 7-days curing.

Fig. 3 shows the stress–strain diagram in compression which begins with an initial non-linear toe region. Then, the main region is a linear region. Next, the concave region starts until it reaches the failure point. According to the compressive stress–strain diagram in Figure (3), initially, the samples (1 for each delay time) experienced the elastic displacement then the failure in the whole body of the cube. During the visual inspection, microcrack generations can be observed in the margin wall of the cubic structure vertically through the cube. Furthermore, the cracks sometimes went through the middle of the cube like an hourglass shape. Thus, the internal structure core has an important effect on the mechanical behaviours of 3DP specimens.

As shown in Figure (2), a differential delay in printing between layers results in different values in compressive strengths for 3-day and 7-day. S100 specimens were found to have relatively low compressive strength. Incrementing the printing delay from 100 ms to 200 ms increased the compression strength and toughness of the printed structure. S300 specimens had higher compressive strength values compared to S100. However, overall S200 recorded the highest results among all printing layer delays. Thus, amongst the delays testing for the three (100, 200, 300 ms) selected times, 200 ms is the optimum printing delay between layers for CP materials.

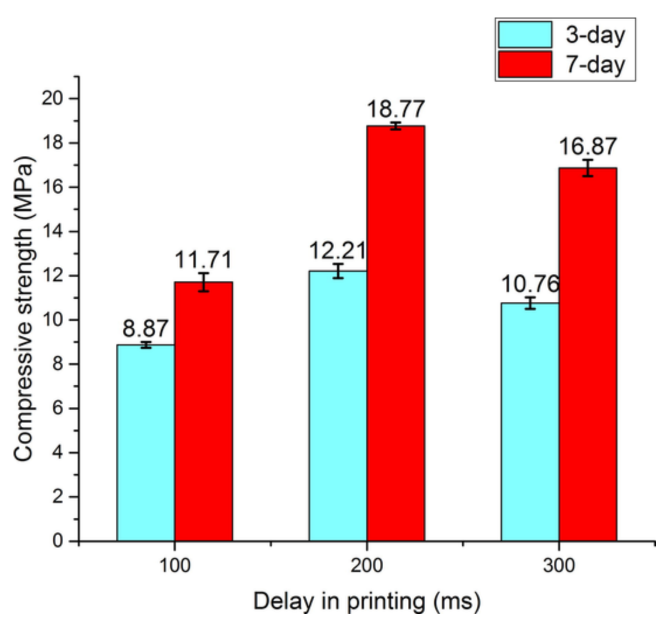

Fig. 2. Compressive strength in printed CP with a different delay in printing time.

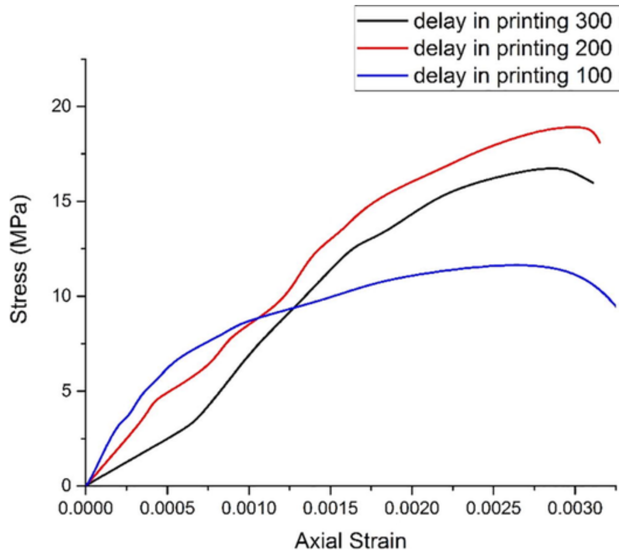

Fig. 3. Compressive stress–strain curve for different layer printing delay times of CP specimens for the maximum printed sample and with 7-day curing.

In an earlier study, it has been shown that when the saturation level of powder is high, the strength of CP specimens increases [2,3]. Therefore, in this paper the optimum saturation levels were chosen. From this study, it appears that a rise in the delay time between layers results in better binder uniformity and spreading, which in turn enhances the strength. One noteworthy result shown in Figure (2), is that under the same binder saturation, an increased printing delay (from 100 ms to 200 ms) leads to an increase in compressive strength. This is since the delay enables the sprayed binder to penetrate more efficiently in lateral and vertical directions on the surface of the powder; hence, resulting in fewer voids between powder particles. This is consistent with a study by Vaezi [7], which states that inadequate spreading of the binder vertically and laterally reduces the sample strength and integrity. According to Figure (2), the weakest average compressive strength was found in S100 specimens. Another reason for the weakness of S100 is due to weak compactions by the roller on the powder bed. The roller moves faster when the delay in printing time is reduced, which in turn leads to inconsistent and less compaction in the powder bed. Consequently, the new layers will not have enough time to react with the previous layer (i.e. 100 ms), this has been confirmed by the study [3]. They proved that the penetration of the liquid binder into the cement-based materials quicker than the plaster (original) materials.

It has been observed that as the delay in printing time between layers decreases, the fresh layer of powder is not spread homogeneously on the bed surface. This creates voids in the bed-powder, making the printed specimen porous, and the final product inconsistent. In another case, the binder is not fully solidified, and the following layer powders will be placed on to the previous earlier layer that is not completely hardened. Alternatively, the binder may harden relatively quickly once it is placed; meaning that particles deposited from the new layer on a surface of the former layer are not subject to particle restructuring due to capillary forces. Further, a binder droplet on the surface layer can react and penetrate entirely before the next layer is laid on. In this way, the previous layer will be more coherently created and as a result, the compression strength will be improved.

It has been shown that the delay time can be optimised to improve mechanical performance. An ideal delay time results in better binder spreading and uniformity, which in turn leads to improvements in strength. If the delay time is increased to be more than the ideal time it leads to the penetration of liquid droplets to pass through to the lower layers of the print bed. Therefore, the binding between the two layers would be difficult due to delay new layer bedding on the previous layer and occurred partial penetration [8].

Consequently, finding the optimum delay in printing time is crucial for printing different geometries in CP [9]. In regard to the delay in printing time, drop penetration depth, drop penetration speed and wettability ratios account for delays in layer printing and green part strength of the final 3DP product [10,3]. Overall, the shearing of the layers during or after the printing process occurred while non-ideal (i.e. too high or low) printing delays times were used when printing structures. The factors discussed significantly influence the mechanical behaviours of the printed product.

4. Conclusion

Recently, 3DP technology has emerged as an advanced technique to the construction of highly precise complicated structures, which are conventionally difficult to construct. This study has investigated the use of delay time between printing layers, and how it affects the mechanical properties of the specimens. Groups of samples have been constructed using a variety of printing delay times, and curing conditions, to comprehend and choose the most appropriate manufacturing parameters. The results show that the layer printing delay has a major influence on the compressive strength of the printed objects. The printed cube with 200 ms delays between the printing of each layer has been found to the most suitable for cementitious mortar (CP), with the highest compressive strength recorded as (18.77)MPa for 7-day curing. Therefore, going forward, it is highly recommended that a delay value of 200 ms is used when printing for CP materials.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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