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Improving flexural characteristics of 3D printed geopolymer composites with in-process steel cable reinforcement

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ABSTRACT

3D concrete printing has recently become the subject of very rapidly growing research activities all over the world. An obstacle to develop 3D concrete has been the lack of tensile strength and therefore, limiting the printed component for structural application. This can be partly solved by designing fiber reinforced concrete or concrete with in-process embedded steel reinforcement. This article presents our first findings of using a steel cable reinforcing nozzle which can directly entrain continuous steel cable inside any extrudable mortar (e.g geopolymer), thus creating a hybrid reinforcement, that will improve flexural strength and ductility of the geopolymer composite. We have tested different cable reinforcements and compared their performance based on 4-point bending test. From experimental results, it was found that steel cables can provide a suitable reinforcement and hence improve the flexural strength of 3D printed concrete by 290%. Further research into optimal reinforcement placement, configuration and reinforcement material is recommended.

1. Introduction

In the last few years, 3D printing in the construction industry has generated a considerable interest, both in academic and industry owing to significant benefits in terms of higher quality and productivity, faster construction processes, higher geometrical freedom, and cost-efficiency. Various technologies involving 3D-printing with gantry and robotic printer have been developed, and the number of demonstration projects has been increasing exponentially [1–3]. Most of these approaches were initiated to explore additive manufacturing of concrete (for instance: a free-shaped bench [4], a children castle [5]) that does not meet the requirements of structural applications or actual load regimes. However, with recent successful case studies for e.g. 3D printing of an office [6], a pedestrian bridge [7], a hotel extension [8], the trend has moved towards structural application, with an aim to increase ductility and (flexural) tensile capacity of the printed structures.

Since the plain concrete is often brittle, the general strategy to use printed concrete is as formwork (for conventional reinforced concrete) or applying external pre-stressing tendons to obtain enough tensile capacity and ductility. Another possibility is to include fibers to achieve ductility and in this regard, Hambach and Volkmer [9] reported significantly improved tensile strengths in mortar samples, reinforced with 1 vol% 3–6 mm carbon, glass, and basalt fibers.

In literature, the most widespread approach for reinforcing 3D printed concrete is the cast in-place formwork method, first seen in Contour Crafting [10] and later, adopted by WinSun and Heijmans [11]. The cast in place formwork method combine both printing and casting methodology. It requires the printing of concrete filaments to build a permanent, integrated formwork that is subsequently installed with horizontal and vertical reinforcement bars and filled with flowable concrete to form a reinforced structure. A subsequently development from the cast in-place formwork, is the selective printing of a lattice structure, which prestressed steel tendons can be added, as mentioned in [12]. This cast in-place formwork method may restrict the free form capabilities of concrete additive manufacturing, as they all requires printing linear segment prior to conventional steel reinforcement and creates a cold joint between the cast concrete and the printed permanent formwork.

Another very original approach has been developed at ETH Zurich under the name Mesh Moulding [13] that additively prints the steel reinforcement. In mesh moulding, the concrete is manually added to the steel reinforcement cage, as the holes between the mesh is too wide for the application of shotcrete. Peng Feng et al. [14] used mouldable fiber reinforced polymer sheets as an external reinforcement for additive manufacturing of concrete. The fiber reinforced polymer sheets are flexible before curing,

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Table 1
Properties of PVA fiber.

Specific Gravity (g/cm^3)	Diameter (mm)	Thickness (dtex)	Cut length (mm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation (%)
1.29	0.0014	1.8–2.3	12	1500	41.7	7

Table 2
Properties of Stainless Steel cable.

Grade	Tensile Strength (MPA) min	Yield Strength 0.2 Proof (MPA) min	Elongation (in 50 mm) min	Density (kg/m^3)	Elastic Modulus (GPA)	No of Strands
SUS304	515	205	40	7900	193	7 × 7

and allows it to be pasted over a nonlinear printed structure. Use of fiber reinforced polymer sheets may also be prestressed to provide additional strength enhancement by reducing the effective stresses in the concrete structure [15]. Although, these two methods allow free-form additive manufacturing, it is quite labour intensive because of the hand layup technique, used to attach all required reinforcements.

In a recent paper by Freek P.Bos, an automated cable entraining reinforcement has been introduced for 3D concrete printing has been introduced for reinforcing printed concrete [16,17]. The authors used single continuous steel cable as reinforcement in the longitudinal direction of the printer sample using active feed mechanism and performed four-point bending (flexural) test on 28 days experiment by varying cable diameter, but this is done without a control group. It was found from the experimental results that the flexural strength of the samples increases with cable diameter, however the two experiment sets suffered from cable slippage before reaching their failure strength.

This paper will describe one of the techniques that is being used at Nanyang Technological University (NTU), Singapore builds on the idea of hybrid reinforcement for 3D concrete printing application. In this research we have used a novel printable geopolymer to study the effect of a steel cable reinforcement with variable diameters. The reinforcement was embedded into the geopolymer matrix using a device that allows smooth introduction of steel cable into the extruded filament. The choice of using hybrid reinforcement was confirmed, from our initial observation of cable slippage when singularly reinforced with steel cable. This cable slippage behavior is similar to smooth fiber effect which is confirmed in an earlier study by Freek P.Bos [17]. In order to prevent cable slippage, it was decided to introduce PVA fibers into the concrete mixture. By adding a second short length fiber, that helps to promote fiber-to-fiber interlock or entanglement [18,19], the effect of hybrid reinforcement has been explored in this study [19,20]. It has been noted that the two fibers are responsible in bridging short and long cracks respectively. Short fibers can bridge microcracks in the initial stages of tensile loading, where the longer fibers become active in the later stages of crack growth.

2. Materials and methods

2.1. Materials

Fly ash based geopolymer was chosen as feed stock in this paper and to formulate the binder, 80% class F grade fly ash (FA) 15% ground granulated blast-furnace slag (GGBS) and 5% micro silica (S) was mixed uniformly in a high shear planetary mixer. Potassium silicate (SiO_2 = 24.94%, K_2O = 21.09%) was consumed (liquid/solid = 0.45) as alkaline reagent in the mixing process with fine river sand (sand/binder = 1.5) of maximum particle size 1.18 mm [20]. Thixotropic additives (magnesium aluminum–silicate nano clay) were separately added into the mortar mixture

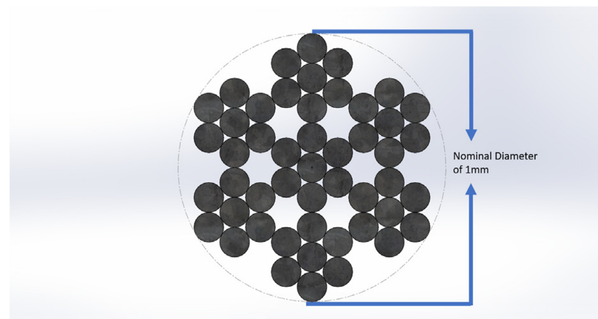

Fig. 1. Cross section of stainless steel cable.

for 3D printing of geopolymer using a 4-axis gantry printer and grouting pump set up [21].

We used 8 mm polyvinyl alcohol (PVA) fibers (0.5 wt%) in this research to investigate and compare the reinforcement (steel cable) performance in both fiber-reinforced and regular/control (without fiber) geopolymer composites. The details of PVA fiber is reported in Table 1.

All stainless steel cable of varying diameter were of the same material, SUS304, whose properties were listed in the Table 2 below. The diameter used were 1 mm, 1.5 mm and 2 mm. The diameter of the cable refers to the diameter of a circumscribed circle that will enclose all the strands of wire, it is also the larger of cross-sectional measurement of the wire. As the cables were twisted together, combining smaller wire strands bundles, the measured perimeter of the cable's cross section was larger than πd, as seen from the Fig. 1. This increase in surface area can provide better interface adhesion between the cables and geopolymer matrix, leading to a better load transfer mechanism, and hence higher strength.

2.2. Methods

2.2.1. 3D printing of hybrid geopolymer composite

A four axis gantry printer (Fig. 2) was used to print eight straight walls of dimension 1000 × 30 × 39 mm, with varying cable reinforcement (C10, C15 and C20)[1] and a control group (C0). The printed filaments were ambient cured prior to flexural testing. Each filament was cut into three pieces on the seventh day, resulting six test samples for each variable and control. The flexural strength results are discussed in the following section.

Since geopolymer binder has higher stiffening rate than normal concrete (OPC), its open window for printing is also much shorter [22]. The time gap between mixing and printing has been reported to contribute towards the tensile strength of 3D printed element, especially when pulled in the layer build up direction, owing to

[1] C10,C15,C20 indicates matrix reinforced with 1 mm, 1.5 mm and 2 mm stainless steel cable