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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.

Keywords: 3D concrete printing; Reinforcement; Stainless steel cable; In-process embedment; Geopolymer

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][2][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 prestressing 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, 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 geopolymers 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 in to 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 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 1mm,

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

1.5mm and 2mm. 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.

Figure 1: Cross section of stainless steel cable

Table 2: Properties of Stainless Steel cable

Grade	Tensile Strength (MPa) min	Yield Strength 0.2 Proof (MPa) min	Elongation (in 50mm) min	Density (kg/m ³)	Elastic Modulus (GPa)	No of Strands
SUS304	515	205	40	7900	193	7x7

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 1000x30x39mm, 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.

Figure 2: 4 axis Gantry Printer at Nanyang Technological University, Singapore [22]

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 an improved bond strength in the 3D printed interface layer when print time was kept to a minimum in both geopolymer [23] and high strength cementitious material [4]. From the results of tensile bond test conducted at Nanyang Technological University, Singapore [23], we found the open time for ideal bond strength of geopolymer is under 20 minutes and therefore all printing activity in this paper has been completed

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

within this open time period. Rest parameters such as speed, feed rate etc are reported in Table 3.

Table 3: Gantry printing parameters

Parameters	Value
Print length	500mm
Layer height	13mm
Layer width	30mm
Nozzle dimension	13mm x 30mm
Feed rate	60mm/s
Pump mass flow rate	110g/s

2.2.2. Insertion Method and Mechanism

The concept of embedding continuous reinforcement is similar to the conventional fused deposition method (FDM) printer that is available on the market. Embedding continuous reinforcement in additive manufacturing was first described in FDM printers, printing carbon fiber in a thermoplastic matrix [24]. Similarly, in this research we embedded a continuous steel cable into a geopolymer concrete matrix. In our extruder setup, we used a direct extruder feeder system (Fig. 3), that was powered by a stepper motor and controlled by a microcontroller. The choice of a direct cable extruder over the Bowden extruder was that it requires less torque to push the cable into the geopolymer concrete matrix, hence saving on a lighter motor, and conforming to the specifications of our gantry printer. A lighter nozzle would also allowed for a more precise and controllable motion, with less jerk due to inertia. The extruder unit was a stand alone unit, which can be fitted onto the gantry’s existing nozzle, through a slip ring connection. The slip ring is essential in allowing the nozzle to retain its rotating capabilities without being entangled by the electrical wiring, necessary for data communication and handshaking between the microcontroller and the onboard main computer. The extruder is configured

to take up to a 2mm diameter cable. Traction of the cable was maintained by the spring pushing the idler wheel and keeping the cable in constant contact with the drive gear of the extruder. As the extruder pushed the cable into the concrete nozzle, the pressure inside the nozzle encased the cable in the concrete matrix and extruded a reinforced concrete composite, with the cable at a predefined section. The microcontroller was set to control the stepper motor to keep pace with the traverse speed of the concrete print nozzle. It prevented the cable from slipping in the fresh concrete matrix due to the different speed. Steel cable was chosen over conventional steel rods due to its bending stiffness afforded by flexible cable. Steel cable will be increasingly easier to bend as the number of strands within the cable is increased. In this experiment, 7x7 strands of varying diameter cable was used. The minimum bending radius of the 7x7 steel cable was about eight times its diameter, as such the print nozzle should not turn a radius smaller than the minimum bending radius of 16mm for a 2mm diameter cable, which is sufficient as the nozzle width alone is 30mm wide.

Figure 3: The design and prototype of the steel cable extruder.

2.2.3. Experimental Procedures

Rheology of printable mix design: Two rheological experiments were conducted at room temperature using Anton Par MCR 102 rotational rheometer [25] to explore the rheological properties of printable geopolymers mix: (1) steady-state flow tests

in a range of shear rate 1 to 100 s^{-1} ; and (2) 3TT recovery tests under low (0.1 s^{-1} for 60 sec) - high (100 s^{-1} for 60 sec) - low (0.1 s^{-1} for 30 sec) shear rates.

Flexural testing: The four-point bending was conducted on an Instron universal testing machine according to the loading configuration and dimension as shown in Fig.4. Geopolymer samples were printed and left to ambient cured for 7 days, before being cut using a radial arm saw to 280x30x39mm dimensions for testing. The load was applied at a rate of 1mm/min without shock to the geopolymer sample.

Figure 4: 4 point bending test of 3D printed geopolymer with dimensions

Statistical Analysis: A one-way ANOVA test at $p = 0.05$ significance were used to evaluate statistical significance [26][27][28] in the four groups regarding the improvement due to hybrid reinforcement in max load, deflection and fracture energy.

Micro-scale Investigation: The micro structure of the reinforced geopolymer sample was examined using a JEOL JED-2300 scanning electron microscope (SEM) equipped with a concentric back scatter detector, under high vacuum at 10KV with a working distance of 100 μm . Large back scatter electron (BSE) mapping areas were collected using its microanalysis software. The imaged geopolymer samples were taken from an unbroken portion of the printed concrete, and cut with a diamond cutter exposing the cross section of the reinforced concrete, and subsequently cut to expose the longitudinal side of the steel cable.

3. Results

3.1. Time dependent rheology of printable geopolimer

Fresh property of geopolimer is very important in 3D concrete printing application since this technique needs the material to have high yield stress at rest and low viscosity under shear force [29][30]. In other words, the material must possess thixotropic behavior so that it can extrude out smoothly and after the extrusion, it can retain its shape. Roussel et al pointed out that this origin of thixotropy in cement science is because of colloidal flocculation between cement grains[?]. However, in geopolimer, thixotropy is hardly observed due to lack of colloidal interactions and therefore addition of thixotropic agent is highly essential for 3D printing of geopolimer material. Thixotropy is generally measured by the area between Torque (T) and rotational speed (N). Alternatively, use of structural recovery method can be used to measure this property since it related to three different stages of 3D printing process i.e., resting (before extrusion), extrusion/pumping and resting (after deposition). Fig.5a shows shear thinning property of geopolimer which indicates that the material loses its viscosity upon increasing in shear rate.

Ideally, 3D printable material should recover its original viscosity immediately after the removal of any external force. Recovery plots in Fig 5b illustrates that the developed geopolimer is able to recover 70% of its initial viscosity in stage (3) within 60 seconds of resting period. In this paper, stage (1) and (3) are maintained at low shear rates to mimic the resting period before and after pumping. Stage (2) is carried out at 100 s⁻¹ to replicate the pumping/extrusion process. From the low viscosity value at stage (2), it is understood that during extrusion the viscosity goes down to below 100 CPs from 10000 CPs which helps the geopolimer to extrude out smoothly and after the extrusion, gradual rise in the viscosity value, results good shape retention without significant deformation.

Figure 5: Rheological behavior of printable geopolymer mortar

3.2. Bending strength of hybrid geopolymer composite

The hybrid reinforced printed geopolymer sample is shown in Fig.6. On four-point loading, it shows a series of flexural cracks, which developed upwards through the printed layers. The cracked layers were restrained by the steel cable, and held in tension. As the load was increased, the steel cable elongates and the crack mouth extends upwards. The experiment was stop when the top most layer of the printed geopolymer sample was observed to fail in compression crushing.

Figure 6: Cable reinforced 3D printed geopolymer beam during flexural strength testing

Fig.7 shows load vs displacement graphs of the three sets of sample (C10, C15, C20) and control group (C0), with respect to a common axes, for ease of comparison.

Figure 7: Plot of load vs displacement graph
for control (C0) and C10, C15, C20
geopolymer composite

The load displacement graph represents the strength and service characteristics of the sample as it undergoes loading, which helps to describe flexural properties of the geopolymer composite.

All geopolymer samples reinforced with hybrid reinforcement of stainless steel cable and PVA fiber shows a similar trend in their load deflection graphs, with their first crack occurring before the max load. However for the control group, C0, it began to undergo flexural softening upon first crack. Flexural softening behavior of this fiber reinforced geopolymer system is expected due to the strain softening properties of the PVA fibers used in this experiment, coupled with the opening of the crack mouth as load increase. As the crack mouth expands, a lesser amount of short fibers were able to successfully bridge the spacing across the crack and provide tensile strength to the reinforced system. Together they results in a decrease in flexural strength and thus unable to bear incremental loads.

For geopolymer samples reinforced with hybrid reinforcement, the steel cable continues to carry increasing load after the concrete has cracked. The steel cable provides the majority of the tensile strength after crack, with a small amount provided by the short PVA fibers at the crack tip. However there is a secondary effect of the short PVA fibers in this hybrid reinforcement system. As the steel cable elongates, it is pulled out of the geopolymer matrix, causing secondary cracks in the pull out region. This small cracks were restrained by the short PVA fibers and contributes to the system's flexural strength. On failure, most hybrid reinforced geopolymer samples failed by compression crushing at the top layer of the printed geopolymer as shown in Fig.8a, with noticeable yielding of the stainless steel cable. A small portion of the geopolymer samples experienced shear slipping between the interlayer bonds of the printed geopolymer filaments, which causes a sudden and steep drop in loading before being restrained by the steel cable, as seen in Fig.8b.

From Fig.9, it was noticed that hybrid reinforced geopolymer was able to bear higher loads, have higher fracture toughness and higher energy absorption, as seen

(a) Compression crushing at top layer of printed geopolymer

(b) Shear slip between printed geopolymer filaments

Figure 8: Shear slip and compression crushing during 4 point bending test

(a) Max load

(b) Deflection at max load

(c) Energy absorption to max load

Figure 9: Comparison of (a) Maximum (max.) load (b) Deflection at max load and (c) Energy absorption at max load for C0, C10, C15, C20 geopolymer composite

from the much larger area under the load deflection curve[31]. It also shows that with increasing diameter of stainless steel cable, increases the flexural properties of the hybrid reinforced geopolymer samples increases in flexural toughness for all hybrid reinforced test geopolymer samples was much more significant than the increase in its flexural strength. This finding i.e. enhancement in energy absorption being much higher than flexural capacity have also been observed by researchers investigating normal fiber reinforced concrete [31] [32].

For C20 sample, although its flexural properties are higher than C15, the increase in ductility is not increasing as great as compared to C10 and C15. This suggest that increasing diameter of stainless steel cable will reach an optimal point where any additional increment in cable diameter can no longer significantly improves fracture toughness and ductility.

The energy absorption mechanism of the hybrid reinforcement geopolymer samples utilizes both the short PVA fiber and long stainless steel cables. During the four-point bending test, microcracks first appears on the tensile side of the geopolymer composite. These microcracks were bridged by the short PVA fibers. As the crack grows and develops into macrocracks, the stainless steel cables becomes active in joining the two cracked regions together and continue to resist tensile stresses. With increasing load, the cable start to transfer tensile loads to the subsequent 2nd and 3rd topmost layer of the printed composite through shear stresses in the geopolymer matrix. The cable will continue to carry the increase loads and finally yield. This is seen from Fig.9, that geopolymer samples with cable reinforcement have much higher ductility than plain PVA fiber reinforced geopolymer.

3.3. Statistical analysis

Statistical analyses were undertaken using one way ANOVA test and Tukey HSD post hoc test. Tables 4,5 and 6 presents the results of the one way ANOVA test which was carried out to compare the effect of steel cable reinforcement on geopolymer's

flexural strength in C10, C15 and C20 conditions. The analysis has been performed at $p = 0.05$ level of significance.

Through the analysis, the p-values for max load, elongation and fracture were calculated to be ($P = 0.00001$, 0.00034 and 0.00001) respectively, and less than the p level of significance 0.05 , we can reject the null hypothesis that that steel cable reinforcement is not meaningful and accept the alternative hypothesis that it was meaningful to use steel cable as a reinforcement to improve on the flexural strength of the geopolymer mortar samples for the three conditions, C10, C15 and C20

Table 4: One way ANOVA (Geopolymer sample max load)

Treatments					
	1	2	3	4	Total
N	6	6	6	6	24
$\sum X$	4.3×10^3	9.1×10^3	1.2×10^4	1.2×10^4	3.7×10^4
Mean	7.2×10^2	1.5×10^3	1.9×10^3	2.1×10^3	1.6×10^3
$\sum X^2$	3.2×10^6	1.4×10^7	2.2×10^7	2.6×10^7	6.5×10^7
Std.Dev.	1.3×10^2	9.4×10^1	2.1×10^2	3.0×10^2	5.7×10^2

(a) Summary of Data

Source	SS	df	MS	
Between-treatments	6.6×10^6	3	2.2×10^6	$F = 56$
Within-treatments	7.9×10^5	20	4.0×10^4	$P = 1.0 \times 10^{-5}$
Total	7.4×10^6	23		

(b) Result Details

Table 5: One way ANOVA (Geopolymer sample deflection)

Treatments					
	1	2	3	4	Total
N	6	6	6	6	24
$\sum X$	6.9	15	22	29	64
Mean	1.2	2.6	3.7	3.3	2.7
$\sum X^2$	8.3	40	91	71	210
Std.Dev.	0.27	0.31	1.4	1.0	1.3

(a) Summary of Data

Source	SS	df	MS	
Between-treatments	22	3	7.5	$F = 9.8$
Within-treatments	15	20	0.76	$P = 3.4 \times 10^{-4}$
Total	37	23		

(b) Result Details

Because we have found a statistically significant result in the one way ANOVA test, we conducted a Tukey HSD post hoc test. This test is designed to compare each of our conditions to every other conditions, and determine the degree of impact of adding steel cable reinforcement to geopolymer mortar.

The critical value in the studentized range distribution used in Tukey HSD test

Table 6: One way ANOVA (Geopolymer sample fracture energy)

Treatments					
	1	2	3	4	Total
N	6	6	6	6	24
$\sum X$	4.3×10^3	9.1×10^3	2.2×10^4	1.2×10^4	4.8×10^4
Mean	7.2×10^2	1.5×10^3	3.7×10^3	2.1×10^3	2.0×10^3
$\sum X^2$	3.2×10^6	1.4×10^7	8.7×10^7	2.6×10^7	1.3×10^8
Std.Dev.	130	94	830	300	1.2×10^3

(a) Summary of Data

Source	SS	df	MS	
Between-treatments	2.9×10^7	3	9.8×10^6	F = 49
Within-treatments	4.0×10^6	20	2.0×10^5	P = 1.0×10^{-5}
Total	3.3×10^7	23		

(b) Result Details

for $\alpha = 0.05$, κ number of samples = 4 and degrees of freedom for the error term $\nu = 20$ is $Q_{critical}^{\alpha=0.05, \kappa=4, \nu=20} = 3.96$. The Tukey HSD score is given by $HSD = \frac{M_i - M_j}{\sqrt{\frac{MS_w}{n}}}$, where M_i and M_j are the means of the sample to be compared, MS_w is the mean square within sample (error) and n is the number of samples in each condition (C0, C10, C15 and C20).

Tables 7, 8 and 9 show the Tukey's score for all possible pairs of different mean for max load, deflection and fracture energy. When the Tukey's score is higher than the critical value of 3.96, it shows that the varying the diameter of the steel cable reinforcement is meaningful for improving max load, deflection or fracture energy.

From tables 7, 8 and 9, it is worth noting that the adding steel cables of all three diameters are meaningful in improving the flexural strength of the geopolymer mortar. However the effect of a small increase in steel cable diameters (C10 to C15, C15 to C20) does not have meaningful impact in improving the geopolymer's deflection and fracture energy, and only helps to increase the max load that the geopolymer mortar is able to sustain without cracking.

Table 7: Tukey HSD score for all pair's max load

	C20	C15	C10
C0	17	15	9.8
C10	6.9	5.0	
C15	1.9		

Table 8: Tukey HSD score for all pair's deflection

	C20	C15	C10
C0	6.1	7.1	4.0
C10	2.2	3.1	
C15	0.9		

Table 9: Tukey HSD score for all pair's fracture energy

	C20	C15	C10
C0	10	8.2	5.2
C10	5.1	3.0	
C15	2.1		

3.4. Microstructure image of steel cable reinforced concrete

The micro structure of the reinforced geopolymer sample (Fig. 10) shows penetration of the geopolymer mortar into the steel cable core, suggesting good mechanical bonding between the steel cable and the geopolymer mortar, and that method of insertion of steel cable into the printed geopolymer mortar did not introduces noticeable air voids into the concrete. In the longitudinal view, by nature of the twisted strands of steel threads into a cable, provides groves for mechanical lock to the concrete, similar to the ribs in the traditional rebars.

Figure 10: SEM micro images of the hybrid reinforced geopolymer mortar

4. Discussion

The objective of this paper was to improve the structural capabilities of 3D printed concrete, which hereby achieved by the addition of a hybrid reinforcement system with continuous steel cable and short PVA fibers. The flexural performance of the hybrid reinforced system was shown in Fig.9 to significantly improve in contrast to fiber reinforced geopolymer. Stainless steel SUS 304 cable with 7x7 strand configuration was used in three geopolymer sample groups and experimental results reveal that an improvement of 290% value tensile load capacity compared to the control one. In order to further increase the tensile load capacity of the reinforced geopolymer, one simple solution is to use thicker diameter cable. However the thicker the cable, the stiff it gets, and it would require a higher minimum bending radius, limiting the free form design of 3D printable concrete. One solution is to use a higher wire strand configuration such as 6x37 or 8x19, which has a smaller minimum bending radius at the same cable diameter. Another solution is the adopting a different cable design such as the Filler wire or Warrington design, instead of the single size cable design. Both the Filler wire and Warrington wire design, used a variation of small and large diameter wires to provide greater flexibility and strength.

It is interesting to note that, a majority of the geopolymer sample in this experiment failed through compression crushing, which was a sign of overly reinforced

concrete. Therefore there was a need to use higher strength geopolymer matrix, to improve the overall performance of the reinforced system or use smaller diameter cables, such that the system would be an under reinforced concrete structure, and fail through ductile yielding of the reinforcement cables.

In some of geopolymer samples (Fig.8b), shear slips occurred due to poor bonding between the printed filaments. Such a failure is undesirable, as they are sudden and can be catastrophic. This poor bonding between layers can be extensively studied in multiple 3D printing concrete papers [33][34][32], and this orthotropic nature is characteristic of 3D printed concrete. It is possible to avoid shear failures, through improvement to the bonding between layers by improving the 3D printing process, the inclusion of additional reinforcement stirrups (perpendicular to the longitudinal axis of beam) or the application of fiber reinforced polymer (FRP) sheets as a near surface mounted reinforcement on the 3D printed concrete structure [35].

5. Conclusion

The article at hand has presented a hybrid reinforcement method for 3D concrete printing application, pointing out the advantages and drawbacks of existing techniques. The performance of hybrid reinforced geopolymer composite, with different cable diameter was investigated in this research, with the following conclusions:

- The method of hybrid reinforcement is capable of enhancing the flexural performance of geopolymer composite up to 290% compared to the control sample.
- Usage of hybrid reinforcement in printable geopolymer can alleviate the issue of cable slippage and this improvement is attributed to the interaction between short PVA fibers and microcracks formed due to the pull out of the long steel cables.
- 3D printed geopolymer samples reinforced with cable shows an increase in

their first crack load, with positive association in increasing diameter of the steel cable.

- The fracture toughness of the hybrid reinforced geopolymer composite improved significantly, with increase in cable diameter, when compared to the control sample.

This work constitutes the basis for wider research in the framework of suggested hybrid reinforcement technique for 3D printing of concrete. Future work can be focused on exploring cyclic loading (fatigue behavior) behavior of this hybrid reinforced printed geopolymer and their (steel cable) durability in concrete environment. Also, the effectiveness of such methods should be tested and compared with large scale reinforced concrete beams.

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