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EFFECT OF FIBER REINFORCED POLYMER ON MECHANICAL PERFORMANCE OF 3D PRINTED CEMENTITIOUS MATERIAL

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ABSTRACT: Cementitious material is mechanically brittle and weak in tensile by nature. Moreover, 3D printed cementitious material is orthotropic and have a weakness line between layers. Conventional reinforcement technique for concrete utilizes rigid rebars to impart mechanical performance of concrete structures and improve its loading carrying capacity. However, rigid rebars limit the free-form capabilities of additive manufacturing and goes against its freedom of design principle. To overcome this issue, glass fiber reinforced polymer and carbon fiber reinforced polymer sheets were used to reinforced 3D printed cementitious material in this study. The reinforced printed concrete specimens were tested on four-point bending test, and the influence of FRP on 3D printable mortar and fiber reinforced mortar were analyzed based on load capacity, ductility, fracture energy and failure mode.

KEYWORDS: 3D printed cementitious material, Fiber reinforced polymer, Mechanical performance, Additive Manufacturing

1. INTRODUCTION

3D printable materials focus their advantage towards printing increasingly freeform designs(Tay et al., 2017), which can be deemed technically challenging using traditional methods. In the case of 3D cementitious material printing, it will be a significant advantage that shifts the industry from linear precast concrete structures towards architecturally stimulating printed concrete. However, there is a discord in printing curved architectural concrete structure as traditional reinforcement rebars are linear, and effort made to install traditional straight rebars into complex curved structures could be substantial and costly. Hence, there is a need to adopt alternative reinforcement methods such as fibre reinforced polymer (FRP) sheet into 3D cementitious material printing(Feng et al., 2015).

FRP sheets are composites with a polymer matrix reinforced with fibres. These fibres are flexible and mouldable prior to curing to take form of the printed structure even in complex shaped confinements. The weight advantage afforded by FRP reinforcement would also mean that less consideration is needed to account for dead weight when reinforcing printed structural concrete. Additionally, FRP sheets are directional and can be optimally applied along the stress lines distribution of the printed structure.

In this study, 3D printed mortar was printed using an ordinary Portland cement mix design with and without short PVA fibres. The printed specimens were subsequently reinforced with FRP (Glass fibre reinforced polymer and Carbon fibre reinforced polymer) through a wet layup method and ambient cured The reinforced printed specimens were tested by four-point bending method and the influences of FRP on 3D printable mortar and fibre reinforced mortar were analyzed based on flexural characteristics.

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2. EXPERIMENTAL PROGRAM

2.1 Test specimens

This experimental study was to test 12 simply supported 3D printed mortar beams. All beams were printed using an in situ four axis gantry printer . They were strengthened with FRP and ambient cured under a plastic sheet for 28 days before being cut to dimension. The flexural results are shown in the following section.

The fibre reinforced polymer (FRP) sheets used in this research were unidirectional fabric of glass fibres (MapeWrap G Uni-AX) and unidirectional fabric of carbon fibres (Nitowrap FRC 300). The characteristics of the manufactured fibres polymer sheets are shown in Table 1.

Table 1. FRP material properties

Materials	Modulus of elasticity (GPa)	Tensile strength (MPa)	Fibre orientation	Thickness (mm)	Elongation at failure (%)	Surface mass (g/m^2)
GFRP	72	2350	Unidirectional	0.35	3-4	900
CFRP	230	3481.5	Unidirectional	0.167	1.5	300

2.2 Mixture proportion and mixing process

In this research, printable cementitious material for both plain cementitious material (PC) and fibre reinforced cementitious material (FRC) were prepared with using the mixture proportion developed by (Weng et al., 2018)(Table 2), with FRC having additional PVA fibres in the mixture design. A Hobart mixer X200L was used in mixing. Factors such mixing time, speed and temperature are known to affect the cement's rheological properties, hence, mixing procedures were kept constant to the procedures developed by (Weng et al., 2016).

Table 2: Mixture proportions

Materials	OPC	Sand	Water	Fly ash	Silica fume	Superplasticizer/(g/l)	PVA fibre
Proportion	1	0.5	0.3	1	0.1	1.3	0.05

Note: All ingredients contents are expressed as weight proportion of cement content

2.3 Mechanical performance characterization and experimental procedures

After 7 days of curing of the 3D printed beam, the beams were strengthened by bonding the FRP sheets using synthetic resin (60% fabric and 40% epoxy resin) onto the bottom surface of the beam (Figure 1), as it is on the base layer that is subjected to the maximum tensile forces.

Bonding of the FRP sheets to the printed beams was done using a wet layup method(Bakis et al., 2002). First, the beam surface was wipe down and brushed with an air gun to remove any dust and loose particles. The FRP sheets were cut to the desired dimension of 300 × 30 mm. The 2-part epoxy resin was prepared and applied to bond the FRP on the bottom of printed beam. The strengthened fabricated specimens were cured at room temperature till the 28th day for testing.

Figure 1: Unidirectional FRP wet layup on the underside of the printed concrete

All the beams were subjected to a four-point bending test, conducted on an Instron universal testing machine. Specimens were printed and cured under a plastic sheet for 28 days. The load was applied at a monotonic rate of 0.2 mm/min until failure.

3. RESULTS

The four-point bending test results of all specimens are given in Figure 2. Key results are presented in Figure 3, which included peak load, displacement and fracture energy.

In the reference plain cementitious material (PC) beam specimen and reference fibre reinforced cementitious material (FRC) beam specimen, the increased load was applied until failure. Both specimens experience an initial elastic loading phase for which no cracking appears. In the reference PC, the beam fails suddenly when the beam exceeded its ultimate tensile stress. As the moment the first crack appears, the PC beam had a reduction in its moment of inertia. The remaining concrete was no longer able to sustain the bending moment and the flexural crack (Figure 4a) extended rapidly up from the base to the load point, and thus stopped the test. For the reference FRC beam, the short PVA fibres can restrain the crack mouth from opening, and therefore has a flexural strain softening effect. All FRP reinforced beams failed in shear at a significantly higher maximum load and displacement as compared to the control PC and FRC beams, thus FRP is effective as a structural reinforcement.

The FRP beams shared a trend line in which the load was increased linearly to its maximum load before experiencing a sudden drop in load capacity of the beam, as shear crack (Figure 4b) develops from the support rollers to the loading points (left shear span region). The reinforced beams were able to recover the loading as the FRP has not yielded and ruptured at the ultimate load. As the displacement increases, the FRP sheets was observed to debond from the concrete layer, which grew with increasing load.

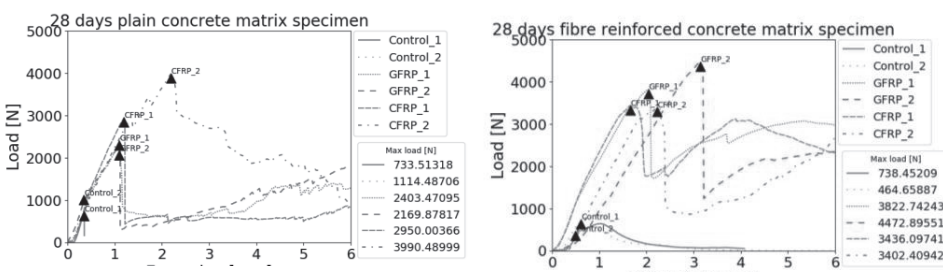

Figure 2: Load displacement graphs

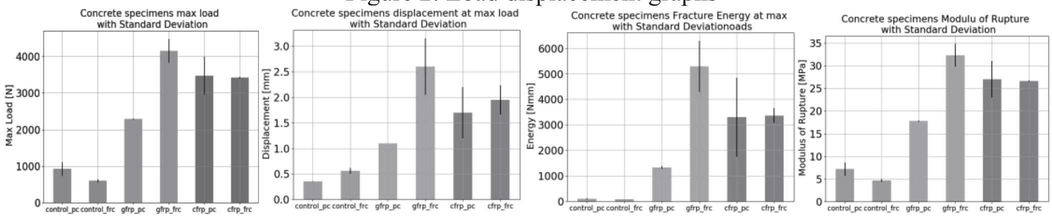

Figure 3: Key results of the load displacement graph

(a): Flexural crack in control beam (b): Shear crack in FRP reinforced beams

Figure 4: Modes of failures in 4 point bending test

The FRP reinforced beam ultimate load was on average 400% higher, displacement 400% higher and fracture energy 436% higher than unstrengthen PC and FRC beams. FRP-FRC beams have a better flexural characteristic as compared to FRP reinforced PC beams. As the short PVA fibre bridges any micro-cracks and therefore the beam has a higher shear capacity. Hence it fails in shear at higher load.

CFRP beams have a better flexural performance than GFRP beams in a PC matrix, as carbon fibre have a higher tensile strength. This allows the CFRP reinforced beams to bear higher tensile stress before shear cracking. However, in FRC matrix, GFRP have a better flexural performance than CFRP. The glass fibre used has significantly lower modulus of elasticity and thus more ductile. This ductility allows the GFRP concrete to bear higher load under bending(Duthinh et al., 2001).

4. DISCUSSION

The inclusion of short PVA fibres goes toward bridging micro-cracks and improving the mechanical performance of the concrete matrix. This allows the FRP reinforced specimens to not develop premature flexural shear cracks that prevent it from reaching its theoretical strength.

In this study, the FRP reinforced PC and FRC 3D printed beams failed by shear cracks. Shear reinforcement to the PC and FRC beams can be achieved by wrapping the beams in FRP rather than just the underside(Tottori et al., 1993; Triantafillou, 1998; Triantafillou et al., 2000). This will also add a confinement effect on the reinforced beams and will further increases its flexural performance(Manie et al., 2017; Seffo et al., 2012).

In the FRP reinforced PC and FRC beams, debonding of the FRP sheets (Figure 4b) were observed in correspondence to the opening flexural shear crack, away from the load point. This is because of the high interfacial shear and normal stresses surrounding the FRP sheet nearer the end(Hollaway et al., 2008; Smith et al., 2002). To avoid debonding of FRP sheets, a large contact area with epoxy can increase the area of shear stress, or use of mechanical anchor bolts to secure the FRP sheets to the beam(Grelle et al., 2013; Lamanna, 2003).

The modulus of rupture, $\left(MOR = \frac{PL}{bd^2}\right)$, was on average 25MPa for the specimens reinforced with 0.5% (by volume) fibre polymer sheet, which is comparatively higher than a 2% high strength steel fibre reinforced concrete (HSSFRC) with 15MPa MOR(Song et al., 2004). Fracture energy improvement is also comparable to improvement reported in HSSFRC. HSSFRC is typical used in hydraulic structures, airport and highway paving, as such proposed method is also sufficient.

5. CONCLUSION

The results of the experimental study indicate that externally bonded FRP sheets is an effective method to strengthen the reinforced 3D printed beam, with a 400% increase in maximum load, deflection and fracture energy. Higher loading can be achieved by using FRP sheets that have higher tensile strength, such as CFRP. While increase ductility can be reached by using GFRP with low modulus of elasticity. This suggests that a combination of GFRP and CFRP in a hybrid reinforcement setup can produce 3D printed cementitious material with high flexural strength and high ductility.

Future work on the application of FRP to 3D printable cementitious material will focus on shear reinforcement, as 3D printed cementitious material have a distinct interlayer weakness line that is susceptible to shear cracks. An automated FRP application nozzle need to be developed to selectively reinforce tensile stressed areas of 3D printed cementitious material. Additionally, finite element analysis on the application of FRP on complex 3D printed curved cementitious material should be studied.

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