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EFFECT OF POLYPROPYLENE FIBRES ON THE WORKABILITY PARAMETERS OF EXTRUDABLE CEMENTITIOUS MATERIALS

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Abstract: Additive manufacturing in construction industry has been introduced as an aspiration for a more sustainable built environment and currently evolving with high demand amongst researches. This study is an investigation of the influence of polypropylene (PP) fibre addition on the workability parameters of a new extrudable concrete mixture. As the quality of final printed structure prominently depends on the fresh state properties of concrete, this investigation mainly focused on the rheological properties such as workability (flow), setting time, extrudability and buildability. These parameters were systematically investigated through a small scale experimental process with time after mixing. The selected control mix with Ground granulated blast furnace slag (GGBS) and Silica Fume (SF) was used in this analysis. The Control cementitious specimens without fibre inclusion and with fibre addition in different volume fraction of binder, ranging from 0.5% to 3% were printed. The results showed that the fibre addition of 0, 0.5 and 1.0% have the better flowability and extrudability compared to 1.5, 2 and 3%. Also, reduction in the print quality was assessed visually with increasing fibre percentage. However, results indicated that the initial setting time is comparatively low for those mixes with higher fibre inclusion which is required for better bond strength between layers. Moreover, higher fibre content caused better buildability and shape retention in the extruded samples.

Keywords: Additive manufacturing; Extrusion-based 3D concrete printing; Polypropylene (PP) fibres; Fresh properties; Workability.

1. Introduction

Three dimensional printing (3DP), also known as Additive Manufacturing (AM) is an automated process which builds three-dimensional physical objects by laying down consecutive layers according to the computer controlled model (Beyhan and Arslan Selçuk, 2018). The potential of 3D printing has been clearly recognized in a wide range of applications, varying from the household needs to aerospace engineering. Unsurprisingly, the building construction industry has adopted this technique with the aim of turning the complex building design into reality and developing environmentally friendly structures in large scale.

The positive characteristics of concrete such as flexibility, durability and non-combustibility directly contribute it to be the most extensively used construction material. Despite the fact, the conventional formwork concrete technology is restricted geometrically and has obvious sustainability issues towards the environment. Hence 3D concrete printing has been introduced as an aspiration for a more sustainable built environment. There are excellent advantages of 3D concrete printing technique over the conventional formwork concreting method such as labour efficiency, time and cost savings, environmental and economic impacts, and design complexity (Kidwell, 2017).

Material is the prime limiting factor in 3D concrete printing. A particular composite and concrete mixture which is denser than the typical concrete has to be used, while ensuring the mix design of concrete meets the performance requirements of both fresh and hardened state properties of concrete (De Schutter *et al*., 2018). The main challenge in the development of a printable mix is to have no-slump and self-compaction concrete, which are two conflicting aims. In principle, materials (thixotropic) with high (static) yield stress and low viscosity are suitable for concrete printing application (Panda and Tan, 2018). The material must be extrudable through a nozzle smoothly and able to maintain its shape, once deposited over the printing bed. Secondly, the deposited layers should not collapse under the load of subsequent layers and thirdly, a good bond strength between the layers to achieve required hardened strengths must be ensured.

Further limitation is the crucial fluctuation of material properties with unique setup and specifications of 3D concrete printer. Therefore, the major challenge is to develop a suitable printable material for corresponding printing machine (Kazemian *et al.*, 2017). Hence, Lim *et al.* (2012) has defined four critical parameters of the fresh printable concrete as pumpability, printability or extrudability, buildability and open time which are controlled by the rheology and hydration properties of the printable material.

Based on previous literatures (Le *et al.*, 2012a, Perrot *et al.*, 2015),the requisitions for a printable concrete are; high powder content, no coarse aggregate, improved paste fraction, and use of viscosity modifying accelerator. Hambach and Volkmer (2017) were the first to endeavour adding short different types of fibres (carbon, glass and basalt fibres) into 3D printed composite of Portland cement paste. Feng *et al.* (2015) also used fibres in powder based concrete printing and observed significant strength reduction between layers due to formation of air bubbles. Recently, Nematollahi *et al.* (2018a) investigated the effect of polypropylene (PP) fibres on the hardened properties of 3D-printed fibre-reinforced geopolymer mortars, Nematollahi *et al.* (2018b) investigated the effect of type of fibre on inter-layer bond and flexural strengths of extrusion-based 3D printed geopolymer and Bos *et al.* (2018) studied the effect of adding short straight steel fibres on the failure behaviour of print mortar through several tests on cast and printed concrete, on different scales. However, a detailed analysis on the effect of fibre in the fresh properties and workability loss with time has not been investigated.

Hence, this paper is concerned about the influence of polypropylene (PP) fibre on the workability parameters of a novel extrudable concrete mixture. The purpose of current study is to present and examine an outline for experimental based laboratory testing and evaluation of extrudable mixture.

Moreover, it has to be noted that only fresh properties of a mixture are considered in this study, while further examination is desired to examine the mechanical performance for hardened mixture.

2. Experimental Investigation

2.1 Materials and Mix Design

Type I Ordinary Portland Cement and tap water were used for all the mixtures. Midas Sand and Limestone Fines were used as fine aggregates. Ground Granulated Blast furnace Slag (GGBS) and Silica Fume (SF) were used as a partial cement substitute and SF based 3D printing concrete mixture showed better adhesiveness. A high range water reducing admixture (HRWRA) was added with water in order to reduce the water consumption while improving the workability and strength. In addition, to increase the plastic viscosity and cohesion of printing mixtures, a viscosity modifying admixture (VMA) was used. Polypropylene fibre was also used as a shrinkage reinforcement for a printing mixture. Addition of this fibre inhibits and controls the formation of plastic and drying shrinkage cracking in concrete.

Initially, eight control mixes were selected and tested for the fresh properties such as flowability, extrudability, initial setting time, buildability and print quality. Hence, according to the results three mix designs those were satisfying all the aforementioned criteria were selected for further printing and experimental analysis. Printing quality and dimensions of printed layers are the criteria used to decide whether it could be an extrudable material or not.

Afterwards, one of the selected three control mixes were printed with fibre addition in different volume fraction of binder in order to examine the effect on fresh properties. Fibre was added in different mass fraction of binder in 0.5, 1.0, 1.5, 2.0 and 3%. The material composition investigated in this study are given in Table 1. All proportions were kept constant in the control mixes, except the fibre and the amount of water. The water/binder ratio was maintained in a range of 0.31-0.33 with the intention of satisfying the smooth extrudability criteria. The fibres and water content variation is given in Table 2.

Table 1: Material composition of the control mix (kg/m^3)

Binder	Cement	350
	GGBS	185
	SF	100
Fine Aggregate	Midas Sand	500
	Limestone fines	250
Admixtures	HRWRA	8
	VMA	4
	Block	10

Table 2: Fibre and water content variation (kg/m^3)

Mix ID	**Water**	**W/B**	**Fibre**
Control Mix	195	0.31	0
PP 0.5%	195	0.31	3.18
PP 1.0%	200	0.31	6.35
PP 1.5%	210	0.33	9.53
PP 2.0%	210	0.33	12.70
PP 3.0%	212	0.33	19.05

2.2 Mixing of extrudable concrete

The mixtures were prepared in a free fall Hobart mixer with tilting drum and two rotating blades. The Midas sand and other dry components were dry mixed for about a minute. Then the solution of admixtures with water was gradually added to the dry mix and the mixing was continued for about 5 minutes. After the mixture ingredients were thoroughly mixed, the fibres with different volume fractions were gradually added and mixed. The mixing was continued for about 3-4 minutes to achieve the appropriate rheology for the extrusion. Sufficient amount of water was added to avoid the loss of material while mixing. The mix was decided to be extrudable by visual assessment. The total mixing time was maintained for all the mixes approximately for 10 minutes.

2.3 Concrete Printing

The samples were manually extruded using a custom made small scale cement mortar pointing gun fitted with a rectangular nozzle of 25mm x 25 mm cross section. This was used to simulate the extrusion based 3D concrete printing in the laboratory scale. The samples were printed as blocks with approximate size of 300 mm length, 220 mm wide and 50 mm depth. The block size was decided as above in order to extract minimum 6 samples for the flexural tests from each mixture. The sample preparation is shown in Figures 1. The printed specimens consisted of two extruded layers and the print time interval between subsequent layers was maintained as 15 minutes.

2.4 Fresh state tests on concrete

2.4.1 Flow table test

Flowability is a rheological parameter of the mixture consistency with time. There are several Standards dedicated to determination of this characteristic. The flowability of the concrete was tested using the flow table test according to ASTM C1437 (2007). The control mix was printed with different volume fraction of fibre and the flowability of each batch was tested at 0, 15,30,45,60 minutes interval after mixing in order to determine the rate of workability loss. The mixture was placed inside a mini conical brass mould. During the test, the mortar was flowed to form a circular mass by the vibration of 1.67 Hz as the flow table rose and dropped 25 times in 15 seconds and the diameter of the mass was measured and compared to the initial size.

2.4.2 Initial Setting Time

Setting time is another essential parameter, which determines the working time of printable concrete (Zhu et al., 2017). Vicat needle apparatus was used to measure the initial setting time according to EN 196-3 (2005). This test was performed measuring the penetration of a steel needle into the mortar over the course of several minutes. When the penetration of the needle into the material was less than 5mm from the bottom in mortar, the material is assumed to be achieved its initial setting time.

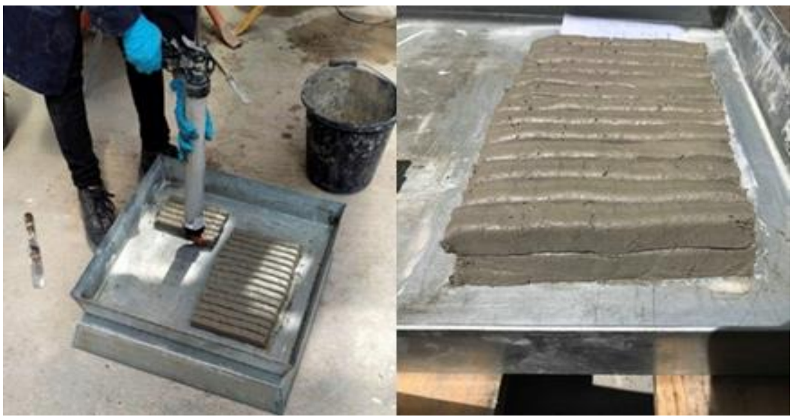

Figure 1: Material Extrusion

2.4.3 Extrudability and Buildability

The extrudability of concrete is interconnected with rheological characteristics of the fresh mix. The print quality of the extruded layers was evaluated using classification presented by Kazemian et al. (2017) such as defect free surface, squared edges, dimension conformity and dimension consistency. The chosen criteria for a mixture to be extrudable through the nozzle smoothly and continuously to produce the layers without being blocked in the path.

Buildability defines the feasibility of fresh mix for layer by layer deposition and its resistance to deformation under the stress caused by the subsequent layers. The parameter is extensively associated with workability and extrudability of the mix. In this study, the constant open time of 15 minutes was retained for the considered mix. Specimens of two extruded layers were printed in time interval of 15 minutes to examine the buildability. The print quality and buildability were examined solely through visual assessment on the two extruded layers.

2.5 Results and Discussion

2.5.1 Flow table test

It is known from the preliminary examination that the increasing quantity of fibre inversely affect the workability. The workability loss of all mixes is described in Figure 2. It is clearly identified, the mixtures lost its workability with increasing time. But some of the mixtures behave differently. These phenomenon should be examined further.

PP 0.5% shows higher flow compared to the control mix in 15 and 30 minutes after mixing. However, a reducing tendency after 45 and 60 minutes could be noticed. PP 1.0% mix exhibited the maximum spread diameter compared to all other mix. For the mixtures with increasing fibre percentage more than 1.5% indicated a reducing flowability. It appeared to be too rigid and formation of fibre lumps was also witnessed.

As seen in Fig. 2, the change of flow value of the fresh extrudable concrete declined gradually with time but there is still 116–142 mm spread value was achieved according to flow table test in 60 min. It makes a realistic situation to pump and extrude the 3D printing concrete mix due to fluidity. Moreover, it must be noted that all mixes did not reveal high flow when lifting the mini conical brass mould, before shocks were applied to the flow table. Therefore, the assumption of all the fresh mixtures had approximately zero-slump can be justified, which is an important material aspect for the extrusion process.

2.5.2 Initial Setting Time

The variation of initial setting time of each mix is illustrated in the following graph (Figure 3). These results specify that the initial setting time is progressively decreasing with increasing fibre addition which is required for better bond strength between layers. Since there is no significant deviation within the setting time, the PP fibres had insignificant influence on the initial setting time.

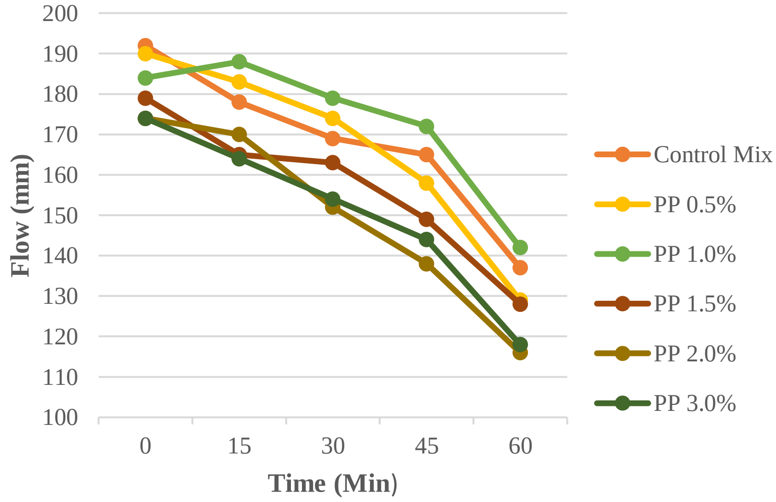

Figure 2: Loss of workability with time of the mix with different fibre percentage

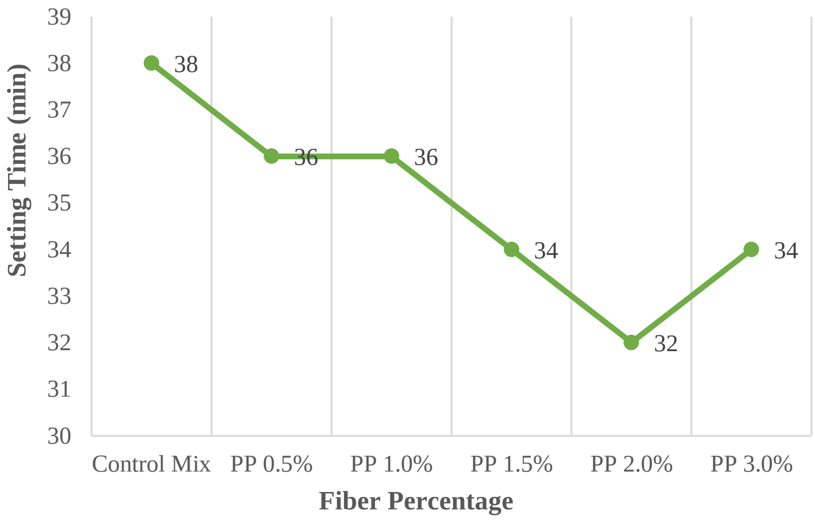

Figure 3: Initial setting time variation

2.5.3 Extrudability and Buildability

The extrusion of material through the nozzle became difficult with increasing volume fraction of fibre content. Moreover, imperfections in the print quality was assessed visually with both very low and very high fibre percentage. Only PP 1.0% and PP 1.5% mixes satisfied the print quality criteria mentioned above.

Higher fibre content caused better buildability and shape retention in the extruded samples. The top surface was achieved to be level and smooth with 25 mm width, almost close to the nozzle diameter with the mixtures PP 1.0% and above. On the other hand, the simultaneous discontinuity in the extrusion was identified with increasing fibre inclusion. Figure 4(a)-4(d) illustrates the extruded samples with different fibre content. Hence, PP 1.0% and PP 1.5% fulfilled the extrudability and buildability measures compared to other mixtures.

4(a)

4(b)

4(c)

4(d)

Figure 4: (a) Extruded specimen of PP 0.5%, (b) Extruded specimen of PP 1.0%, (c) Extruded specimen of PP 1.5%. (d) Extruded specimen of PP 2.0%

3. Conclusion and Recommendations

A novel concrete that has extrudability and buildability was developed for the custom made extruder. The crucial properties of this printing concrete mix were the flowability and buildability which have contradict mutual relationship were analysed for the selected mixture. In allusion to the experimental study and results analysis the following summary were concluded.

i. All mixes developed in this study, with and without fibres are showing sufficient workability in terms of flowability and setting time. However, the mixes PP 0.5% and PP 1.0% showed the better flowability with time and further investigation between the fibre percentages 0.5 and 1.0 will desired to have a clear conclusion in the variation with increasing time.

ii. There is no major variation was identified in the setting time for selected mixtures. Therefore, the effect of PP fibres on the initial setting time is negotiable.

iii. Buildability and shape retention ability have been increased with increasing fibre content. Moreover, PP 1.0% and PP 1.5% achieved the extrudability and buildability criteria compared to other mixtures.

iv. As per the overall investigation, the incorporation of 1% and 1.5 % fibre considerably satisfies all the fresh property criteria to be accepted as the optimized extrudable mixture for the customized extruder used in this experiment series.

v. The anomalous behaviour of the flow with fibre addition for the mixes requires further investigation to identify the causes behind the fluctuating behaviour.

vi. Study has indicated that the open time is one of the most significant aspect in 3D printing of concrete.

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