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Cement-fibre composites for aerial additive manufacturing

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ABSTRACT

The fused deposition principal of additive manufacturing (AM) involves the deposition of a material one layer at a time allowing the creation of an object from 3D digital design. The associated reduction in the amount of material wastage offers benefits to the construction industry and over the last decade, investigations have been carried out using cementitious materials for AM in construction. Central to the profile of the technology increasing in the industry is the development of a suitable cementitious material which may be deposited without formwork. Research currently consists of ground based gantry or robotic arm methods reliant upon suitable terrain and environmental conditions. This paper presents development of fibrous cementitious mortars and pastes suitable for a miniaturised deposition system designed for use in a multiple agent AM approach. Synthetic PVA, aramid and kevlar fibres along with natural fibres from the banana plant were investigated to evaluate contributions to the workability, buildability, mechanical strength and mechanism of failure of cementitious composite material. The addition of fibres to a cementitious matrix augmented by synthetic hydrocolloids results in compressive and flexural strength increases and transforms the method of failure from brittle to ductile. Results suggest PVA and kevlar fibres are suitable for a composite cementitious material with optimised rheology specifically designed for a multiple-agent, miniaturised deposition approach for AM.

1. INTRODUCTION

Research into the use of cementitious materials in additive manufacturing (AM, often referred to as ‘3D printing’) has developed considerably over the past decade, with an estimated thirty projects worldwide investigating 3D printing with material of a cementitious nature for building and civil use in the construction industry (Buswell et al. 2018). The majority of projects are based upon the AM principal of fused deposition modelling (FDM), which involves the extrusion of a suitably viscous-like material through a nozzle to create an object one discreet layer at a time (Kalsoom et al. 2016) without the use of supporting formwork. This additive approach, which only uses material specifically required, is in stark contrast to the traditional subtractive methods (Buswell et al. 2007) employed in the conservative and risk-averse construction industry (Arora et al. 2014), in which AM technology is still in a relative state of infancy (Bos et al. 2016).

A cementitious material suitable for AM must possess an appropriate balance between ‘pumpability’ (the ability of a fresh mix to move through a deposition system), ‘printability’ (the level of ease at which material passes through a nozzle) and ‘buildability’ (the ability of freshly deposited material to retain shape following extrusion and when subjected to load from subsequent layers) (Le et al. 2012). In this study, ‘pumpability’ and ‘printability’ will be encompassed by the term ‘workability’. A workable mix requires liquid-like behavior and low viscosity, whereas a buildable mix exhibits more solid-like behavior and high viscosity.

Studies concerning cementitious materials in AM have involved differing deposition approaches. Equipment could be of building envelope scale, housed on a large frame or gantry, with examples being concrete printing, developed at Loughborough University, UK (Le et al. 2012), (Lim et al. 2012) and Contour Crafting, developed at the University of Southern California, USA (Zhang and Khoshnevis 2013). A further method is the use of a large compound robotic arm with multiple degrees of freedom, which could be stationary, or mobile on a moving platform, an example being the digital construction platform project developed by the Massachusetts Institute of Technology, USA (Keating et al. 2017). Another possibility is the use of smaller, coordinated multiple mobile agents.

Concrete is weak in tension and prone to brittle failure (Soltan and Li 2018), with design traditionally focusing upon compressive strength and the use of structural steel reinforcement to carry tensile forces and facilitate ductile failure (Bos et al. 2017). When considering the use of multiple smaller robots in AM construction, and the inherent relative miniaturisation of the deposition process required, traditional steel rebar is not naturally compatible. Indeed, rebar may be detrimental to an AM construction procedure (Asprone et al. 2018). Alternative options to integrate reinforcement must be investigated to increase tensile capacity and resist drying shrinkage and crack propagation. Options include fibrous reinforcement as part of the cementitious mix, automated placement of passive reinforcement during deposition or digital fabrication post-deposition (Asprone et al. 2018).

This study investigated multiple types of chopped fibres, adding them in differing quantities to a cementitious paste mix suitable for a miniaturised AM extrusion process. The study used natural, untreated fibres from the banana plant along with synthetic aramid, kevlar and polyvinyl alcohol (PVA) fibres. Workability, buildability, morphology, mechanical properties and failure modes of the fibrous cement pastes were evaluated for suitability with a miniaturised AM process.

2. Materials and Methodology

High fibre volume (2%+) materials present challenges regarding workability (Noushini et al. 2014). Fibres were added in this study to a cementitious paste of density ≈1400 kg/m^3 at volume fractions <1%, levels usually associated with reducing drying shrinkage and resisting crack propagation, in order to facilitate enough workability for the material to pass through the miniature deposition system. PVA fibres, (supplied by Flints Theatrical Chandlers, London) were uniformly cut to a length of 12mm as part of the manufacturing process, whereas the aramid, kevlar (both supplied by Easy Composites, Staffordshire) and banana fibres (supplied by Moomin, UK) were hand-cut to a length of 12mm ±5mm from bulk quantities. Kevlar is a type, or brand name, of the synthetic fibre class aramid, which is based around a chemical reaction between an amine group and a carboxylic acid halide group. In this study, the woven fibre strands Kevlar tex 40, supplied in sewing reel form, are termed 'kevlar' and the dtex 1600 yarn, manufactured as strands of unwoven fibres, are termed 'aramid'. Fibre properties are presented in Table 1. Kevlar fibres were the most expensive option, with banana and PVA the least.

Table 1. Properties of the fibres. Please refer to Figure 5 for macro-images.

FIBRE	LENGTH	DIAMETER	DENSITY
	(mm)	(microns)	(g/cm^3)
PVA	12	280-350	1.29
ARAMID	12 ±5	12-14	1.40
KEVLAR	12 ±5	210 (thread)	1.40
BANANA	12 ±5	35-50	1.35

Nine mixes were formulated for the experiments – a control mix without fibres and the four fibres each added at 0.35% and 0.75% by mix volume. The cementitious matrix was based upon Dragon Alfa CEM I 42.5 R Portland cement blended with Cemex EN-450 pulverised fuel ash (PFA) in a respective ratio of 65:35. Cellulose gum and a lignin-based plasticiser were added to aid both workability and buildability. Coarse aggregate is inherently incompatible with the miniaturised system. Fine aggregate is possible, but this study focused upon fibre concentrations and fine aggregate was not used. A water/binder ratio of 0.46 and superplasticiser content of 1% by mass of binder were kept consistent throughout all mixes. Prisms for mechanical tests were cast in 160 mm x 40 mm x 40 mm moulds, cured and tested in accordance with BS EN 1015-11:1999, at both 7 days and 28 days, to attain compressive and flexural strengths with the use of a 50kN loading capacity Instron Universal 2630-120/305632 device.

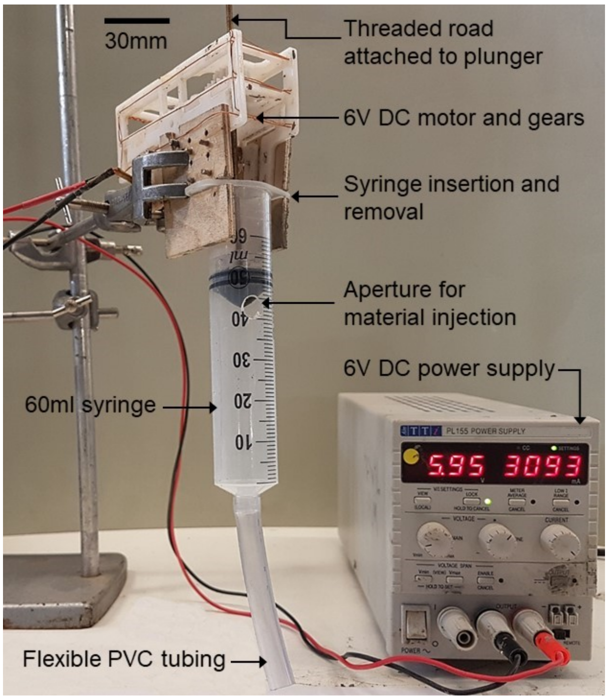

Figure 1. Adapted automated deposition device facilitating swift removal and insertion of syringes.

Workability and buildability of freshly mixed pastes were evaluated using an adapted miniature syringe-based deposition device (Figure 1). The device consisted of one 60 ml, 28mm internal diameter concentric luer-loc syringe, with plunger movement in the vertical direction actuated by a 6V DC brushed motor (Dams et al. 2017). Each mix was injected into the device through a circular aperture in the syringe using a hand-held second syringe and extruded from the syringe through an 8mm circular nozzle and an 80mm length of 8mm internal diameter flexible PVC tubing so produce a smooth, defined bead of extruded material in four circular layers. Workability was assessed by the level of ease at which the deposition device could extrude the fresh mix, as quantified by the electrical current required. Buildability was evaluated by whether the extruded fresh mix could retain its shape and resist excessive deformation when subjected to loading from subsequent layers.

Fibre morphology and fracture surfaces of the tested flexural specimens (at 7-day strength) were investigated using a JEOL SEM6480LV Scanning Electron Microscope (SEM). Magnifications of 1000x and 43x were used for the fibres and the flexural prism fractured surfaces respectively. A gold coating of 10 nm thickness was applied to the SEM samples immediately prior to insertion into the microscope chamber insertion in order to prevent charging and increase signal-to-noise ratio.

3. Results and Discussion

Figure 2 shows 7-day and 28-day compressive and flexural strengths. Aramid, kevlar and banana fibres all increased flexural strength at 0.75% fibre volume. Standard deviations, though largely <1 MPa, demonstrated variable concentrations of fibres within cementitious matrices. While compressive strength categorically increased between 7 and 28 days, flexural strength did not, suggesting the molecular bonding between fibre and cementitious matrix was established at 7 days. All fibres improved compressive strength at 28 days in comparison to the non-fibrous control mix. Figure 3 shows modes of failure following flexural tests. The non-fibrous control mix exhibited brittle failure, while all 0.35% fibrous specimens failed in a ductile manner and resisted crack propagation, improving further with 0.75% volume (0.75% banana fibre specimen is shown in Figure 3).

The current required for the deposition device to extrude the fresh mixes is shown in Table 2, with mixes too stiff to be processed identified as 'Could Not Process' (CNP). The presence of cellulose gum allowed extruded mixes to retain structure to varying extents in the buildability tests (shown in Figure 4). PVA and Kevlar performed well, whereas Banana at 0.35% volume, while a smoother, aesthetically pleasing bead of material, showed greater layer deformation. Aramid fibres performed well in mechanical tests but produced a stiff mix with poor workability. This is also true to a lesser extent with 0.75% volume banana fibres. Aramid and Banana fibre mixes couldn't be processed at 0.75% volume.

Table 2. Current required for deposition device extrusion. CNP = could not process.

Fibres contained in the mix	Fibre volume	Current required
	(%)	(mA)
Control (none)	-	160-181
PVA	0.35	162-184
PVA	0.75	172-220
ARAMID	0.35	169-209
ARAMID	0.75	CNP
KEVLAR	0.35	156-192
KEVLAR	0.75	174-210
BANANA	0.35	171-212
BANANA	0.75	CNP

Figure 5 shows macro (left) and SEM (centre, right) images of fibres and fracture surfaces. The larger PVA fibres were relatively uniform in being broadly aligned parallel to the specimen length axis compared to the random orientation of banana and aramid fibre strands. Kevlar can be observed as both uniform (while intact in woven reel form) and randomly aligned (the result of a reel de-woven into component fibre-strands due to manual and mechanical mixing processes). Aramid has the smoothest surface and it is reasoned that the multiple orientation of low-diameter fibre strands forms an effective mat of reinforcement, resisting crack propagation and improving flexural strength, rather than relying on an uneven surface providing anchorage as is the case for PVA and Kevlar fibres. Banana fibres provide both, with a natural uneven surface and multiple orientation of fibre strands providing a mat of reinforcement located more consistently throughout the cementitious matrices.

Rupture was observed with aramid and banana fibres, a combination of the mat effect and brittle nature of the fibres. A major drawback of the mat effect is the detrimental effect on workability, which threatens suitability for a miniaturised AM process. PVA fibres were observed to fail by pull-out, as confirmed by Figure 5 (top, centre) which shows a smooth, unbroken fibre-end. It is suggested this is due to high tensile capacity rather than inadequacy in molecular bonding or mechanical anchorage.

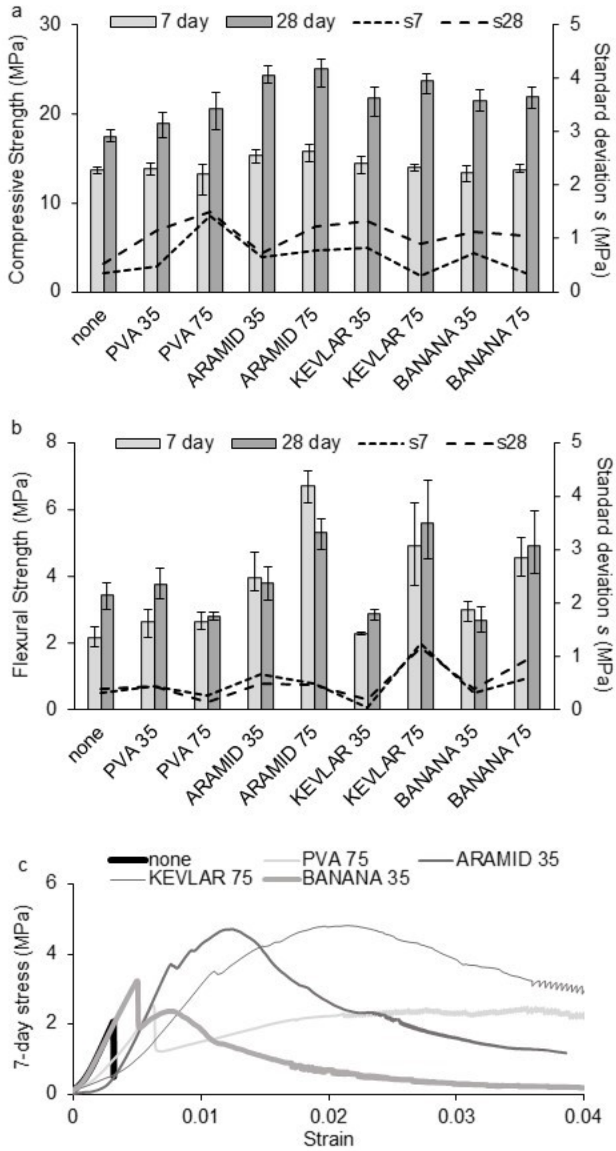

Figure 2. 7-day and 28-day compressive (a) and flexural (b) strengths. 35 and 75 refer to 0.35% and 0.75% fibre volume. *s*7 and *s*28 denote standard deviation (secondary vertical axis). Error bars represent highest and lowest recorded values. Stress/strain profiles of 7-day specimens (c) show mixes successfully processed autonomously by the deposition device.

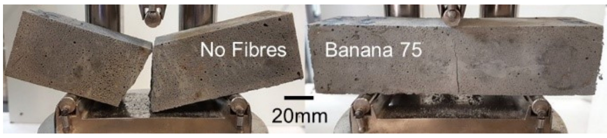

Figure 3. **F**lexural failure at 2mm displacement, with brittle failure of a non-fibrous prism (left) and a more ductile 0.75% banana fibre prism resisting crack propagation (right).

Figure 4. Buildability tests with four fresh circular layers extruded by the powered deposition device for each mix shown.

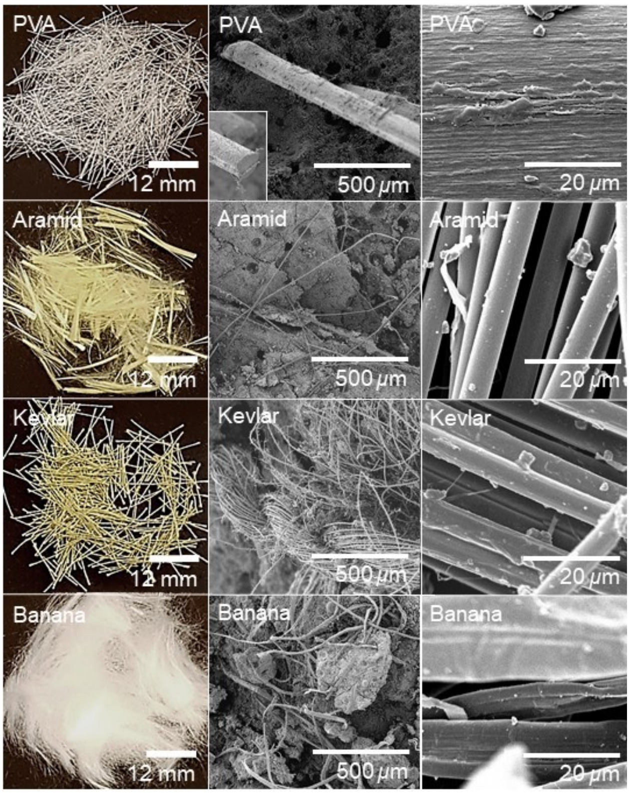

Figure 5. Macro (left) and SEM (centre, right) micro images, top to bottom: PVA, Aramid, kevlar and Banana. Fibre images are 43x magnification (within matrices, centre) and 1000x (right).

4. Conclusions and further work

All fibres used in this study contributed to the buildability and ductility of cementitious pastes but impacted upon workability. Though Aramid and banana fibres provided the highest flexural strengths and most ductile failure, they are challenging for the deposition device to process and in higher volumes are concluded to be unsuitable for miniaturised AM. Pastes containing 0.75% volume PVA and Kevlar fibres possessed a suitable balance between workability and buildability, being competitive in mechanical tests and possessing sufficient workability for the deposition device. Uneven surfaces of fibres facilitated good anchorage in cementitious paste matrices, transforming method of failure but not necessarily flexural strength. It is concluded that for higher fibre volumes, PVA and Kevlar (aramid in woven reel form) are the most suitable, as fibres are discreet from each other and do not entangle (though a drawback of Kevlar is the high cost). Further work would encompass development of a more powerful deposition system and mix modification to further increase the fibre volume, which may require foam or further rheological modifying agents to decrease density and strength and attain viable workability. A suitable parallel approach would focus miniaturised AM design on compression-loaded structures.

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