3D Printable Composites for Productive and Sustainable Built Environment

Sook-Fun Wong, Kim-Cheng Tan, Wen-Suey Ferne Leong, and Yin-Yen Lim

***Abstract*—This paper reports the development of 3D printable composites and laboratory-scale 3D printing technology, which are capable of producing building and construction components of properties and performance comparable to conventional casting methods. The slump test was carried out to examine the consistency and workability of fresh 3D printable eementitious mixtures; whereas the hardened density and compressive strength measurements were conducted to assess the performance of hardened 3D printable cementitious composites.**

***Index Terms*—3D printing, cementitious composites, slump, hardened density, compressive strength.**

I. Introduction

3D printing has been popularized in the past few years, and is currently reaching out towards the built environment sector [1]. The main benefits of 3D printing technology include a reduction in labour and raw materials as well as the freedom to design and create structures without the use of a mould [2].

As 3D-printed structures are fabricated in layers, it is crucial for the initial layer to not only able to withstand its own weight, but that of the subsequent layers above it without slumping. It is also important that there is adhesion of the layers to minimize gaps that may compromise the mechanical properties of the structures.

II. Problem Statement

This project aims to develop 3D printable composites and laboratory-scale 3D printing technology, which are capable of producing building construction materials with properties and performance comparable to conventional casting methods.

The research study is proposed with a view to achieve productivity and sustainability in a tropical built environment (e.g. in Singapore and the Southeast Asia region). However, to date, most research work on materials development and 3D printing additive manufacturing in Singapore had focused on bio-materials and bio-organs as well as metals and alloys; whereas studies related to 3D printable composite materials for the built environment are still limited.

Manuscript received December 10, 2018; revised April 12, 2019. This work was supported by the Singapore MOE TIF - Ministry of Education Translational and Innovation Fund under Project Code: MOE2016-TIF-1-G-033.

Sook-Fun Wong is with Centre for Urban Sustainability (CUS), School of Applied Science, Temasek Polytechnic, 21 Tampines Avenue 1, (S)529757, Singapore (e-mail: drsfwong@tp.edu.sg).

Kim-Cheng Tan is with School of Engineering, Temasek Polytechnic, 21 Tampines Ave 1, Singapore (e-mail: kimcheng@tp.edu.sg).

Wen-Suey Ferne Leong is with School of Applied Science, Temasek Polytechnic, 21 Tampines Ave 1, Singapore (e-mail: fernelws@tp.edu.sg).

Yin-Yen Lim is with Digital Fabrication and Additive Manufacturing Centre (DFAMC), School of Engineering, Temasek Polytechnic, 21 Tampines Ave 1, Singapore 7 (e-mail: yinyen@tp.edu.sg).

III. Research Objectives

In view of the above-mentioned limitations, the objectives of this research are:

- To formulate and optimize building composite mixtures that can be produced using 3D printing technology.
- To evaluate the properties and performance of 3D printable composite materials.
- To design and fabricate a laboratory-scale 3D printer, capable of printing composite materials into 100-mm cubes for compressive testing.
- To assess the properties and performance of 3D printed cubes in comparison with those of conventionally cast cubes, in accordance with current test standards for building materials.

IV. Literature Review

Feng *et al*. [3] studied the mechanical properties of 3D-printed structures using cementitious powder and reported that the printing direction had significant influence on the load-bearing capacity of the structure.

An approach had been proposed by Ferraris [4] to predict the physical and mechanical properties of concrete from rheological measurements of cement paste composition.

Various mixture feedstock/ingredients, mixing process and equipment had been reviewed by van Zijl *et al*. [5], so as to achieve the required adjustments from highly workable cementitious mixtures for pumping to dough-like consistency for extrusion and 3D printing.

Weng *et al*. [6] applied Fuller Thompson theory and Marson-Percy model, being classic approaches for sand gradation and packing fraction optimization respectively, to study the rheological properties of various cementitious mixtures and design for 3D cementitious materials printing.

The relationship between fresh and hardened paste, mortar and concrete properties was examined by Buswell et al. [7] to see its effect on the geometry of 3D-printed components.

Yeon *et al*. [8] examined the feasibility of using a polymer-modified cement composite, comprising Portland cement, fly ash, blast furnace slag, silica fume and a water-soluble polymer. The fresh properties studied were flowability, extrudability, open time, and buildability. The addition of water-soluble polymer effectively improved the performance of the 3D concrete printing material.

DOI: 10.7763/IJET.2019.V11.1142

The potential of fly ash based geopolymer cement had been studied extensively by Panda *et al*. [9] for large-scale additive manufacturing. They cited that the compressive, flexural and tensile strengths of extrusion-based 3D printable geopolymer mortar were mostly dependent on loading directions.

A new additive manufacturing processing route was introduced by Gosselin et al. [10] for ultra-high performance concrete, which allowed the production of 3D large-scale complex geometries without the need for temporary supports.

V. Materials and Methods

For the additive manufacturing process, the project team had designed and fabricated a laboratory-scale 3D printer using the screw extrusion system (SES) capable of printing 100-mm cubes for compressive strength analysis. Three cementitious mixtures had been developed to achieve composites which could flow within the controllable slump limits when 3D-printed, namely:

- Cement Paste X (CPX)
- Cement Paste Y (CPY)
- Cement Mortar A (CMA)

For cement pastes, CPX had a smaller water-cement ratio (w/c) compared to CPY; whereas the w/c of cement paste (CPY) was nearly similar to that of cement mortar (CMA).

The SES method of extrusion was found to be more efficient than the positive displacement pump used in many 3D printing research laboratories [11]. General compositions for the cementitious mixtures consisted of fly-ash blended cement, sand (for mortar) and tap water as the mixing water.

A miniature truncated cone of 40-mm height was used to measure the slump of the cementitious mixtures. A higher slump indicated better consistency and workability.

The 100-mm block specimens were 3D-printed using a laboratory-scale gantry type 3D printer (Fig. 1). Specimens of similar mixtures were also conventionally cast using 100-mm cube moulds.

The 3D-printed and cast specimens of cement pastes (CPX and CPY) were air-cured for 21 days and cement mortar (CMA) for 7, 14, 21 and 28 days. Their hardened densities were measured (in accordance with ASTM C642), followed by compressive strength testing (BS EN 12390-3). A lower hardened density value implied a lighter-weight composite; whereas a higher compressive strength denoted better mechanical performance in axial compression.

Fig. 1. Laboratory-scale gantry type 3D printer and 3D-printed block specimens using different nozzle diameters.

VI. Results and Discussion

The average slumps of cement pastes (CPX and CPY) and mortar (CMA) were found to be in the range of 10 to 15 mm, in order for the mixtures to be 3D-printed smoothly.

From Fig. 2, it is noted that the hardened densities of these cementitious composites varied from 1538.07 to 1984 kg/m^3.

The hardened density of 3D-printed mixture X (3DCPX) was 1913.75 kg/m³, which was 23.75 kg/m³ or 1.26% higher than conventionally cast mixture X (CCPX) of 1890 kg/m³, as shown in Fig. 2. The 3D-printed mixture Y (3DCPY) was 1984 kg/m³, which was 115 kg/m³ or 6.15% higher than cast mixture Y (CCPY) of 1869 kg/m³. These findings were in good agreement with those reported by Le *et al*. [11].

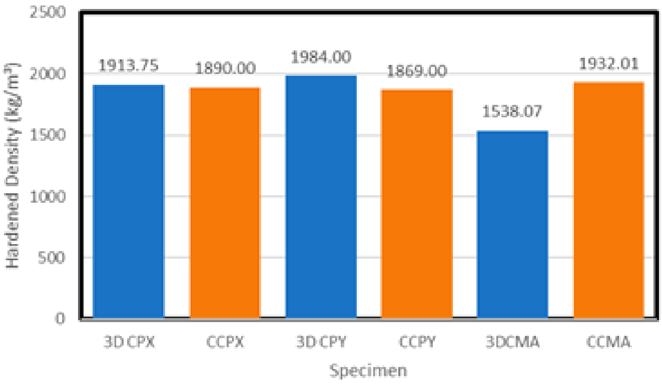

Fig. 2. Hardened densities of 3D-printed and cast specimens.

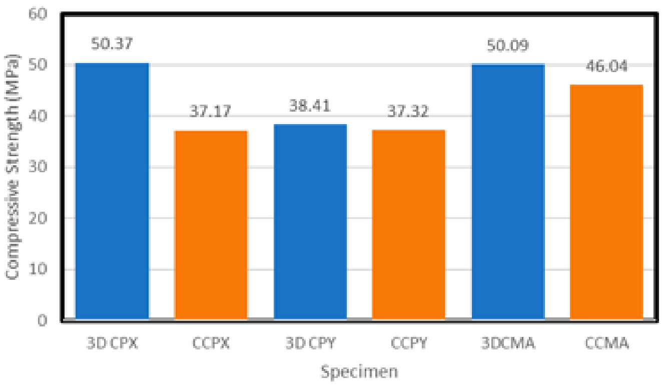

Fig. 3. Compressive strengths of 3D-printed and cast specimens.

As observed in Fig. 3, compressive strength was higher in 3D-printed specimens as compared to conventionally cast specimens; the difference being more significant at lower w/c:

- The 3DCPX specimen recorded a higher compressive strength of 50.37 MPa, which was 13.20 MPa or 35.51% higher compared to CCPX of 37.17 MPa.
- The 3DCPY specimen exhibited a greater compressive strength of 38.41 MPa, which was 1.09 MPa or 2.92% larger as compared to CCPY of 37.32 MPa.
- The 3DCMA specimen also showed a larger compressive strength (49.52 MPa), which was 3.47 MPa or 7.54% greater as compared to CCMA of 46.05 MPa.

This could be due to the screw extrusion mechanism of the SES equipment which facilitated a more thorough mixing of the composite cement and water, and also compacted the mixture further as it was extruded at the nozzle, leading to rapid densification and strengthening of material. This is also consistent with the observation by Pitt *et al*. [12] who reported up to 73% increase in tensile strength of 3D-printed samples compared to moulded composites due to densification of paste and fibre in-situ directional alignment.

The layering flow pattern was highly critical in controlling the slump, shape, and adhesion of the subsequent layers [13], [14]. For example, Megid and Khayat [15] cautioned that the multi-layer casting of self-consolidating concrete can be critical in situations involving the casting of successive lifts.

Fig. 4 shows that the compressive strengths of 3D-printed cement mortar (3DCMA) and conventionally cast cement mortar (CCMA) increased with curing age in air from 7 to 28 days, due to increased cement hydration with time. As with cement pastes, 3D-printed cement mortar specimens had greater compressive strengths compared to conventionally cast cement mortar specimens.

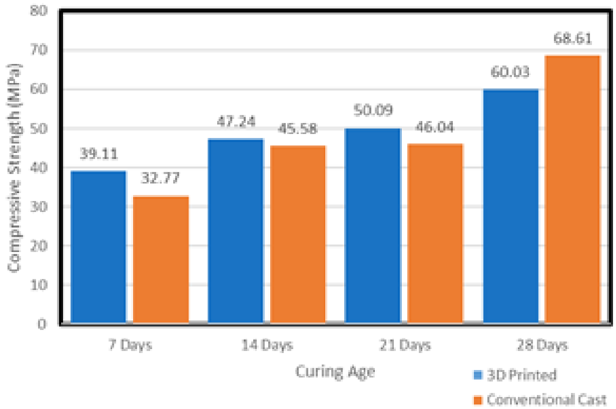

Fig. 4. Compressive strengths of 3D-printed and cast cement mortars.

VII. Contribution and Potential Impacts

As there are limited studies on 3D printable cementitious composites, compared to the well-established standards for conventionally cast composites (e.g. cement paste, mortar and concrete), the data and correlation between 3D-printed and cast specimens from this study can be geared towards the generation of technical references leading to SS (Singapore Standard) or ISO/ASTM Standard for industry adoption.

VIII. Conclusions and Recommendations

The custom-built lab-scale 3D printer of screw extrusion system (SES) can be used to print 100-mm cubes of three optimized cementitious mixtures for analysis of slump, hardened density and compressive strength.

Optimum parameters were identified with the SES method in relation to hopper feed rate; extruder screw revolution; compression ratio; nozzle, barrel, and screw diameters.

The 3D-printed cementitious composites (cement paste and mortar) had higher compressive strengths compared to those of conventionally cast composites, especially at lower water-cement ratios (w/c).

Compressive strengths of 3D-printed and conventionally cast cement mortars increased with curing age in air from 7 to 28 days.

Further tests are needed to study and correlate rheological properties of cement paste, mortar and concrete mixtures with 3D printer optimum parameters and specifications.

Acknowledgment

The authors are thankful for the research grant awarded by Singapore MOE TIF - Ministry of Education Translational and Innovation Fund: Project Code MOE2016-TIF-1-G-033. The authors are also indebted to the technical staff of School of Applied Science and School of Engineering, Temasek Polytechnic, for their kind support.

References

[1] V. Richardson, "3D printing becomes concrete: Exploring the structural potential of concrete 3D printing," *The Structural Engineer*, pp. 10-17, October 2017.

[2] Z. Malaeb, H. Hachem, A. Tourbah, T. Maalouf, N. El Zarwi, and F. Hamzeh, "3D concrete printing: machine and mix design," *International Journal of Civil Engineering and Technology*, vol. 6, issue 6, pp. 14-22, June 2015.

[3] P. Feng, X. Meng, J.-F. Chen, and L. Ye, "Mechanical properties of structures 3D printed with cementitious powders," *Construction and Building Materials*, vol. 93, pp. 486-497, 2015.

[4] C. F. Ferraris, "Measurement of the rheological properties of cement paste: A new approach," in *Proc. Role of Admixtures in High Performance Concrete, RILEM International Symposium*, J. G. Cabrera, and R. R. Rivera-Villarreal, Eds. Mexico: RILEM Publications S.A.R.L., 1999, pp. 333-342.

[5] G. P. A. G. van Zijl, S. C. Paul, and M. J. Tan, "Properties of 3D printable concrete," in *Proc. 2nd International Conference on Progress in Additive Manufacturing*, 2016, pp. 421-426.

[6] Y. Weng, M. Li, M. J. Tan, and S. Qian, "Design 3D printing cementitious materials via Fuller Thompson theory and Marson-Percy model," *Construction and Building Materials*, vol. 163, pp. 600-610, 2018.

[7] R. A. Buswell, W. R. L. D. Silva, S. Z. Jones, and J. Dirrenberger, "3D printing using concrete extrusion: A roadmap for research," *Cement and Concrete Research*, vol. 112, pp. 37-49, 2018.

[8] K.-S. Yeon, K.-K. Kim, and J. Yeon, "Feasibility study of the use of polymer-modified cement composites as 3D concrete printing material," in *Proc. 16th ICPIC International Congress on Polymers in Concrete, Washington D.C., USA*, 2018, pp. 27-36.

[9] B. Panda, S. C. Paul, J. H. Lim, Y. W. D. Tay, and M. J. Tan, "Additive manufacturing of geopolymer for sustainable built environment," *Journal of Cleaner Production*, vol. 167, pp. 281-288, 2017.

[10] C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger, and P. Morel, "Large-scale 3D printing of ultra-high performance concrete – A new processing route for architects and builders," *Materials and Design*, vol. 100, pp. 102-109, 2016.

[11] T. Le, S. A. Austin, S. Lim, R. A. Buswell, R. Law, A. G. F. Gibb, and T. Thorpe, "Hardened properties of high-performance printing concrete," *Cement and Concrete Research*, vol. 42, pp. 558-566, 2012.

[12] K. Pitt, O. Lopez-Botello, A. D. Lafferty, I. Todd, and K. Mumtaz, "Investigation into the material properties of wooden composite structures with in-situ fibre reinforcement using additive manufacturing," *Composites Science and Technology*, vol. 138, pp. 32-39, 2017.

[13] S. C. Paul, Y. W. D. Tay, B. Panda, and M. J. Tan, "Fresh and hardened properties of 3D printable cementitious materials for building and construction," *Archives of Civil and Mechanical Engineering*, vol. 18, pp. 311-319, 2018.

[14] M. Rubio, M. Sonebi, and S. Amiziane, "Fresh and rheological properties of 3D printing bio-cement-based materials," in *Proc. ICBBM 2017, 2nd International Conference on Bio-Based Building Materials*, 2017, pp. 1-9.

[15] W. A. Megid and K. H. Khayat, "Bond strength in multilayer casting of self-consolidating concrete," *ACI Materials Journal*, vol. 114, pp. 467-476, 2017.

Sook-Fun Wong received her BE(Hons) in civil engineering (1986) and the Mengsci in materials engineering (1989) from Monash University, Australia; and the PhD in civil engineering (1998) from National University of Singapore.

She is the head of Centre for Urban Sustainability (CUS) at Temasek Polytechnic, Singapore.

She was the president of American Concrete

Institute-Singapore Chapter (ACI-SC) from 2007-2009, and is now re-elected as president from 2017-2019 in ACI-SC of over 500-strong membership. She is also an active member of SCI (Singapore Concrete Institute) as well as Institution of Engineers in Singapore and Malaysia.

She was the recipient of Scott and Furphy Engineers Pty Ltd Prize in Australia and SsangYong Young Concrete Researcher Award in Singapore. She also received the Monash Research Scholarship in Australia and NUS Research Scholarship in Singapore. She is a reviewer for ACI Materials Journal and ACI Structural Journal published by ACI (International) in USA.

She has published over 40 journal articles and international conference papers. Her recent three publications include:

(I) S. F. Wong, S. K. Ting, M. Lin, M. Shamini, and B. K. Tay, "Novel Geopolymers incorporating Wollastonite and Recycled Mixed Plastics," in *Polymers in Concrete - Towards Innovation, Productivity & Sustainability in the Built Environment*, *Advanced Materials Research, 1129*, S. F. Wong (Editor-in-Chief), K. H. Tan, and K. C. G. Ong, Eds. Switzerland: Trans Tech Publications Ltd, 2015, pp. 39-48.

(II) S. F. Wong, A. A. Htwe, S. H. Oh, T. Y. Leo, J. Cheng, and B. K. Tay, "Utilization of Waste Plastics in Stone Mastic Asphalt for Infrastructural Applications," in *Materials Science Forum (MSF) – Civil and Building Materials, 902*, 2017, pp. 55-59.

(III) S. F. Wong, "Use of recycled polymers in asphalt concrete for infrastructural applications," in *Proc. 16th ICPIC International Congress on Polymers in Concrete, Washington D.C., USA*, 2018, pp. 437-442.

Her research interests comprise advanced manufacturing (e.g. additive 3D printing) via rheology - printer specifications - performance correlation; integrated system for recycling urban wastes (e.g. municipal solid waste, organic/food waste); as well as development of sustainable raw materials and finished products for building and infrastructure.

Kim-Cheng Tan received his B.Sc. (1986) and the M.Sc. (1996), both in mechanical engineering from Oklahoma State University, Stillwater, Oklahoma, U.S.A.

He is a senior lecturer at School of Engineering, Temasek Polytechnic. His research interests cover bioresorbable scaffold design, fabrication for biomedical applications, 3D printing via direct extrusion method for polymeric and cementitious composites.

His awards include Asian Innovation Awards: The Winners 2004; Gold Award: Healing Heads – doctors and engineers in Singapore have found a safer way to mend damaged skulls and to help bone regrow in other parts of the body; FEER Issue Cover: dated October 21, 2004; Institute of Engineers Singapore (IES): Prestigious Engineering Achievement Award 2004 – for the development of platform technology for scaffolds in bone tissue engineering applications.

Wen-Suey Ferne Leong received her diploma in chemical engineering (2012) from Temasek Polytechnic, Singapore.

She is a Technical Support Officer in Materials Technology Domain at School of Applied Science, Temasek Polytechnic. Her research areas include green composites and recycling of waste materials.

Yin-Yen Lim received his diploma in mechatronic engineering with Merits (2002) from Temasek Polytechnic, Singapore.

He was an associate engineer, a highly accomplished technical professional, with 24 years of extensive work experiences in support manufacturing fields in Singapore. He is currently a Technical Support Officer at School of Engineering, Temasek Polytechnic, for students, staff and research projects in areas of digital fabrication and additive manufacturing.