PROGRESS IN CONSTRUCTION AUTOMATION:
REVIEW ON 3D PRINTING OF CONCRETE MATERIALS

Yi Wei Daniel Tay, Biranchi Panda, Ye Qian and Ming Jen Tan

Singapore Center for 3D Printing,
School of Mechanical and Aerospace Engineering,
Nanyang Technological University, Singapore

Abstract:

3D Printing or additive manufacturing has been gaining popularity in the concrete research community and the field. Compared with conventional vibrating concrete or self- consolidating concrete, 3D printing technique do not require formwork, which is labor intensive and costly in construction sites. With the advantages in depositing the materials freely, 3D printing technique could construct more complicated structures at lower cost. In the past 4 years, the building and construction group at Singapore Centre for 3D Printing (SC3DP, NTU) has done a series of studies on concrete 3D printing. Presented in this paper are the overview of the current research at SC3DP focusing on 3D concrete printing with consideration in materials, machines and design. Conventional cementitious materials have been printed, including mixtures with supplementary cementitious materials (SCM), admixtures, recycled glass as aggregates, as well as geopolymer. Stainless steel cable and various types of fibres have also been incorporated to strengthen the cementitious mixtures. The interlayer bonding was studied and improved with novel nozzle design and a good balance between printing and pumping speed. Architecture design is further adapted considering the features of 3D printing technique, thus yielding some unique structures with optimized geometries.

Keywords: Concrete 3D printing; 3D printable material; interlayer bonding; nozzle; design

1. Introduction

3D concrete printing, or additive manufacturing (AM), is a construction process where materials are pumped and deposited layer by layer, thus no tradition formwork is needed. There are some requirements for successful 3d printable cementitious materials. Firstly, it has to be flowable and pumpable through the pipes till the nozzle (Roussel 2018). Secondly, it has to be stronger and stiff enough to sustain itself and the weight of subsequent layers (Wolfs, Bos et al. 2018). Thirdly, the interlay bonding between layers, which is a distinct feature compared with conventional casted concrete, should be strong enough to sustain the structures. These interfaces between layers tend to be the weakness of the whole structure (Le, Austin et al. 2012, Tay, Ting et al. 2018). In terms of rheology, it requires low dynamic yield stress, high static yield stress, high structural rebuilding rate, and high adhesion/cohesion. The low dynamic yield stress and high static yield stress is related to high thixotropy (Qian and Kawashima 2018).

In the meanwhile, parameters in controlling the printer are also very critical for a successful 3D printed structure. Printing speed, flow rate, time gap and nozzle orifice are some of the parameters that can control the surface finish and strength. In addition, freedom in design and structural optimization is an important advantage of 3D printing over conventional casted concrete structures. Since 3D printing offers the possibility of depositing material where it is needed, it is possible to produce geometrical complex structures. This paper presents an overview of the findings in current research focusing on 3D concrete printing and considerations in materials, machines and design.

2. 3D printable cementitious materials

Currently, due to the limitation of printer and pumping systems, most 3D printed structures use mortars instead of concrete with coarse aggregates. The basic component of 3D printed mortars are cement, water and fine aggregates. Supplementary cementitious materials (SCM) are also added to obtain more sustainable mixtures. Admixtures including nanoclay, accelerator and superplasticizers are added to adjust the rheological performance (Marchon, Kawashima et al. 2018). Rebars and fibers are added to enhance the flexural strength and mitigate micro cracks. New types of binders such as geopolymer are also probed in 3D printing.

2.1. Supplementary cementitious materials (SCM)

As a replacement of cement as binder, fly ash, slag, silica fume have been largely used in 3D printing. They all contains mineral particles, with the similar medium particle sizes as cement. So, addition of SCM usually don’t modify the rheological properties dramatically, as compared with chemical admixtures. Fly ash and slag tend to decrease the early rheological properties thus inducing more flowable materials (Bentz, Ferraris et al. 2012). While, silica fume induces higher rheological results, due to small particle sizes and adsorption of water (Zhang, Zhang et al. 2018). 1.5 meters high toilet design has been printed at Nanyang Technological University using high volume fly ash based mortars.

2.2. Admixtures

Superplasticizers are commonly added to enhance the flowability and pumpability of modern concrete. They are adsorbed on the surface of cement particles/agglomerates and prevent the flocculation of particles through steric hindrance or electrostatic repulsion, thus decreasing the dynamic yield stress (Qian and De Schutter 2018, Qian, Lesage et al. 2018).

Viscosity modification agent (VMA) are also commonly used to stabilize the mixtures (Ma, Qian et al. 2018). One commonly used VMA is nanoclay. It has been largely studied and used to enhance thixotropy (Qian and Schutter 2018). It also increases static yield stress (Qian and Kawashima 2016) and cohesion (Qian 2017), which indicates higher shape retention and higher buildability. During pumping, nanoclay also mitigates shear migration of sands (Qian and Kawashima 2016), thus inducing higher stability of the mortars. It is found that nanoclay addition increases shape stability of mortars in 3D printing (Kazemian, Yuan et al. 2017). Nanoclay has better performance than diutan gum on structure stability without decreasing the workability and time gap dramatically in 3D printing (Rubio, Sonebi et al. 2017). It is also found that the mixture with both nanoclay and silica fume addition has the highest buildability (Zhang, Zhang et al. 2018).

Accelerators are also commonly added to increase the rate of structural rebuilding, thus increasing the buildability. However, care should be taken as the addition of calcium chloride ($CaCl_2$) shortened initial setting time, as well as printability limit and blockage limit (Kazemian, Yuan et al. 2017).

2.3. Sand gradation

Sand gradation is also a parameter affecting the printing performance. Using Fuller Thompson theory and Marson-Perry model, an optimum sand gradation is successfully developed for high performance 3D printed structures (Weng, Li et al. 2018). In the meanwhile, recycled glass is also used to replace sand and promote sustainability. It has been found that mortars with recycled glass is more flowable (Guan Heng Andrew Ting, Yi Wei Daniel Tay et al. 2018)

2.4. Sustainable cementitious material

As a new sustainable material replacing ordinary Portland cement, geopolymers have been largely studied and used in 3D printing applications. It was found out that geopolymers tend to be less thixotropic. Fly ash based geopolymers have been successfully formulated and used in 3D printing(Panda, Paul et al. 2017, Panda and Tan 2018). The mechanical performance of geopolymers is also evaluated in terms of interlayer bonding (Panda, Paul et al. 2018).

2.5. Reinforcement

Stainless steel cables have been added while the filament is extruded (Lim, Panda et al. 2018). An independent system is built at the nozzle to add steel cable automatically. It showed that the addition of hybrid reinforcement increases the flexural performance of printed mortars up to 290%. Another group also used an automated cable entraining enforcement to strengthening the 3D printed mortars (Bos, Ahmed et al. 2017, Bos, Ahmed et al. 2018). Mortars with reinforcement showed higher flexural performance. Rebars are also printed in situ as concrete reinforcement (Mechtcherine, Grafe et al. 2018).

As an alternative replacement of rebars, fibres including plastic or steel fibres are added into the mortar matrix to strengthen the materials and the structures.Carbon, glass, and basalt fibers are added, and the flexural strength as high as 30 MPa is achieved through an optimized printing path at 1% of carbon fibre addition (Hambach and Volkmer 2017). The anisotropic mechanical performance of fibre reinforced geopolymer is also studied. It was found that fibre addition barely increases compressive strength, while enhances the flexural and tensile strength dramatically (Panda, Paul et al. 2017).

3. 3D printing parameters

3.1. Travel speed and flow rate

Figure 1 shows how travel speed and flow rate affect a printed filament. In region A (low travel speed and high flow rate), inaccuracy in the dimension of the filament is observed as the printed filament thickness is larger than the nozzle width, as shown in Figure 2 (a). In region C (high travel speed and low flow rate), breaks and voids appear in the printed filament as shown in Figure 2 (c). In region B, where the travel speed and flow rate are well proportioned, the width of the filament extruded matches the width of the nozzle. To print with high accuracy (filament extruded is the same with as the nozzle width) and to obtain a filament without voids, the parameters used should be within region B.

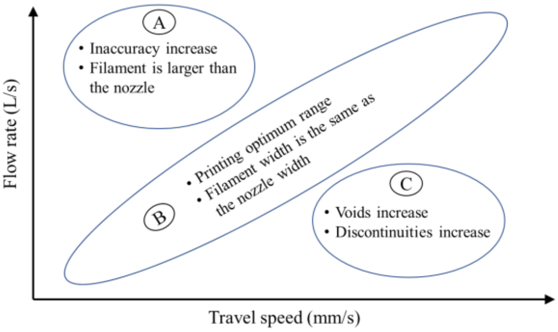


Figure 1: Effect of flow rate and travel speed on printing performance

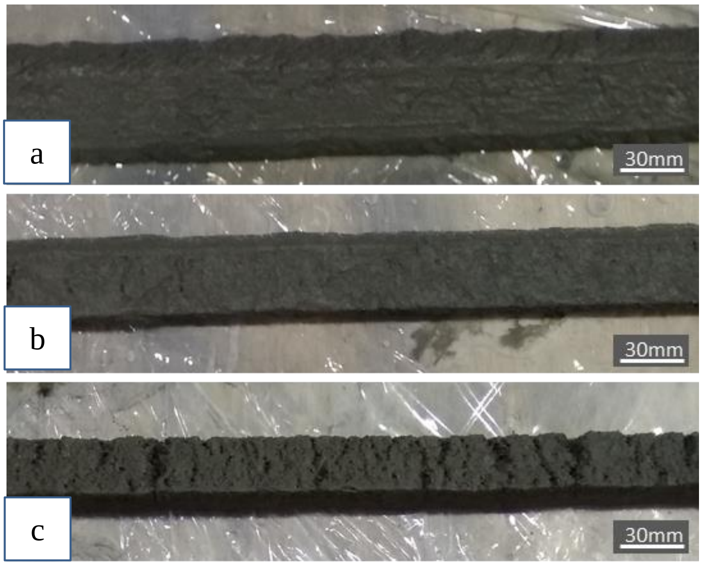


Figure 2: Effect of flow rate and travel speed on filament: (a) Region A, (b) Region B, (c) Region C

3.2. Time gap effect on bond strength

“Time-gap” is the time needed for the nozzle to trace out the two-dimensional (2D) profile of a single layer. It is dependent on the printing speed and the distance needed to cover for the 2D profile. It has been reported in past literature that the time- gap have a significant influence on the tensile bond strength of the inter-bond layer (Lim, Buswell et al. 2012, Panda, Paul et al. 2018, Tay, Ting et al. 2018). Due to the manufacturing process, printed concrete has an anisotropic property, and the tensile strength is the strongest in the direction parallel to its printed direction (Le, Austin et al. 2012, Paul, Tay et al. 2018).

Figure 3 shows samples printed with different time gaps. After extrusion, the bottom layer stiffness increases with time. The increase in stiffness might cause the interface of the bottom and top layer harder to mix well, thus causing a weaker interlayer bonding (Tay, Ting et al. 2018).. In the meanwhile, some researchers found the correlation between moisture at the interface and the interlayer bond strength. They reasoned that the decrease in strength as time-gap increase was due to the loss of moisture (Sanjayan, Nematollahi et al. 2018).

5 mm 5 mm

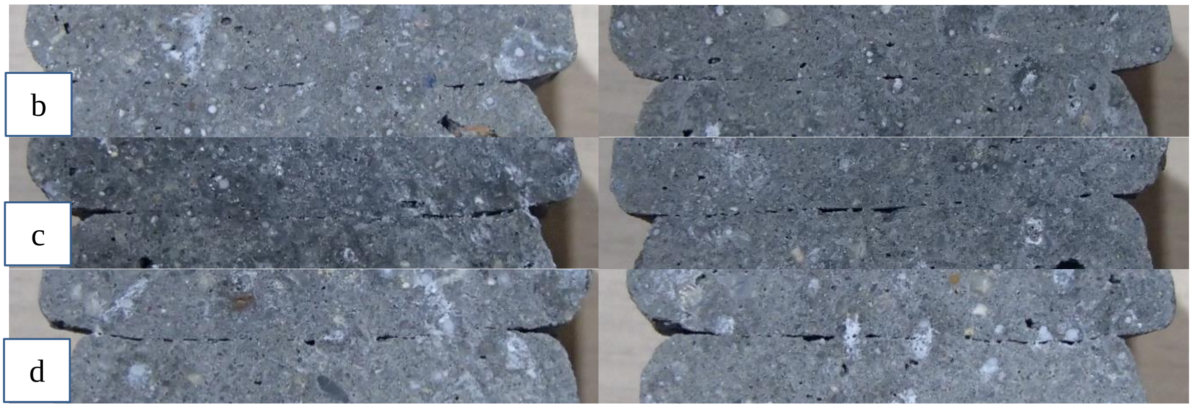


Figure 3: Samples printed at (a) 1-minute time-gap (b) 5 minutes time-gap (c) 10 minutes time-gap (d) 20 minutes time-gap (Tay, Ting et al. 2018)

3.3. Nozzle orifice

3.3.1. Alteration of nozzle orifice to improve surface finish

The nozzle orifice shape can have an effect on surface finish as well as the strength of the printed structure. Optimization of the nozzle orifice shape to improve the surface finish was demonstrated (Lao, Li et al. 2017). The aim of such approach is to improve the surface finish without reducing the layer height. Other 3D printing technologies, such as Fused Deposition Modelling (FDM), reduce the layer height to improve the definition of the surface finish (Lao, Li et al. 2017). However, such approach could potentially increase the total printing time and number of interlayers, which usually are the weak points of the whole structure.

Figure 4 (a) and (b) show a rectangular nozzle and the printed filament. It could be seen that the printed filament shows obvious slump, thus creating a notch in between layers. With the optimized nozzle, as shown in Figure 4 (c), the printed filament shows rectangular cross section and better surface quality in Figure 4 (d). The optimized nozzle was obtained by using an experimental iterative method and were fabricated using an FDM printer. Although this study only examined the rectangular nozzle, the technique could be applied to extrude other shapes precisely once the relationship between the nozzle and the filament is established (Lao, Li et al. 2017).

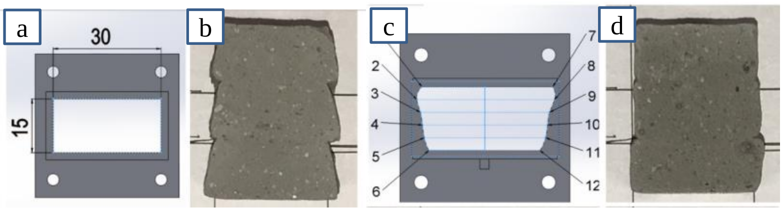


Figure 4: (a) Rectangular nozzle design; (c) optimised nozzle design and (b, d) the corresponding filament cross-sections (Lao, Li et al. 2017)

3.3.2. Alteration of nozzle orifice to improve mechanical properties

Altering the nozzle orifice shape to increase the contact area between two different filaments is one of the possible ways to improve interlayer bonding. Round nozzle shown in Figure 5 is not effective in bonding with the subsequent layer as the extrudates have least contact area between the top and bottom filament.

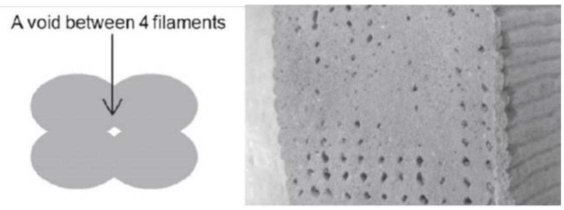


Figure 5: Round filament printed with round nozzle [29]

Rectangular nozzle, which is commonly used, gives better structural stability, however, is not the best in terms of the contact area between the filaments. To change the contact surface area, the nozzle orifice needs to be altered. Research shows the importance of interlocking bond between filament. Although the specimen is not printed, preparation of the tooth-like filament samples can cause void in the tooth interface (Zareiyan and Khoshnevis 2017). Therefore, to reduce the voids appearing at the interface, a U-shape nozzle was designed and tested in concrete printing.

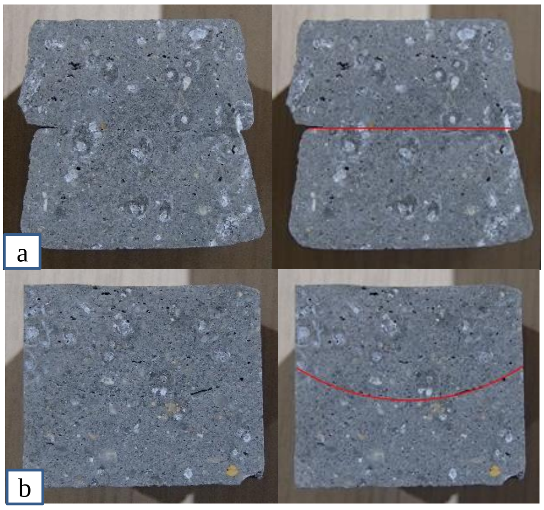


Figure 6: (a) Rectangular nozzle and (b) U-shaped nozzle

Direct tensile test results show that samples with U-shaped nozzle has slightly higher tensile strength at 28 days. It could possibly be due to the slight increase in the contact surface area. Future work of the U-shaped nozzle is ongoing to determine the best contact surface area that provide the highest tensile strength at the interface.

4. Architecture design for 3D printing applications

The scope of this section is limited to construction applications with cementitious materials through digital fabrication, specifically those extrusion based. Digital fabrication has been applied to 3D freeform architectural design and model prototyping for many years. Some of these applications of digital fabrication and companies involved can be referred in (Dirrenberger 2018, Schwartz 2018). Countries like Dubai and Saudi Arabia have plans to use 3D printed components to constitute around 25% of the new buildings with an aim to save labour and energy (Forum 2018). Labour costs for these printed parts could be cut down by 90%

compared to a traditionally constructed building. Researchers also testing 3D printed buildings, which are inspired by biological world (Moini, Olek et al. 2018). Architects could now rethink their building design since 3D printing technology offers the possibility of depositing materials on demand. A French company, XtreeE, has successfully applied structural optimization techniques to improve the material distribution in a complex truss-shaped 4-meter- high column, as shown in Figure 7 (a) (XtreeE 2017). Among other designs, “Triple S” project, by a Thai cement manufacturer SCG, reveals their unique weaving 3D printed pattern (Figure 7 (b)), inspired by folk handicraft (3dp 2018). A close look of these 3D printed designs reflects the ground breaking potential of digital fabrication, which allows architects to envisage their freeform designs beyond imagination. The most common example in the realm of digital fabrication can be found as 3D printing of cellular walls with a concept of placing outer boundaries followed by an inside zig-zag pattern as shown in Figure 7 (c).

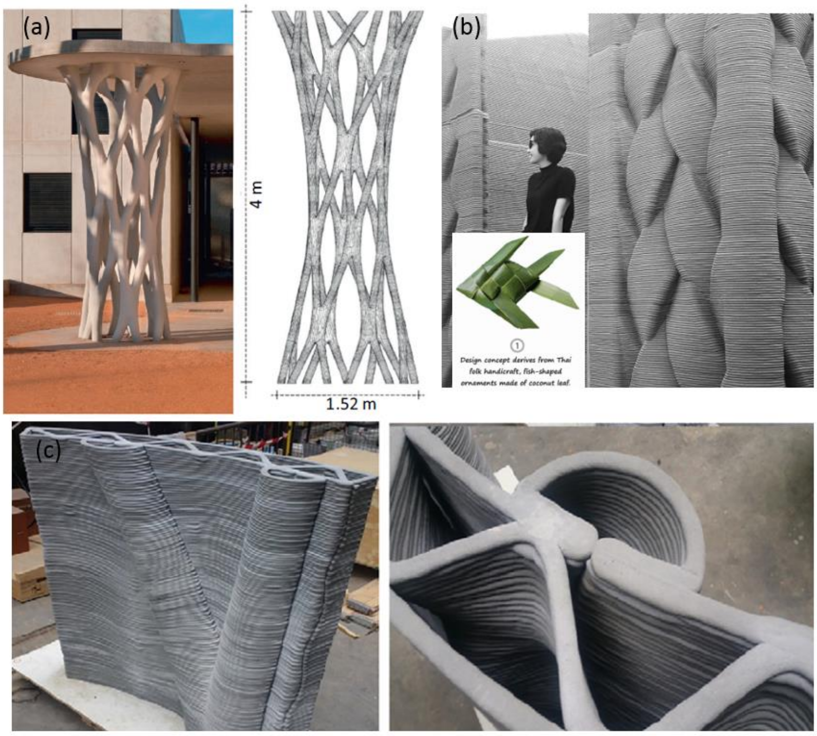


Figure 7 (a) Complex truss-shaped structure (XtreeE 2017) (b) Weaving concrete printed structure (3dp 2018) and (c) 3D printed concrete wall by XtreeE (XtreeE 2017)

Since the evolution of Contour Crafting in 2004, 3D printed houses are being built with such design concept that will not only save materials but also reduce the total production time. Sometimes, if the designs are beyond the working limit of the printer, researchers have performed an intelligent splitting of the entire object that can be later easily printed and assembled to realize the final design. The 3D printed canopy at UC Berkley, USA (3ders 2015) is one of such examples where the individual sections are printed and joined together to meet the design expectations (Figure 8 (a)). Recently, a research group at SC3DP, NTU, Singapore have attempted concrete printing of a small-scale bridge by group of robots, which were programed to work concurrently without any kind of inter-collision and tool path overlapping (Figure 8 (b)) (Zhang, Li et al. 2018). The big advantage of this system is that structures could be built without changing individual systems, since the robots themselves could define their own build volumes and printing paths by moving around. From these examples, it is very clear that digital fabrication has the potential to accelerate our production process irrespective of the design complexity and its large-scale application.

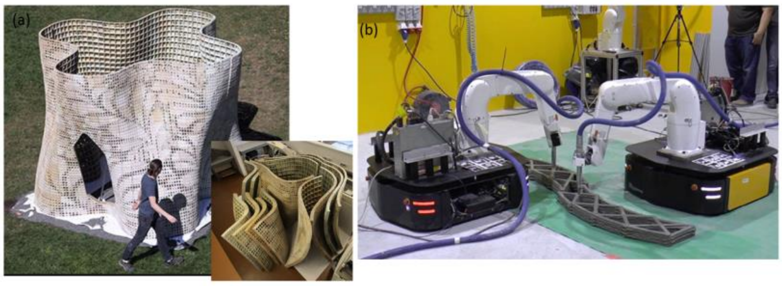
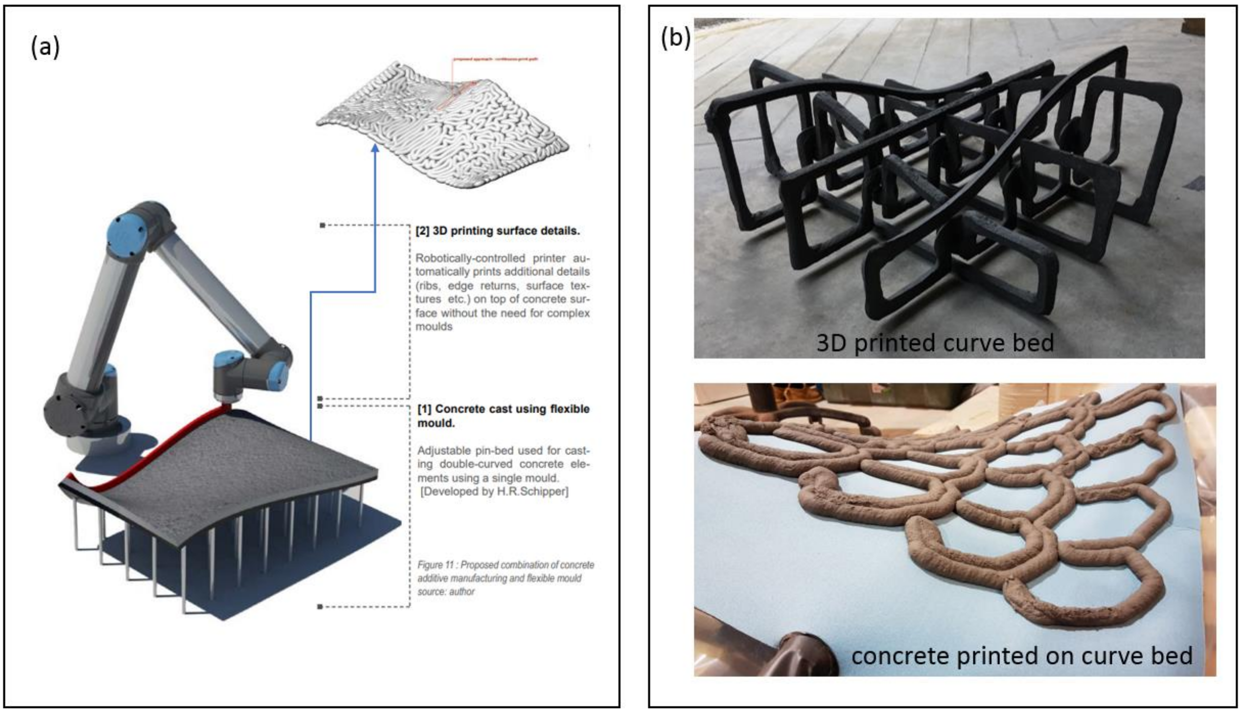


Figure 8 (a) 3D concrete printed bloom at UC Berkley, USA [43] (b) Concrete printing by a group of robots at SC3DP, NTU, Singapore (Zhang, Li et al. 2018

Not only in flat bed printing, digital fabrication has also proved its potential in producing three-dimensional complex structures by extruding concrete over curve platform. The shape can be automatically adjusted into various designs, directly from computer models. An example of curve bed concrete printing developed by TU Delft is shown in Figure 9 (a), where the robot is depositing printable material over the curve surface similar to regular 3D printing. This research considers the issue of standoff distance variation by the top surface of the bed and the need of maintaining uniform print height during extrudate deposition (Borg Costanzi 2016). Accordingly, tool path planning and printing speed are adjusted to smoothly deposit the concrete layers without any disruption. Alternate to printing on curve bed, researchers at SC3DP, NTU, Singapore have printed their own curve bed followed by concrete printing over it with an intention to demonstrate the possibility of fabricating complex curve bed and printing over it (Figure 9 (b)). The main challenge in this study was to design the tool path and optimize it together with the material rheology. A complete summary of curve bed 3D concrete printing can be referred in (Borg Costanzi 2016).



[2] 3D printing surface details.

Robotically-controlled printer automatically prints additional details (ribs, edge returns, surface textures etc.) on top of concrete surface without the need for complex moulds

[1] Concrete cast using flexible mould.

Adjustable pin-bed used for casting double-curved concrete elements using a single mould. [Developed by H.R.Schipper]

Figure 11 : Proposed combination of concrete additive manufacturing and flexible mould source: author

Figure 9 (a) Schematic of concrete printing on flexible surface at TU/e, Netherland (Borg Costanzi 2016) (b) Adaptable concrete printing at NTU, Singapore (Image courtesy: Catherine Soderberg at SC3DP, NTU)

Despite of advances in digitally fabrication, there are still some challenges related to material performance (in terms of rheology and stiffening behaviour) that limits printing of optimized structures. It is true that structural optimization can improve the material distribution and achieve more complex shapes. However, the material should be modified to fit the needs of printing those optimized structures. Therefore, the future goal should focus more on synthesis of geometries that are structurally and materially feasible via 3D printing process (Bhooshan, an Mele et al. 2018). These 3D printed structures could be used, both in structural (3D printed bridge (Salet, Ahmed et al. 2018)) and non-structural applications (facade, decoration panel etc.) depending on their design and material properties.

5. Conclusions

3D printing as an emerging technique requires many considerations in developing the system. This study summarizes the work done at SC3DP, NTU in terms of cementitious materials, machines and printing control, and architectural design for 3D printing applications. Conventional cementitious materials are printable, including mixtures with supplementary cementitious materials (SCM), various types of admixtures, recycled glass, and geopolymers. 3D printing system includes not only the printing head, but also the pumping system, nozzles, etc. Control in printing speed and flow rate, nozzle shape could help to achieve successfully printed structures. Architecture design further strengthens the advantage of 3D printing when the features of 3D printing structures are well considered.

Acknowledgements

This research is supported by the National Research Foundation, Prime Minister's Office, Singapore under its Medium-Sized Centre funding scheme, Singapore Centre for 3D Printing and Sembcorp Design & Construction Pte Ltd.

References

3ders (2015). "Emerging objects to unveil 9-foot-tall, the largest 3D printed cement pavilion. https://www.3ders.org/articles/20150305-emerging-objects-to-unveil-nine-foot-high-3d-printed-cement-structure.html (accessed date: 18 August 2018)."

3dp (2018). "New concrete 3D printing technique creates weaving structures in Thailand, https://all3dp.com/thai-company-uses-3d-printed-concrete-create-twisting-architecture/ (accessed date: 18 August 2018)."

Bentz, D. P., C. F. Ferraris, M. A. Galler, A. S. Hansen and J. M. Guynn (2012). "Influence of particle size distributions on yield stress and viscosity of cement–fly ash pastes." Cement and Concrete Research 42(2): 404-409.

Bhooshan, S., T. Van Mele and P. Block (2018). Equilibrium-Aware Shape Design for Concrete Printing. Humanizing Digital Reality, Springer: 493-508.

Borg Costanzi, C. (2016). "3d Printing Concrete onto Flexible Surfaces." Master Thesis, TU Delft, Delft, the Netherland.

Bos, F. P., Z. Y. Ahmed, E. R. Jutinov and T. A. Salet (2017). "Experimental exploration of metal cable as reinforcement in 3D printed concrete." Materials 10(11): 1314.

Bos, F. P., Z. Y. Ahmed, R. J. Wolfs and T. A. Salet (2018). 3D printing concrete with reinforcement. High Tech Concrete: Where Technology and Engineering Meet, Springer: 2484-2493.

Dirrenberger, J. (2018). From Architectured Materials to Large-Scale Additive Manufacturing. Robotic Building, Springer: 79-96. Forum, W. E. (2018). "One-quarter of Dubai's buildings will be 3D printed by 2025 https://www.weforum.org/agenda/2018/05/25-of-dubai-s-buildings-will-be-3d-printed-by- 2025/ (Accessed date: 18 August 2018)."

Guan Heng Andrew Ting, Yi Wei Daniel Tay, Ye Qian and M. J. Tan (2018). "Utilization of recycled glass for 3D concrete printing." Journal of Materials Science (under review).

Hambach, M. and D. Volkmer (2017). "Properties of 3D-printed fiber-reinforced Portland cement paste." Cement and Concrete Composites 79: 62-70.

Kazemian, A., X. Yuan, E. Cochran and B. Khoshnevis (2017). "Cementitious materials for construction- scale 3D printing: Laboratory testing of fresh printing mixture." Construction and Building Materials 145: 639-647.

Lao, W., M. Li, L. Masia and M. J. Tan (2017). "Approaching Rectangular Extrudate in 3D Printing for Building and Construction by Experimental Iteration of Nozzle Design."

Le, T. T., S. A. Austin, S. Lim, R. A. Buswell, A. G. Gibb and T. Thorpe (2012). "Mix design and fresh properties for high-performance printing concrete." Materials and structures 45(8): 1221-1232.

Le, T. T., S. A. Austin, S. Lim, R. A. Buswell, R. Law, A. G. Gibb and T. Thorpe (2012). "Hardened properties of high-performance printing concrete." Cement and Concrete Research 42(3): 558-566.

Lim, J. H., B. Panda and Q.-C. Pham (2018). "Improving flexural characteristics of 3D printed geopolymer composites with in-process steel cable reinforcement." Construction and Building Materials 178: 32- 41.

Lim, S., R. A. Buswell, T. T. Le, S. A. Austin, A. G. Gibb and T. Thorpe (2012). "Developments in construction-scale additive manufacturing processes." Automation in construction 21: 262-268.

Ma, S., Y. Qian and S. Kawashima (2018). "Performance-based study on the rheological and hardened properties of blended cement mortars incorporating palygorskite clays and carbon nanotubes." Construction and Building Materials 171: 663-671.

Sanjayan, J. G., Nematollahi, B., Xia, M., & Marchment, T. (2018). Effect of surface moisture on inter- layer strength of 3D printed concrete. Construction and Building Materials, 172, 468-475.

Mechtcherine, V., J. Grafe, V. N. Nerella, E. Spaniol, M. Hertel and U. Füssel (2018). "3D-printed steel reinforcement for digital concrete construction–Manufacture, mechanical properties and bond behaviour." Construction and Building Materials 179: 125-137.

Bong, S.H., Nematollahi, B., Nazari, A., Xia, M. and Sanjayan, J.G., 2018, September. Fresh and Hardened Properties of 3D Printable Geopolymer Cured in Ambient Temperature. In RILEM International Conference on Concrete and Digital Fabrication (pp. 3-11). Springer, Cham.

Panda, B., S. C. Paul, L. J. Hui, Y. W. D. Tay and M. J. Tan (2017). "Additive manufacturing of geopolymer for sustainable built environment." Journal of Cleaner Production 167: 281-288.

Panda, B., S. C. Paul, N. A. N. Mohamed, Y. W. D. Tay and M. J. Tan (2018). "Measurement of tensile bond strength of 3D printed geopolymer mortar." Measurement 113: 108-116.

Panda, B., S. C. Paul and M. J. Tan (2017). "Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material." Materials Letters 209: 146-149.

Panda, B. and M. J. Tan (2018). "Experimental study on mix proportion and fresh properties of fly ash based geopolymer for 3D concrete printing." Ceramics International 44(9): 10258-10265.

Paul, S. C., Y. W. D. Tay, B. Panda and M. J. Tan (2018). "Fresh and hardened properties of 3D printable cementitious materials for building and construction." Archives of Civil and Mechanical Engineering 18(1): 311-319.

Qian, Y. (2017). Characterization of Structural Rebuilding and Shear Migration in Cementitious Materials in Consideration of Thixotropy. Ph.D. Thesis, Columbia University.

Qian, Y. and G. De Schutter (2018). "Different Effects of NSF and PCE Superplasticizer on Adsorption, Dynamic Yield Stress and Thixotropy of Cement Pastes." Materials 11(5).

Qian, Y. and S. Kawashima (2016). "Flow onset of fresh mortars in rheometers: contribution of paste deflocculation and sand particle migration." Cement and Concrete Research 90: 97-103.

Qian, Y. and S. Kawashima (2016). "Use of creep recovery protocol to measure static yield stress and structural rebuilding of fresh cement pastes." Cement and Concrete Research 90: 73-79.

Qian, Y. and S. Kawashima (2018). "Distinguishing dynamic and static yield stress of fresh cement mortars through thixotropy." Cement and Concrete Composites 86: 288-296.

Qian, Y. and G. D. Schutter (2018). "Enhancing thixotropy of fresh cement pastes with nanoclay in presence of Polycarboxylate ether superplasticizer (PCE)." Cement and Concrete Research 111: 15- 22.

Roussel, N. (2018). "Rheological requirements for printable concretes." Cement and Concrete Research.

Rubio, M., M. Sonebi and S. Amziane (2017). 3D PRINTING OF FIBRE CEMENT- BASED MATERIALS: FRESH AND RHEOLOGICAL PERFORMANCES. ICBBM 2017, 2 nd International Conference On Bio- Based Building Materials, RILEM.

Salet, T. A., Z. Y. Ahmed, F. P. Bos and H. L. Laagland (2018). "Design of a 3D printed concrete bridge by testing." Virtual and Physical Prototyping: 1-15.

Sanjayan, J. G., B. Nematollahi, M. Xia and T. Marchment (2018). "Effect of surface moisture on inter- layer strength of 3D printed concrete." Construction and Building Materials 172: 468-475.

Schwartz, J. (2018). "Graphic statics and their potential for digital design and fabrication with concrete." Cement and Concrete Research.

Tay, Y. W. D., G. H. A. Ting, Y. Qian, B. Panda, L. He and M. J. Tan (2018). "Time gap effect on bond strength of 3D-printed concrete." Virtual and Physical Prototyping: 1-10.

Weng, Y., M. Li, M. J. Tan and S. Qian (2018). "Design 3D printing cementitious materials via Fuller Thompson theory and Marson-Percy model." Construction and Building Materials 163: 600-610.

Wolfs, R., F. Bos and T. Salet (2018). "Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing." Cement and Concrete Research 106: 103-116.

XtreeE (2017). "Post in Aix-en-Provence, http://www.xtreee.eu/post-in-aix-en-provence/ (accessed date: 18 August 2018)."

Zareiyan, B. and B. Khoshnevis (2017). "Interlayer adhesion and strength of structures in Contour Crafting-Effects of aggregate size, extrusion rate, and layer thickness." Automation in Construction 81: 112-121.

Zhang, X., M. Li, J. H. Lim, Y. Weng, Y. W. D. Tay, H. Pham and Q.-C. Pham (2018). "Large-scale 3D printing by a team of mobile robots." Automation in Construction 95: 98-106.

Zhang, Y., Y. Zhang, G. Liu, Y. Yang, M. Wu and B. Pang (2018). "Fresh properties of a novel 3D printing concrete ink." Construction and Building Materials 174: 263-271.

B. Panda, C. Unluer, M.J. Tan, 2018, Investigation of the rheology and strength of geopolymer mixtures for extrusion-based 3D printing, Cement and Concrete Composites DOI:
https://doi.org/10.1016/j.cemconcomp.2018.10.002.