Current Progress of 3D Concrete Printing Technologies

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Abstract –

The construction industry is expected to go through large transformations since construction automation is anticipated to drastically alter standard processing technologies and could lead to possible disrupting technologies such as 3D concrete printing (3DCP). While 3D printing techniques have been successfully applied in a wide range of industries such as aerospace and automotive, its application in concrete construction industry is still in its infancy. 3DCP can allow freeform construction without the use of expensive formwork, which in return offers excellent advantages compared to conventional approach of casting concrete into a formwork. In the last few years, different 3DCP technologies have been developed. This paper presents the current progress of 3DCP technologies. An innovative methodology recently developed by the authors of this study for formulating geopolymer-based material for the requirements and demands of commercially available powder-based 3D printers is also briefly presented.

Keywords –

Additive manufacturing; 3D printing; 3D concrete printing; concrete construction; geopolymer

1 Introduction

Concrete is the most widely used construction material on this planet. The current concrete construction industry faces several challenges. One of them is the high cost. According to a recent study conducted by Boral Innovation Factory [1], formwork is responsible for about 80% of the total costs of concrete construction in the Sydney CBD (central business district). In fact, this is typical for concrete construction worldwide.

The significant amount of wastage generated in the construction is another challenge. Formwork is a significant source of waste, since all of it is discarded sooner or later, contributing to a generally growing amount of waste in the construction industry. Astonishing data presented in Llatas [2]'s paper showed that the construction industry is responsible for generating approximately 80% of the total waste in the world.

Furthermore, the conventional approach of casting concrete into a formwork limits geometrical freedom for the architects to build in various geometries, unless very high costs are paid for bespoke formworks. Rectilinear forms not only limit the creativity of the architects, but they are also structurally weaker than curvilinear forms owing to stress concentration.

Another challenge is the slow speed of construction (i.e. long and hard to control lead time). The concrete construction often comprises many steps including material production, transportation, and in-situ manufacture of formwork, and each step is time consuming.

Moreover, the current concrete construction industry is labor intensive and has issues with safety. According to Safe Work Australia's report [3], on average, 35 construction employees per day are seriously injured in Australia. In addition, over one-quarter of construction deaths are caused by falls from a height [3]. This is despite the fact that Australia has one of the highest levels of safety regulations in construction sites in the world.

Last but not least, the current construction industry has serious issues with sustainability. In general, the current construction methods and materials are not environmentally friendly. The entire construction process, including off-site manufacturing, transportation of materials, installation and assembly, and on-site construction, emits huge amounts of greenhouse gases and consumes large quantities of energy [4]. In addition, conventional concrete made by ordinary Portland cement (OPC) is not sustainable. Manufacture of OPC is highly energy and carbon intensive [5].

Application of three-dimensional (3D) printing techniques in concrete construction could solve the aforementioned challenges. 3D printing technology is recently gaining popularity in construction industry. In the last few years, different 3D concrete printing (3DCP) technologies have been explored. This paper presents the current progress of 3DCP technologies. An innovative methodology recently developed by the authors of this study for formulating geopolymer-based material for the requirements and demands of commercially available powder-based 3D printers is also briefly presented.

2 Background

3D printing, also known as additive manufacturing (AM), is a group of emerging techniques for fabricating 3D structures directly from a digital model in successive layers with less waste material. The American Society for Testing and Materials (ASTM) International Committee F42 on AM technologies defines AM as “the process of joining materials to make objects from 3D model data, usually layer upon layer” [6]. The AM technologies have been initially developed in the 1980s. Currently, AM technologies have become an integral part of modern product development and have been successfully applied in a wide range of industries including aerospace and automotive manufacturing, biomedical, consumer and food [7].

3 Application of 3D Printing in Concrete Construction

The first attempt to adopt AM in construction using cementitious materials was made by Pegna [8]. An intermediate process was used to glue sand layers together with a Portland cement paste [8]. Unlike the conventional approach of casting concrete into a formwork, 3DCP will combine digital technology and new insights from materials technology to allow freeform construction without the use of expensive formwork. The freeform construction would enhance architectural expression, where the cost of producing a structural component will be independent of the shape, providing the much needed freedom from the rectilinear designs.

When compared with conventional construction processes, the application of 3D printing techniques in concrete construction may offer excellent advantages incluidng:

1. Reduction of construction costs by eliminating formwork;
2. Reduction of injury rates by eliminating dangerous jobs (e.g., working at heights), which would result in an increased level of safety in construction;
3. Creation of high-end-technology-based jobs;
4. Reduction of on-site construction time by operating at a constant rate;
5. Minimizing the chance of errors by highly precise material deposition;
6. Increasing sustainability in construction by reducing wastages of formwork,
7. Increasing architectural freedom, which would enable more sophisticated designs for structural and aesthetic purposes; and
8. Enabling potential of multifunctionality for structural/architectural elements by taking advantege of the complex geometry [9,10].

4 Current 3D Concrete Printing Technologies

In the last few years, different 3DCP technologies have been developed to adopt AM in concrete construction. These technologies are mainly based on two techniques, namely extrusion-based and powder-based. In the following sub-sections these techniques are explained and the currently available 3DCP technologies including the powder-based 3DCP using geopolymer developed by the authors of this study are reviewed. The similarities and differences and the pros and cons of different 3DCP technologies are highlighted.

4.1 Extrusion-Based Technique

The extrusion-based technique is analogous to the fussed deposition modelling (FDM) method which extrudes cementitious material from a nozzle mounted on a gantry, crane or a 6-axes robotic arm to print a structure layer by layer. This technique has been aimed at on-site construction applications such as large-scale building components with complex geometries, and has a great potential to make a significant and positive contribution to the construction industry. A schematic of the powder-based technique is illustrated in Figure 1.

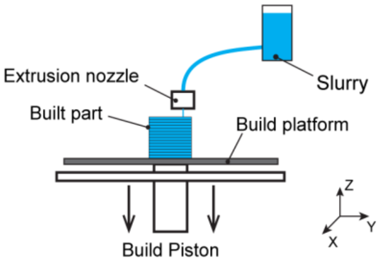

Figure 1. Schematic of extrusion-based technique

4.1.1 Contour Crafting

Contour Crafting (CC) technology has been developed at the University of Southern California, USA. This technology uses the extrusion-based technique to extrude two layers of cementitious mixture to build a vertical concrete formwork. Custom-made reinforcement ties are manually inserted between layers (at every 30 cm horizontally and 13 cm vertically) while the CC machine is constantly extruding the layers. Trowel-like fins are attached to the print head to create smooth extruded surfaces. Once the extruded formwork is completed, concrete is then manually poured to a height of 13 cm and a second batch is poured on top of the first batch after one hour. A one hour delay batch is to control the lateral pressure of the concrete by allowing it to partially cure and harden [11]. A concrete wall form fabricated by the CC machine is shown in Figure 2.

Figure 2. A concrete wall form fabricated by the CC machine with custom-made reinforcement ties manually inserted between layers [11]

The chief advantages of the CC technology are the superior surface finish and the greatly enhanced speed of fabrication. Other key advantage of CC is possibility of integration with other robotics methods for installing internal components such as pipes, electrical conductors, and reinforcement modules to enhance mechanical property [11]. The CC technology currently produces vertical elements largely in compression. When a doorway or window is required a lintel is placed to bridge the gap and the wall can be placed above. Therefore, it avoids the cantilever problem [12].

Gosselin et al. [10] reported the following drawbacks for the CC technology: (1) this technology is limited to vertical extrusion, hence yielding 2.5D topologies (vertical extension of a planar shape), (2) the initial formwork and trowel system can be rather complex to implement for production, depending on the size and shape of the object being printed, and (3) the interrupted sequential casting of concrete within the formwork due to hydrostatic pressure and weak mechanical properties of the extruded concrete may result in weakened interfacial zones between the layers.

4.1.2 Concrete Printing

Concrete Printing technology has been developed by a team at Loughborough University in the United Kingdom. This technology also uses the extrusion-based technique and to some extent is similar to the CC technology. However, the Concrete Printing technology has been developed to retain 3D freedom and has a smaller resolution of deposition, which allows for greater control of internal and external geometries [12]. In addition, the material used in Concrete Printing is a high performance fiber-reinforced fine-aggregate concrete, resulting in superior material properties to those obtained in the CC technology [12].

Figure 3 shows a full scale bench fabricated using Concrete Printing. The bench was 2 m long, 0.9 m maximum width and 0.8 m high and comprised of 128 layers of 6 mm thickness. The bench includes 12 voids that minimize weight, and could be utilized as acoustic structure, thermal insulation, and/or path for other building services. The bench also demonstrates a reinforcement strategy where carefully designed voids form conduits for post placement of reinforcement [12].

Figure 3. A full scale bench fabricated by the Concrete Printing with functional voids and post-tensioned reinforcement [12]

Concrete Printing requires additional support to create overhangs and other freeform features. It uses a second material, in a similar manner to the FDM method. The disadvantage of this process is that an additional deposition device is needed for the second material resulting in more maintenance, cleaning and control instructions and the secondary structure must be cleaned away in a post processing operation [12].

Gosselin et al. [10] reported the following drawbacks in regards to the Concrete Printing technology: (1) the trade-off necessary for maintaining its dimensional accuracy makes the process quite slow with regards to the envisioned industrial application, (2) although the technology initially aimed at the generation of 3D topologies rather than 2.5D, the use of second material to support overhangs reduces the efficiency and flexibility of the process while increasing its material cost, and (3) dimensions and possibilities in terms of shape-design are limited by the dimensions of the printing frame.

4.1.3 CONPrint3D: Concrete On-Site 3D Printing

Contour Crafting and Concrete Printing technologies, while demonstrating many technological advantages, are subjected to some inherent limitations such as the necessity of using new and advanced machinery, small mineral aggregate sizes (fine-aggregate mortar rather than concrete), and limited size of the printed elements (i.e. the size of the 3D printer must be larger than the size of the element to be printed). To overcome these limitations, a novel approach for 3DCP technology for on-site construction, named CONPrint3D, is currently being developed at the TU Dresden, Germany, which intends to bring 3DCP directly into the building sites. The main advantages of CONPrint3D technology are high geometrical flexibility, usage of commonly used construction machinery and low dependency on skilled labor [13].

One of the focal points of CONPrint3D is not only to develop a time, labor and resource efficient advanced construction process but also to make the new process economically viable while achieving broader acceptance from the existing industry practitioners. This is achieved by using existing construction and production techniques as much as possible and by adapting the new process to construction site constraints. One vital aspect of the project strategy is adapting a concrete boom pump to deliver material to specific positions autonomously and accurately using a custom-developed print head attached to the boom (see Figure 4) [13].

Figure 4. Schematic of CONPrint3D [13]

4.1.4 Large-Scale 3DCP using Ultra-High Performance Concrete

Based upon an understanding of the limitations identified in the aforementioned CC and Concrete Printing technologies, a new technology has been introduced by a research team in France for large-scale 3DCP using ultra-high performance concrete (UHPC) [10]. The developed technology uses the extrusion-based technique to deposit UHPC layer by layer through an extrusion print head mounted on a 6-axes robotic arm. The main advantages of the proposed technology are (1) allowing the production of large-scale 3D printed complex geometries without the use of temporary supports, (2) fully exploiting the possibilities of 3D printing by creating layers with varying thickness via the use of the tangential continuity method for slicing, which results in mechanically sounder constructions from a structural viewpoint, (3) enabling geometrical complexity and total control by relying on a generic 6-axes robotic arm instead of an overhead crane or a gantry frame and (4) enabling multifunctionality for structural elements by taking advantage of the complex geometry [10].

The proposed technology was used to manufacture a “multifunctional wall element” (see Figure 5) consisted of an absorptive formwork to be filled either with fiber-reinforced UHPC on structural parts or with an insulating material such as foam for thermal insulation. Some parts were also left intentionally empty to be able to host pipes or electrical wires. The production of the wall element measuring 1360 mm × 1500 mm × 170 mm, with a weight of 450 kg took approximately 12 h (for 139 layers) [10].

Figure 5. Multifunctional wall element [10]

4.1.5 Current Examples of Extrusion-based 3DCP Elements/Structures

In 2014, the Chinese Winsun company claimed to have built 10 basic houses in less than a day, with the area and cost of each one being about 195 m^2 and US$4’800, respectively. The company used a large extrusion-based 3D printer to manufacture the basic house components separately off-site before they were transported and assembled on site [14]. In 2015, the company also claimed to have built a 5-story apartment building, with the area of about 1’100 m^2, being currently the tallest 3D printed structure. The company also claimed to have built a stand-alone concrete villa with interior fittings for a cost of about US$160’000. The company claimed to 3D print the walls and other components of the structure offsite and then assembled them together on-site [15].

The Chinese Huashang Tengda company in Beijing has recently claimed to 3D print an entire 400 m^2 two-story villa ‘on-site’ in 45 days (see Figure 6-a). Unlike the Winsun company, the Huashang Tengda company uses a unique process allowing to print an ‘entire house’ ‘on-site’ in ‘one go’. The frame of the house inclding conventioinal steel reinforcements and plumbing pipes were first erected. Then, ordinary Class C30 concrete containg coarse aggregates was extruded over the frame and around the rebars through the use of a novel nozzle design and their gigantic 3D printer [16]. The Huashang Tengda project seemingly eliminated one of the major challenges of 3DCP which is incorporation of conventional steel reinforcements if structural concrete is to be 3D printed. The company claimed that the two-story villa is durable enough to withstand an earthquake measuring 8.0 on the Richter scale. Their giant 3D printer has a sort of forked nozzle (see Figure 6-b) that simultaneously lays concrete on both sides of the rebars, swallowing it up and encasing it securely within the walls [16].

Figure 6. (a): The two-story villa printed by Huashang Tengda company and (b): the novel nozzle of the giant 3D printer [16]

The researchers at the University Federico II of Naples, Italy used a 4 m high BIGDELTA WASP (World's Advanced Saving Project) printer to build the first modular reinforced concrete beam of about 3 m long (see Figure 7). With this WASP printer, the researchers have developed a system to produce concrete elements that can be assembled with steel bars and beams or can compose pillars in reinforced concrete [17].

Figure 7. The first 3D printed modular reinforced concrete beam of about 3 m long [17]

As a result of a collaboration between Supermachine Studio and the Siam Cement Group (SCG), recently a 3 m tall cave structure called the "Y-Box Pavilion, 21st-century Cave" was built in Thailand using the 4 m high BIGDELTA WASP printer (see Figure 8). The components of the pavilion was 3D printed off-site at the SCG factory and then all the components were assembled together. The cost of manufacture of the pavilion was reported to be about US$28'000 [18].

In December 2016, the Apis Core company announced to have built the first 'on-site' house in Russia using a 'mobile' 3D concrete printer in just 24 hours (see Figure 9). The entire 38 m^2 house was 3D printed 'on-site'. The total construction cost was claimed to be US$10'134 [19].

Figure 8. The 3 m tall cave structure [18]

Figure 9. On-site' 3D printed house by Apis Core (a): Construction using a 'mobile' 3D concrete printer, (b): House exterior [19]

4.2 Powder-based Technique

The powder-based technique is another typical AM process that creates accurate structures with complex geometries by depositing binder liquid (or "ink") selectively into to powder bed to bind powder where it impacts the bed. This technique is an off-site process designed for manufacturing precast components. It is the authors' belief that powder-based technique is highly suitable for small-scale building components such as panels, permanent formworks and interior structures that can be assembled on-site.

A schematic of the powder-based technique is illustrated in Figure 10. At the start, a roller, mounted together with a print head, spreads a layer of powder (about 3 mm in thickness) to cover the base of the build plate. Then, according to the layer thickness setting of the 3D printer, a thin layer of powder (approximately 0.1 mm) is spread and smoothed by the roller over the powder bed surface. Subsequently, the binder solution is delivered from binder feeder to the print head and selectively jetted by the nozzle(s) on the powder layer, causing powder particles to bind to each other. Repeating the described steps, the built part is completed and removed after a particular drying time and un-bound powder is removed by using air blower.

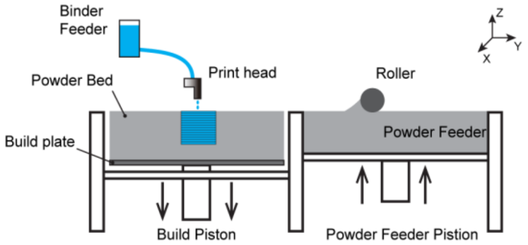

Figure 10. Schematic of powder-based technique

4.2.1 D-shape

The D-shape technology developed by Enrico Dini uses the powder-based technique to selectively harden a large-scale sand-bed by deposition of a binding agent. Sand and magnesium oxychloride cement (also known as Sorel cement) are used as the build material and the binding agent, respectively [20]. In 2008, Shiro Studio collaborated with D-shape to produce the Radiolaria pavilion measuring 3 × 3 × 3 meters (see Figure 11-a). The aim of the Radiolaria pavilion was to demonstrate the capabilities of D-shape technology through complex geometry [20]. In 2010, D-shape also 3D printed the Ferreri house measuring 2.4 × 4 meters in one single process (see Figure 11-b). The printing of the house was completed in 3 weeks [20].

Figure 11. (a): Radiolaria pavilion [20] and (b): the Ferreri house [20] printed by D-shape

4.2.2 Emerging Objects

The Emerging Objects technology developed in the USA uses the powder-based technique to selectively harden a proprietary cement composite formulation by deposition of a binding agent [21]. The technology was used to manufacture the Bloom (see Figure 12-a). Bloom is a 2.74 m tall freestanding tempietto with a footprint that measures approximately 3.66 m by 3.66 m and is composed of 840 customized 3D printed blocks. Each block is printed using a farm of 11 powder 3D printers with a proprietary cement composite formulation comprised chiefly of iron oxide-free OPC. The blocks are held in place using stainless steel hardware and assembled into 16 large, lightweight prefabricated panels, which could be assembled in just a few hours. The technology was also used to manufacture the Shed (see Figure 12-b). Shed is a small 3D printed prototype building constructed with Picoroco Blocks™ which is a modular 3D printed building block for wall fabrication printed from sand measuring 0.3 × 0.3 × 0. 3 meters [22].

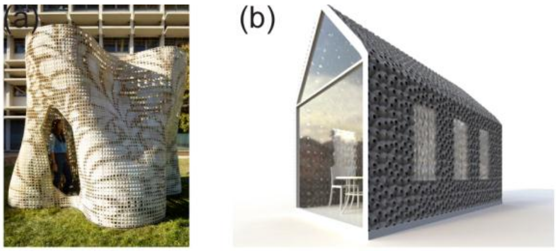

Figure 12. (a): Bloom [21] and (b): Shed [22] printed by Emerging Objects

4.2.3 Powder-based 3DCP using Geopolymer

Powder-based technique is capable of producing building components with fine details and intricate shapes. There is a demand in construction industry for such components which can only be made with expensive formworks with the currently available construction systems. Powder-based technique has the potential to produce robust and durable components at a reasonable speed to satisfy this industrial demand. However, the very limited scope of cement-based printing materials which can be used in commercially available powder-based 3D printers prevent this technique performing at its maximum potential for application in construction industry. To tackle this limitation, recently the authors of this study succeeded in developing an innovative methodology to adopt geopolymer-based material for the requirement and demand of commercially available powder-based 3D printers [23].

Geopolymer is a sustainable alternative to OPC. It is made by alkaline activation of fly ash and/or slag, being industrial by-products of coal power stations and iron manufacture, respectively. Geopolymer has superior mechanical, chemical and thermal properties and 80% less carbon emissions as compared with OPC [5,24].

The authors of this study prepared a printable geopolymer-based material by blending slag, anhydrous sodium metasilicate and fine sand. Different key parameters such as particle size distribution, powder bed surface quality, powder true/bulk densities, powder bed porosity, and binder droplet penetration behavior were studied to quantitatively evaluate the printability of geopolymer-based material. The printing accuracy, apparent porosity and mechanical properties of the printed structures were investigated. Details of these investigations can be found in Xia and Sanjayan [23].

To prepare the geopolymer powder, anhydrous sodium metasilicate beads were first dry milled for 5 min in a planetary ball mill with ceramic balls. Then slag, anhydrous sodium metasilicate and fine sand were dry mixed in a Hobart mixer until a homogeneous mixture was obtained. The particle size distributions of the geopolymer powder is shown in Figure 13. A commercial 3D printer (Zprinter® 150, Z-Corp, USA) was used for 3D printing a cubic structure with dimensions of 20 × 20 × 20 mm and a complex geometrical structure with dimensions of 56 × 35 × 25 mm (see Figure 14). Compressive strength of the printed cubic structure was measured in both X-orientation and Z-orientation before and after post-curing. For the post-curing, the cubic structures were immersed in saturated anhydrous sodium metasilicate solution for 1 and 7 days at a temperature of 60ºC. The 3D printed structures using geopolymer powder are shown in Figure 15.

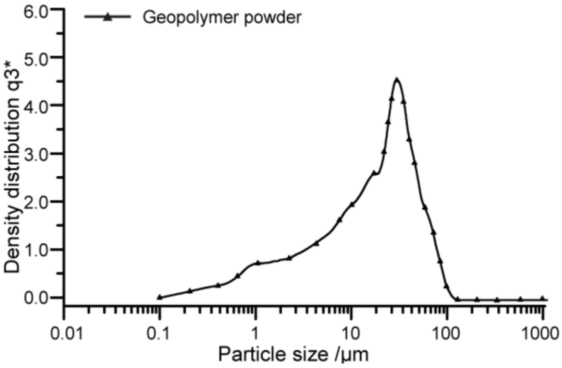

Figure 13. Particle size distributions of the geopolymer powder

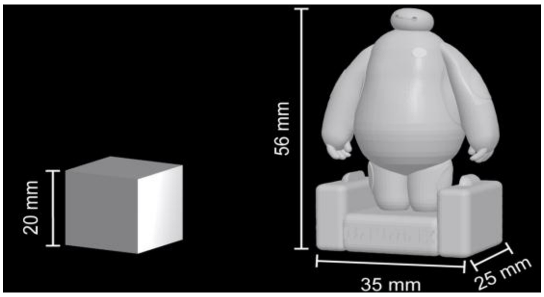

Figure 14. CAD designed 3D structures to be printed

The compressive strength results are presented in Table 1. Although the green strength (before post-curing) was very low, the strength was sufficient to withstand the pressure from the compressed air during de-powdering stage. The 1-day post-cured compressive strength has significantly (1032 to 1110%) higher than the green strength. The 7-days post-cured compressive strength was also significantly (60 to 71%) higher than the 1-day post-cured strength. This increase could be due to continued geopolymerisation process in the presence of alkaline solution.

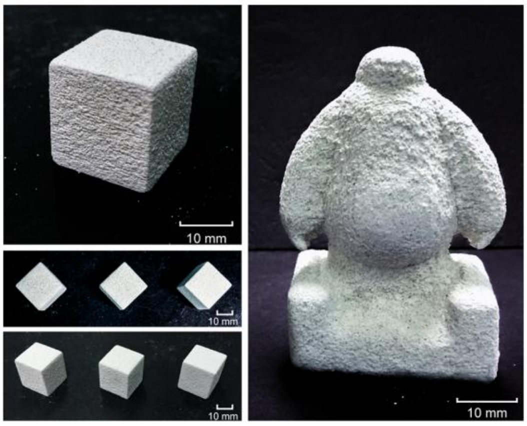

Figure 15. 3D printed structures using the geopolymer powder

Table 1. Compressive strength of cubic structures

		Compressive strength (MPa)	
		X-orientation	Z-orientation
Green strength		0.91 ± 0.03	0.76 ± 0.10
Post-cured	1-day	10.3 ± 0.2	9.2 ± 0.2
strength	7-days	16.5 ± 0.4	15.7 ± 0.2

As can be seen in Table 1, it was also noted that the compressive strength in X-orientation (binder jetting direction) was higher than that in Z-orientation. The green strength in X-orientation was 20% higher than that in Z-orientation. However, the difference between the strength in X-orientation and Z-orientation was reduced to 12% and 5% for 1-day and 7-days post-cured samples, respectively. Therefore, it can be concluded that the post-curing procedure reduces the anisotropic phenomenon in 3D printed geopolymer structures [23].

5 Conclusion

The 3D concrete printing (3DCP) techniques, namely extrusion-based and powder-based techniques, and the currently available 3DCP technologies are reviewed in this paper. The similarities and differences and the pros and cons of different 3DCP technologies are highlighted. The current examples of extrusion-based and powder-based elements/structures are also presented. Although 3DCP is still an emerging technology, the promising examples presented in this paper demonstrate that this technology is rapidly progressing in such a way that 3D printing of large-scale concrete structures may become a reality in near future.

The feasibility of using a geopolymer-based powder for the requirement and demands of commercially available powder-based 3D printers is also demonstrated by the authors of this study, which may offer an innovative manufacturing technique to expand the application of this ecologically friendly material. Future work will be focused on adjusting geopolymer powder formulation, optimizing printing parameters and selecting effective post-curing method to enhance the properties of 3D printed geopolymer structures.

References

[1] Holt C., Edwards L., Keyte L. and Lloyd R. Construction 3D printing. *Concrete in Australia*, 42(3):30–35, 2016.

[2] Llatas C. A model for quantifying construction waste in projects according to the European waste list. *Waste Management*, 6(31):1261–1276, 2011.

[3] Safe Work Australia. *Work-related injuries and fatalities in construction, Australia, 2003 to 2013*. ISBN: 978-1-76028-236-3, 2015.

[4] Yan H., Shen Q., Fan L.C., Wang Y. and Zhang, L. Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong. *Building and Environment*, 45(4):949–55, 2010.

[5] Nematollahi B., Sanjayan J. and Shaikh F.U.A. Synthesis of heat and ambient cured one-part geopolymer mixes with different grades of sodium silicate. *Ceramics International*. 41(4): 5696–5704, 2015.

[6] ASTM F42. *Standard Terminology for Additive Manufacturing Technologies*. West Conshohocken: ASTM International, 2015.

[7] Wohlers T. *3D printing and additive manufacturing state of the industry*, Wohlers Associates Inc., Colorado, 2014.

[8] Pegna J. Exploratory investigation of solid freeform construction, *Automation in Construction*, 5(5):427–437, 1997.

[9] Buswell R.A., Soar R., Gibb A.G. and Thorpe A. Freeform construction: mega-scale rapid manufacturing for construction, *Automation in Construction*, 16:224-231, 2007.

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

[11] Khoshnevis B., Hwang D., Yao K.-T., Yeh Z. Mega-scale fabrication by contour crafting, *International Journal of Industrial and System Engineering*, 1(3):301-320, 2006.

[12] Lim S., Buswell R.A., Le T.T., Austin S.A., Gibb A.G.F and Thorpe T. Developments in construction-scale additive manufacturing processes. *Automation in Construction*, 21:262–268, 2012.

[13] Nerella V.N., Krause M., Näther M. and Mechtcherine, V. CONPrint3D — 3D printing technology for onsite construction. *Concrete in Australia*, 42(3):36–39, 2016.

[14] Wang L. Chinese company assembles 10 3D-printed concrete houses in a day for less than $5,000 each. On-line: http://inhabitat.com/chinese-company-assembles-ten-3d-printed-concrete houses-in-one-day-for-less-than-5000-each/, Accessed: 20/03/2017.

[15] Sevenson B. Shanghai-based Winsun 3D prints 6-story apartment building and an incredible home. On-line: https://3dprint.com/38144/3d-printed-apartment-building/, Accessed: 20/03/2017.

[16] Scott C. Chinese construction company 3D prints an entire two-story house on-site in 45 days. On-line: https://3dprint.com/138664/huashang-tengda-3d-print-house/, Accessed: 20/03/2017.

[17] WASP. Concrete beam created with 3D printing. On-line: http://www.wasproject.it/w/en/concrete-beam-created-with-3d-printing/, Accessed: 20/03/2017.

[18] Alec. Thai cement maker SCG develops an elegant 3m-tall 3D printed 'pavilion' home, 21st C. Cave. On-line: http://www.3ders.org/articles/20160427-thai-cement-maker-scg-develops-an-elegant-3m-tall-3d-printed-pavilion-home-21st-c-cave.html, Accessed: 20/03/2017.

[19] Apis Core. The first on-site house has been printed in Russia. On-line: http://apis-cor.com/en/about/news/first-house, Accessed: 20/03/2017.

[20] Cesaretti G., Dini E., De Kestelier X., Colla V. and Pambaguian L. Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. *Acta Astronautica*, 93:430-450, 2014.

[21] Ronald Rael R. and San Fratello V. Bloom. On-line:http://www.emergingobjects.com/project/bloom-2/, Accessed: 20/03/2017.

[22] Ronald Rael R. and San Fratello V. Shed. On-line: http://www.emergingobjects.com/project/shed/, Accessed: 20/03/2017.

[23] Xia M. and Sanjayan J. Method of formulating geopolymer for 3D printing for construction applications. *Materials and Design*, 110: 382–390, 2016.

[24] Nematollahi, B. and Sanjayan, J. Efficacy of available superplasticizers on geopolymers. Research Journal of Applied Sciences, Engineering and Technology. 7(7): 1278-1282, 2014.