MATEC Web of Conferences **163**, 01002 (2018) https://doi.org/10.1051/matecconf/201816301002
MATBUD'2018

Evaluation of suitability for 3D printing of high performance concretes

Maria Kaszyńska[1], *Marcin* Hoffmann[1], *Szymon* Skibicki[1,*], *Adam* Zieliński[1], *Mateusz* Techman[1], *Norbert* Olczyk[1], and *Tomasz* Wróblewski[1]

[1]West Pomeranian University of Technology, al. Piastow 17, Szczecin, 70-310, Poland

Abstract. The article presents overview of additive manufacturing for concrete structures. Study focuses on specific tests used to determine suitability of high performance mixes for 3D printing. The tests include determination of compressive strength and evaluation of printing speed, extrudability and overall surface quality. Tests were performed on a High-Performance Concrete mix with fine natural aggregate up to 2 mm. Mineral additives such as silica fume and fly ash, and superplasticizer were added to obtain proper consistency. The tests were performed using specially designed site consisting of Cartesian robot and pumping module. The design of printed paths were tailored for specific tests. The evaluation of pump performance was made by measuring pumped mix volume in time. The determination of correct pumping speed was made based on the visual quality of the printed layers. Study determines also the ability to print multilayered structures and printability window of proposed mix.

1 Introduction

Additive manufacturing techniques for building construction have been intensively developed in the recent years. The beginning of this novel technology can be dated to mid '90s. The first technique known as Contour Crafting was invented at the University of Southern California [1–4]. The idea of additive manufacturing have also been studied at University of Loughborough [5–7]. The British research team has developed their own method of printing concrete, that does not utilize trowelling plates. Different approach called D-Shape, utilizes ideas from FDM (*Fused Deposition Modelling*) techniques to create structures using support materials [8]. Since mid-2012 many research teams and companies have taken interest in the additive manufacturing with concrete [3,9].

The major issue with the 3D concrete printing is designing a mix with proper rheological properties for a specific time window [3,4,6,10–12]. There are no standardized methods for determining required properties of the concrete mixes for 3D printing. Many research facilities have proposed their own frameworks for laboratory testing of printing concrete mixes [3–6].

---

[*] Corresponding author: szymon.skibicki@zut.edu.pl

The mixtures are evaluated in terms of extrudability, buildability, flowability, open time and, after curing, compressive strength. Those properties are necessary for proper extrusion and forming of 3D structures.

Extrudability (quality of being extrudable) is the mix ability to pass from the tank through the pump and hose to the nozzle. The concrete must be extrudable with structural integrity, without discontinuity and segregation, maintaining consistency throughout whole process. To determine the extrudability one can print several single layers with certain length and evaluate occuring blockage and tearing/fracturing [5,13]. Other method, called Print Quality, was proposed by the team from University of Southern California [10]. Printed layers are visually tested for surface defects, inadequate cohesion, rounded edges and changes in dimensions.

Workability/Flowability is a rheological parameter of mix consistency in time. There are several Standards dedicated to determination of this characteristic. Le et al. [6] used British test for soils BS1337-9 :1990, while Kazemian et al. [10] performed test according to American Standard ASTM C1437-15. Other methods include Hagermann flow table and mini cone test. Many research teams [4,12–16] correlate the flowability and extrudability with rheological properties. A team from Technische Universität Dresden modified the Sliding Pipe Rheometer to perform the tests according to their assumptions [12]. French research team [16] studied a time-dependant characteristics of the mix, proposing a new framework based on the plastic deformation of printed layer-by-layer structures.

Open time, also known as printability window, is a period in which the mix maintains proper pumpability. The mix must also maintaining proper quality and adhesion in a layer-by-layer structural build-up. Le et al. [5] and Secrieru et al. [12] defined the open time based on the shear stress test in accordance with British BS1377-9:1990 and German DIN 398. Ma et al. [13] proposed to test the open time with the V-Funnel method, Vicat apparatus, jump table, penetration tests and mini cone. Additionally, every couple minutes a layer is printed and measured to determine the dimensions and quality. A team from USA [10] prints 1.2 m long layers in a set period of time. Open time for concrete mixes used in 3D printing should not exceed 90 minutes from water-cement contact. The results of a study [6] showed that the time can be extended with additional use of superplasticizers. It needs to be remembered though that this decreases the quality of the concrete. A research team [13] has determined that the working time should be limited to 50-80 minutes.

Buildability is an important parameter of printed layers. It determines the feasibility of fresh mix for layer-by-layer printing and its resistance to deformation under the pressure of following layers. The parameter is strictly correlated with workability and extrudability of the mix. In order to test the buildability, research teams [5,7,10,13,14,17] have proposed printing several layers on top of each other and determine the shape stability and resistance to deformation. Other method, developed for sole purpose of evaluating shape stability, was proposed in [10]. The cylinder stability test proceeds by applying 5.5 kg load on a cylindrical Φ40x80 mm sample. Mix deformation determines the usability of the mix. Different rheological models are used to determine the buildability of fresh concrete mixes in time [4,15,16]. The buildability of the mix allows to determine the speed of layerwise construction.

There are several types of concrete mixes used in the additive manufacturing. First includes mixes with water-binder ratio of $w/b \approx 0.4\text{-}0.5$ and VMA and superplasticizers for regulating the consistency [10,18]. The compressive strength after 28 days reaches 50-60 MPa. Second type of mixes with $w/b \approx 0.23\text{-}0.3$ have addition of fly ashes and micro silica. The consistency is acquired by adding superplasticizer [6,14,17,19,20]. The compressive strength of those concretes at 28-day age reaches up to 125 MPa. Some studies [16,21], discusses use of mixes with 50-50 content of cement and microfillers like kaolin or limestone powder, with additional superplasticizer. Some mixes incorporate small addition (1.2 kg/m^3) of 12 mm long, 0.18 mm in diameter steel fibres [6,10,13,20].

The article presents printing process of concrete layers used for determination of geometrical characteristics, pump capacity, nozzle movement speed and multilayer buildability. This is a pilot research for testing technical capabilities of a 3D printer of own design.

2 Materials and experimental procedure

Based on the research conducted at Loughborough University [6] a new High-Performance Concrete was designed with w/b=0.23. The density of fresh mix was determined as 2168.25 kg/m^3 (CoV=0.24%, n=3). Preliminary tests determined the 28-day strength of 113.7 MPa (CoV=1.13%, n=4) on 100x100x100 mm samples. Preliminary tests were performed to qualify the mix for the 3D printing purposes. The mix composition is visible in Table 1.

Table 1. Concrete mix composition

Mix	**[kg/m^3]**
Cement CEM I 52.5R	579
Fly Ash	165
Silica Fume	83
Superplasticizer	8.33
Water	185
Aggregate 0-2 mm	1241

Mix preparation and printing were made in a laboratory at temperature of 20°C (± 2°) and relative humidity of RH=55% (± 5%). The printing was made using Cartesian robot of own design connected to a pumping module (Fig. 1a).

Fig. 1. Cartesian robot with pumping module during concrete printing.

The first test was conducted on printed layers with changing geometry. Test was performed to evaluate two things, the correlation between layer geometry and pump output and multilayer buildability (Fig. 2b). The nozzle with internal diameter of D=25 mm, moves 15 mm above from the printed surface. Test were performed for a constant movement speed of v=50 mm/s.

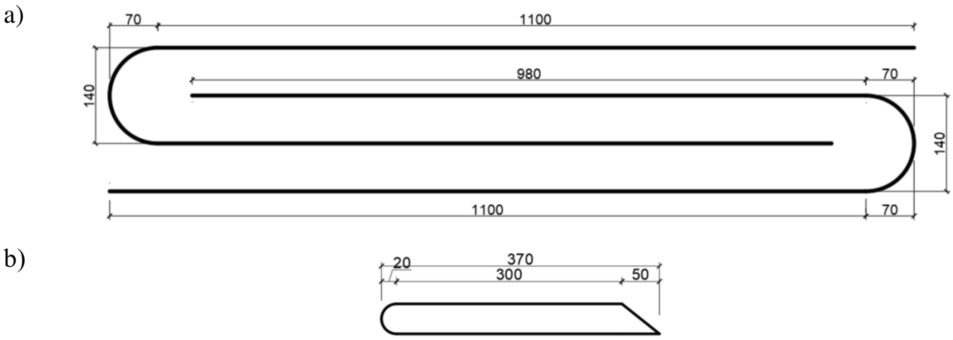

Fig. 2. Designed pathways for determination of layer properties: a) pump output; b) buildability – view on a single layer of printed wall.

3 Test results

3.1 Extrudability and quality issues of printed layers

During the first stage several layers were printed to evaluate the influence of pump output on geometrical characteristics of the layers and their visual quality. The quality of the layers was evaluated using classification presented in a study [10]: surface defects, inadequate cohesion, edge shape and printed layer dimensions. Oval shape of the layer (with increased edge radius) affects negatively the adhesion zone between two consecutive layers, thus decreasing bearing capacity of printed structure. Proper cross section should be symmetrical without rounded edges. The top surface should be flat with width similar to nozzle diameter. Figure 3 presents different cross-sections of layers printed with different pump output. At 2.88 l/min output (Fig. 3a) the layer is 61 mm wide and its edges are rounded significantly. Increased amount of air bubbles is visible in the cross section. With a lower output of 2.12 l/min (Fig. 3b) the layer is 45 mm wide, while at the output of 1.33 l/min the width met assumed requirements. The latter layer had also the least rounded upper edges. Increase in the layer width was noticed on the curves. This was caused by the decrease of the nozzle linear movement speed on curves, without simultaneous reduction of pump output.

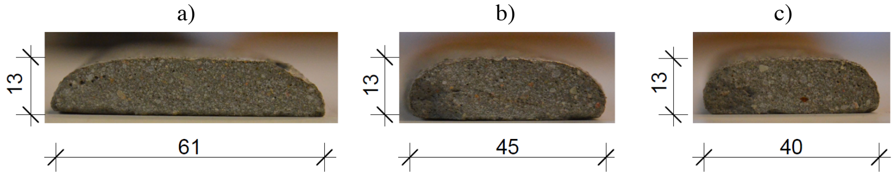

Fig. 3. The influence of pump output on layer dimension: a) output of =2.88 l/min; b) output of = 2.12 l/min; c) output of =1.33 l/min .

The extrudability of concrete is directly correlated with rheological characteristics of the mix and has to be controlled throughout the whole process of additive manufacturing. Based on the results [6] the open window was assumed between 15-60 minutes for designed mix. Exceeding the printability window causes the layer to lose continuity and consistency, exhibiting tearing (Fig. 4a). The surface of printed layer exhibit multiple defects and does not meet the requirements of the extrudability evaluation from [5,10]. The tears decrease significantly the mechanical properties of printed structure. Printing during the open time resulted in a continuous mix with stable geometry and without air bubbles (Fig. 4b). The mix presented in this study met the requirements of the extrudability evaluation.


a) b)

Fig. 4. The influence of open time on the print quality a) open time over 60 min, b) open time between 15 – 60 min.

3.2 Test buildability

The property of the concrete mix to retain its shape under own load and following layers is tested by printing multilayer structure. In this study the test was performed by printing 13 layer on top of each other as a continuous path, with constant 1.33 l/min pump output (Fig. 5a). After visual evaluation it was noticed that consecutive layers were not deformed, and the surface did not exhibit any defects or air bubbles. There was a visible decrease in a linear movement speed of the printing nozzle at the turns of designed path. As the pump output remains the same, the amount of material at the turns has increased causing thickening of the layer, thus additional load. In result there was a visible outflow of laitance (Fig. 5b).


a) b)

Fig. 5. Buildability test: a) printed multilayer structure, b) laitance at the turn of printed structure.

4 Preparation of control code for 3D printer

Previous tests allowed to determine various characteristics necessary for designing of 3D structures with use of additive manufacturing. To prove the findings additional 3D structure, in which the nozzle moved along conical spiral was designed. Designed cone was 345 mm high, with base diameter of 200 mm. Assumed layers were 15 mm high and 40 mm wide (Fig. 6a). Based on proposed geometry a 3D structural model was prepared (Fig. 6b). The visualization of G-Code is visible in Figure 6c [22]. Printing speed was set to v=39 mm/s and pump output to Q=1.33 l/min. Figure 6d shows the printed cone structure. As seen in Figure 6d the cone did not collapse, proving proper characteristics of designed mix and assumed printing setup.

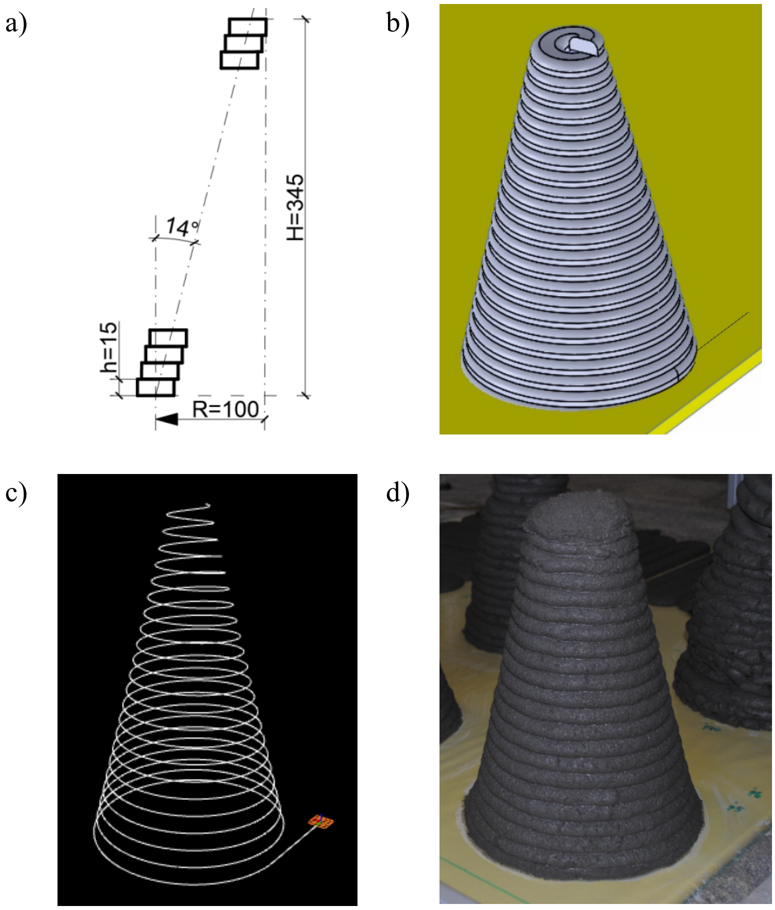

Fig. 6. (a) conical spiral geometry, (b) 3D model, (c) G-code simulation [22], (d) printed structure.

5 Conclusion

Performed tests allowed to correlate the nozzle movement speed and pump output in a manner that produced homogenous layers with constant geometry. Produced layers were evaluated in accordance to different classifications found in the literature. Increasing pump output affected the shape and geometry of the layers. Even though the cross-sections were symmetrical, produced layers had higher width with rounded upper edges.

Study have showed that the open time factor is one of the most significant in 3D printing of concrete. Exceeding the assumed time caused the drop in consistency of the mix, limiting its extrudability and lowering its surface quality.

Proposed design methods and tests allowed to produce structures that met all of the assumed criteria.

References

1. B. Khoshnevis, D. Hwang, K.-T. Yao, Y. Zhenghao, Int. J. Industrial and Systems Engineering **1**, 3 (2006)

2. B. Khoshnevis, Automation in Construction **13**, 1 (2004)
3. F. Bos, R. Wolfs, Z. Ahmed, T. Salet, Virtual and Physical Prototyping **11**, 3 (2016)
4. T. Wangler, E. Lloret, L. Reiter, N. Hack, F. Gramazio, M. Kohler, M. Bernhard, B. Dillenburger, J. Buchli, N. Roussel, et al., Digital Concrete: Opportunities and Challenges. RILEM Letters **1** (2016)
5. T. Le, S. Austin, S. Lim, R. Buswell, A. Gibb, T. Thorpe, Mater. Struct. **45** (2012)
6. T. Le, S. Austin, S. Lim, R. Buswell, R. Law, A.G.F. Gibb, T. Thorpe, Cem. Concr. Res. **42**, 3 (2012)
7. S. Lim, R. Buswell, T. Le, S. Austin, A. Gibb, T. Thorpe, Automation in Construction **21** (2012)
8. G. Cesaretti, E. Dini, X. Kestelier, V. Colla, L. Pambaguian, Acta Astronautica **93** (2014)
9. http://www.3dprinting architecture.net/?p=601 (January 2018)
10. A. Kazemian, X. Yuan, E. Cochran, B. Khoshnevis, Constr. Build. Mater. **145** (2017)
11. N. Labonnote, A. Rønnquist, B. Manum, P. Rüther, Automation in Constr. **72** (2016)
12. E. Secrieru, S. Fataei, C. Schröfl, V. Mechtcherine, Constr. Build. Mater. **144** (2017)
13. G. Ma, Z. Li, L. Wang, Constr. Build. Mater. **162** (2018)
14. V. Nerella, M. Krause, M. Näther, V. Mechtcherine, *25th Conference on Rheology of Building Materials* (2016)
15. N. Roussel, F. Cussigh, Cem. Concr. Res. **38**, 5 (2008)
16. A. Perrot, D. Rangeard, A. Pierre, Mater. Struct. **49**, 4 (2016)
17. Z. Malaeb, H. Hachem, A. Tourbah, T. Maalouf, N. El Zarwi, F. Hamzeh, Int. J. Civ. Eng. Tech. **6**, 6 (2015)
18. B. Khoshnevis, S. Bukkapatnam, H. Kwon, J. Saito, Rapid Prototyping Journal **7**, 1 (2001)
19. L. Anell, *Concrete 3d printer* (Master Thesis, Lund University, 2015)
20. J. Nylund, A. Järf, K. Kekäle, J. Rönnskog, F. Al-Neshawy, P. Kiviluoma, P. Kuosmanen, *10th International DAAAM Baltic Conference "INDUSTRIAL ENGINEERING"* (May 2015)
21. C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger, P. Morel, Mater. Des. **100** (2016)
22. https://nraynaud.github.io/webgcode/ (January, 2018)