Evaluation of Material Modification using PET in 3D Concrete Printing Technology

S Skibicki¹,*, M Pultorak¹ and M Kaszyńska¹

¹West Pomeranian University of Technology, al. Piastów 17, 70-310 Szczecin, Poland

szymon.skibicki@zut.edu.pl

Abstract. Use of recycled materials and incorporation of sustainable development ideas are one of the most popular trends in civil engineering. The 3D concrete printing technology which has been developing rapidly in recent years can benefit from use of both of them. The study evaluates the possibility of using PET granules in mixes suitable for 3D printing. The study compares the properties of two mixes, a reference one (well-studied mix which is suitable for 3D printing) and mix modified by replacing the aggregate with PET (30% of volume). The concretes were tested to evaluate their mechanical properties. The samples for flexural and compressive strength determination were prepared as traditional prisms (40x40x160 mm) as well as printed out with similar dimensions. Additionally, a hollow cylinder structure was printed out and tested for its strength after 24 h. Obtained results has shown that replacement of the aggregate with PET granules did not inhibit the suitability of mix for 3D concrete printing. Use of PET granules decreases the mechanical properties of printed specimens by few to several percent. Presented results can be considered as an initial study for introduction of recommendations for use of PET in printed concretes.

1. Introduction

Increasing costs of labour force, the need to speed-up the process of construction and sometimes harmful work conditions proved the need for automation in construction, particularly 3D printing of cement composites. Only in the last decade the number of studies in this area grown exponentially. The basic problem of this technology is the determination of proper composition of the concrete mix. Various research teams have already developed guidelines for concrete mix design [1–8]. Another important issue is the environmental impact of the technology. The idea of sustainable development recommends solutions that reduce greenhouse gas emissions and use of recycled materials [9]. The 3D printing technology can reduce the construction time [10–12] and material consumption [13–15] while also reducing the total amount of waste [16–18]. The above mentioned advantages result from the printing technology itself and not from the mix composition. However, the most important changes beneficial for the environment are the modifications to the mix itself. The modifications to the composition can be done either to the binder [18–21] or aggregate [22]. The use of recycled plastic waste as a partial replacement of the binder or aggregate seems to be a good solution. Today, as much as 348 million tons of plastic are produced annually for candles (data from 2017 according to [23]), of which less than 10% is recycled (data from 2015 according to [23]). The use of plastic waste (e.g. PET granules) in concrete was already studied [24, 25]. Theoretically, it should be possible to use it in printed concretes. As part of the study, a reference mix and mix modified with PET granules were prepared. Both mixtures were tested for their suitability for 3D printing. Presented research is an introduction to the development of recommendations on the use of PET waste in printed concretes.
Figure 1. Examples of specimens prepared by 3D concrete printing technology: a) specimen during printing process; b) printed Specimen after compression test.

2. Materials and experimental procedure

2.1. Mix composition

Study was based on two mixes. The first mix B800/PET0 was a reference mix that is suitable for 3D printing and was already tested in other studies [7, 22]. The second (alternative) mix B800/PET30 was modified by replacing 30% of fine aggregate volume with PET granules. In both mixes the water/binder ratio was assumed as constant value of 0.3. The binder in each mix consist of 70% of cement, 20% of fly ash and 10% of silica fume. The fly ash used in the study was obtained from a local coal power plant. The aggregate was a fine sand 0-2 mm. The notation for the mixes are as follows: B – amount of binder, PET – the amount of PET granules in the mix.

The study assumes a constant slump flow of 140 mm ± 10 mm at 15 minutes after adding the water as shown in standard [26]. Similar assumptions for suitability of mixes for 3D printing were proposed in other studies [22, 27–29]. To obtain assumed slump flow value the mixes were modified with superplasticizers. The mix design is presented in Table 1.

| No | Mix     | Binder [kg] | Cement [kg] | Fly Ash [kg] | Silica fume [kg] | PET [%] | Superplasticizer [kg] |
|----|---------|-------------|-------------|--------------|------------------|---------|-----------------------|
| 1  | B800/PET0  | 800         | 560         | 160          | 80               | 0%      | 1.0                   |
| 2  | B800/PET30 | 800         | 560         | 160          | 80               | 30%     | 0.7                   |

2.2. Experimental procedure

The tests can be divided into two stages: 1) tests conducted on standard samples; 2) tests conducted on 3D printed samples.

The first stage consisted on determination of compressive strength and flexural strength after 24 h and 168 h (7 days) conducted on 4x4x16 cm standard samples [30].

The samples for the second stage of tests were 3D printed with additive manufacturing method. For this purpose, a cartesian robot combined with a concrete extruder was used. Cartesian robot has three axes driven by stepper motors. Everything is controlled by a G-Code. Figure 1 a) presents an example of sample during printing process. Before printing the mixture was evaluated by print quality tests in accordance with [7, 31]. Following tests were conducted on printed samples:
1) Determination of compressive strength and flexural strength vertically to the printing direction (v). A scheme for the tests is presented in Figure 2. The samples were printed in a way to have dimensions as close to standard prisms 40x40x160 mm. The tests were conducted in accordance with [30]. Figure 3 presents the cross sections of B800/PET0 and B800/PET30 after flexural test.

2) Determination of compressive strength of printed structure. A hollow column was designed with R=160 mm ± 5 mm and height of H=205 mm ± 10 mm. The width of the layer was t = 40 ± 5 mm. The column during printing process is shown in Figure 1 a). The view of the column after the test is shown in Figure 1 b).

Mix preparation and printing were made in a laboratory at temperature of 20°C (± 2°) and relative humidity of RH=55% (± 5%).

3. Test results
Figure 4 and Figure 5 presents the comparison of the results of prepared samples after 1 and 7 days. The bulk density of the mix were ρ=2259 kg/m³ for the reference mix B800/PET0 (n=4; CoV=4,95%) and ρ=2001 kg/m³ (n=4, CoV=3,10%) for the modified (alternative) mix B800/PET30.

Figure 4 presents the results of compressive strength determination. Figure 5 presents the results of flexural strength determination. Each test was conducted on at least 4 samples, except of printed columns where 3 specimen were prepared. The value of CoV were presented in the Figure 4.

Based on obtained results it can be said:

1) For standard samples, the compressive strength ratio of samples B800/PET0 to samples B800/PET30 is in the range between 1.21 and 1.28. In the case of flexural strength, the ratio is approximately 1.24. This means that the usage of PET as an aggregate replacement reduced the compressive strength and flexural strength of standard samples after 1 and 7 days by 20-30%.

2) For printed samples, the compressive strength and flexural strength ratio of samples B800/PET0 to B800/PET30 is in the range between 1.04 and 1.10. In this case, the addition of PET also reduced the compressive strength and tensile strength of printed samples. However, the change was lower than for standard prisms.
In case of printed columns, the use of PET also decreased the overall strength by approximately 7%. However, the CoV for those samples was much higher (CoV=9%) and the results cannot be taken into consideration without additional tests.

The ratio of the compressive strength obtained on the standard specimen to compressive strength obtained on the printed specimen is between 2.48 and 3.27. The similar ratio (standard specimen to printed specimen) for flexural strength is between 1.01 and 1.33. The strength of standard specimen (especially in the case of compression strength) is higher than strength of printed samples. Lower strength of printed samples probably caused by worse compaction and bigger imperfections. Other probable cause lies in interlayer strength in printed samples. Additional tests must be conducted.

![Figure 4. Comparison of the results obtained in compression strength tests.](image)

![Figure 5. Comparison of the results obtained in flexural strength tests.](image)

4. Conclusion

The modification with the PET did not inhibit the required rheological propertied of fresh mix, allowing for proper printing. Additionally, it was possible to pump the mix modified with PET through a typical rotor-stator pumping system, despite increased size of the granules (between 2 mm and 5 mm). To sum up the study proved that the PET granules can be successfully used in 3D printing of cement composites. The study shows that the modification of the mixture with PET reduces its strength by up to 30% in case of standard specimens and by up to 10% in case of printed specimens. However, the most significant conclusion is that even with decreased strength the printing process of
The column with modified mix was successful, with sufficient strength of the structure. Research shows that mixture with PET additives may become a new direction of research in the field of 3D printing of cement composites. Use of PET in 3D concrete printing technology definitely is line with the idea of sustainable development.

5. References

[1] Labonnote N, Rønnquist A, Manum B and Rüther P 2016 Additive construction: State-of-the-art, challenges and opportunities Automation in Construction 72 347–66

[2] Kazemian A, Yuan X, Cochran E and Khoshevis B 2017 Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture Construction and Building Materials 145 639–47

[3] Secriri E, Fataei S, Schröfl C and Mechetcherie V 2017 Study on concrete pumpability combining different laboratory tools and linkage to rheology Construction and Building Materials 144 451–61

[4] Wangler T et al 2016 Digital Concrete: Opportunities and Challenges RILEM Letters 1 67–75

[5] Bos F, Wolfs R, Ahmed Z and Salet T 2016 Additive manufacturing of concrete in construction: Potentials and challenges of 3D concrete printing Virtual and Physical Prototyping 11 209–25

[6] Le T T, Austin S A, Lim S, Buswell R A, Law R, Gibb A and Thorpe T 2012 Hardened properties of high-performance printing concrete Cement and Concrete Research 42 558–66

[7] Kaszynska M, Hoffmann M, Skibicki S, Zielinski A, Techman M, Olczyk N and Wróblewski T 2018 Evaluation of suitability for 3D printing of high performance concretes MATEC Web Conf. 163 1002

[8] Federowicz K, Kaszyńska M, Zielinski A and Hoffmann M 2020 Effect of Curing Methods on Shrinkage Development in 3D-Printed Concrete Materials 13 2590

[9] Kaszynska M and Skibicki S 2017 Influence of Eco-Friendly Mineral Additives on Early Age Compressive Strength and Temperature Development of High-Performance Concrete IOP Conf. Ser.: Earth Environ. Sci. 95 42060

[10] Buswell R A, Soar R C, Gibb A and Thorpe A 2007 Freeform Construction: Mega-scale Rapid Manufacturing for construction Automation in Construction 16 224–31

[11] Ma G, Wang L and Ju Y 2018 State-of-the-art of 3D printing technology of cementitious material—An emerging technique for construction Sci. China Technol. Sci. 61 475–95

[12] Skibicki S 2017 Optimization of Cost of Building with Concrete Slabs Based on the Maturity Method IOP Conf. Ser.: Mater. Sci. Eng. 245 22061

[13] Lowke D, Dini E, Perrot A, Weger D, Gehlen C and Dillenburger B 2018 Particle-bed 3D printing in concrete construction – Possibilities and challenges Cement and Concrete Research 112 50–65

[14] López D, Veenendaal D, Akbarzadeh M and Block P 2014 Prototype of an ultra-thin, concrete vaulted floor system

[15] Siddika A, Mamun M A A, Ferdous W, Saha A K and Alyousef R 2019 3D-printed concrete: Applications, performance, and challenges Journal of Sustainable Cement-Based Materials 24 1–38

[16] Yang H, Chung J K H, Chen Y and Li Y 2018 The cost calculation method of construction 3D printing aligned with internet of things J Wireless Com Network 2018 65

[17] Malaeb Z, Hachem H, Tourbah A, Maalouf T, El Zarwi N. and Hamzeh F. 2015 3d concrete printing: Machine and mix design International Journal of Civil Engineering and Technology (IJCIET) 6 14–22

[18] Panda B, Paul S C, Mohamed N A N, Tay Y W D and Tan M J 2018 Measurement of tensile bond strength of 3D printed geopolymer mortar Measurement 113 108–16

[19] Xia M and Sanjayan J 2016 Method of formulating geopolymer for 3D printing for construction applications Materials & Design 110 382–90

[20] Bong, S., Nematollahi B, Nazari A, Ming Xia and Sanjayan, Jay, G 2019 Fresh and Hardened Properties of 3D Printable Geopolymer Cured in Ambient Temperature First RILEM International Conference on Concrete and Digital Fabrication -- Digital Concrete 2018
(RILEM bookseries, 2211-0852 volume 19) ed T Wangler and R Flatt (Cham, Switzerland: Springer)

[21] Lu B, Weng Y, Li M, Qian Y, Leong K F, Tan M J and Qian S 2019 A systematical review of 3D printable cementitious materials Construction and Building Materials 207 477–90

[22] Skibicki S, Kaszyńska M, Wahib N, Techman M, Federowicz K, Zieliński A, Wróblewski T, Olczyk N and Hoffmann M 2020 Properties of Composite Modified with Limestone Powder for 3D Concrete Printing Second RILEM International Conference on Concrete and Digital Fabrication ed F P Bos et al (Cham: Springer International Publishing) pp 125–34

[23] del Rey Castillo E, Almesfer N, Saggi O and Ingham J M 2020 Light-weight concrete with artificial aggregate manufactured from plastic waste Construction and Building Materials 265 120199

[24] Ismail Z Z and AL-Hashmi E A 2008 Use of waste plastic in concrete mixture as aggregate replacement Waste Management 28 2041–7

[25] Nematollahi B, Vijay P, Sanjayan J, Nazari A, Xia M, Naidu Nerella V and Mechtcherine V 2018 Effect of Polypropylene Fibre Addition on Properties of Geopolymers Made by 3D Printing for Digital Construction Materials 11 2352

[26] EN 1015-3:2000. Methods of test for mortar for masonry - part 3: determination of consistence of fresh mortar (by flow table)

[27] Hoffmann M, Skibicki S, Pankratow P, Zieliński A, Pajor M and Techman M 2020 Automation in the Construction of a 3D-Printed Concrete Wall with the Use of a Lintel Gripper Materials 13 1800

[28] Cho S, Kruger J, Bester F, van den Heever M, van Rooyen A and van Zijl G 2020 A Compendious Rheo-Mechanical Test for Printability Assessment of 3D Printable Concrete Second RILEM International Conference on Concrete and Digital Fabrication ed F P Bos et al (Cham: Springer International Publishing) pp 196–205

[29] Casagrande L, Esposito L, Menna C, Asprone D and Auricchio F 2020 Effect of testing procedures on buildability properties of 3D-printable concrete Construction and Building Materials 245 118286

[30] EN 1015-11:2020. Methods of test for mortar for masonry - Part 11: Determination of flexural and compressive strength of hardened mortar

[31] Le T T, Austin S A, Lim S, Buswell R A, Gibb A G F and Thorpe T 2012 Mix design and fresh properties for high-performance Materials and Structures 45 1221–32