Possibilities of using the 3D printing process in the concrete and geopolymers application

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Abstract. Additive manufacturing, also known as three-dimension printing (3DP) has a lot of advantages over traditional construction technology, including high building efficient, less construction wastes and greatly reduced labor. This paper presents the possibility of applying this technique to 3D printing of geopolymers and concrete. Moreover, a general overview of the research and progress of 3D printing of geopolymers and concrete in recent times was characterized. This paper also identifies the most interesting and innovative solutions in this area and highlights emerging trends to stimulate further research.

1. Introduction

In the last few years, additive manufacturing commonly known as 3D printing is gaining more and more interest, especially in the construction industry [1-7]. This technology creates components directly from a digital model [7, 8]. An innovative process which is three-dimension printing technology can be used with wide applications in many areas, including aerospace and automotive [7-8], fabricating objects [9], concrete components [10], food [11] and medical treatments [12]. Additive manufacturing techniques have a significant asset in the production of components with complex structures and in terms of higher productivity, quality, cost-efficiency and with less waste material [2, 4, 7, 13].

Nowadays, 3D printing of construction materials poses new opportunities for researchers and engineers in this industry and can revolutionize the traditional building practices [1-2, 14-15]. However, the use of suitable cementitious material of 3D printing is critical to conducting a successful process [16].

One of the main problems that should be solved during the 3D concrete printing process is understanding how the material can be sufficiently fluid and at the same time have sufficient viscosity to retain its shape after the printing process [14, 17]. For this purpose, the concrete mix created must have a thixotropic character, and thus should have a low viscosity during flow and high yield strength at rest [14]. Considering these challenges, scientists and industrialists have created cement materials that are easily extruded and retain their shape after the process [14, 17-19].

Unfortunately, despite the fact that technology is developing, the use of conventional raw materials, such as, ordinary Portland cement (OPC) causes direct release of CO₂ into the atmosphere, which has a negative impact on the environment [16-20]. Therefore, to strive for sustainability, one of the
alternatives to Portland Cement may be the use of local materials \[16\]. One of the materials that use locally available products such as slag or fly ash as ingredients are geopolymers. It is well known that the term geopolymer includes a class of modern, amorphous, inorganic aluminosilicate polymers with specific composition and properties. Geopolymers are produced by the following reactions: (1) Dissolution of metakaolin into silicate monomers and aluminate monomers; (2) polymerisation of monomers into aluminosilicate oligomers, and then into small geopolymer fragments or ‘proto-zeolitic nuclei’ (thermodynamically metastable and incompletely cross-linked); (3) fragments combination into larger molecules, that finally form aluminosilicate inorganic polymer gels, and crystallised phases, consisting of \( \text{SiO}_4 \) and \( \text{AlO}_4 \) tetrahedra sharing oxygen corners \[21, 22\]. Moreover, geopolymer material can achieve even better mechanical properties than ordinary Portland cement, and may be used in the construction industry \[16, 23\].

This paper presents the possibility of applying the 3D printing process for geopolymers and concrete applications. Moreover, the potentials of using this technology in terms of materials, mechanical properties and feasibility were presented. Finally, selected applications of 3D printed geopolymers and concrete were discussed.

2. Definition and principles of 3D printing of concrete

The development of concrete 3D printing results from interdisciplinary research of scientists in the fields of materials engineering, design, calculations, architecture and robotics \[1, 24\]. Because traditional technology and thus vibration and formwork setup are not required for 3D printing, printed concrete combines the advantages of self-compacting concrete and spray concrete \[1\].

Modeling of shapes for 3D printing must be carried out in accordance with sets of requirements related to processing restrictions, e.g. element dimensions, layer thickness, etc., and the functional properties of the manufactured part, e.g. mechanical strength. Functional requirements depend mainly on the structural geometry and properties of the hardened material \[24\].

The scheme of the 3D printing setup is shown in figure 1.

![Figure 1. Schematic of the 3D printing setup [based on 24].](image)

In order to implement 3D printing technology, the first step is to design a building path using 3D-to-2D slicing software. First, the constructor cuts the 3D shape of the object into thin layers of specified thickness, and then creates the path of each layer. All paths consist of a contour line and a fill
pattern [21]. The basic principle of this process is that the nozzle moves along the marked path, after which the concrete is extruded. Construction is completed after laying all layers for printing [1, 24].

3. The current progress of 3D printing of concrete

Panda and Tan [6] created a novel 3D printing geopolymer mortar, which can be applied for printing non-structural building components. Moreover, in this solution, it can be directly printed from digital models without the need of any formwork. They tested their produced materials with methods for laboratory testing 3D printing concrete (figure 2).

![Diagram of an experimental method for research 3D printing material](image)

**Figure 2.** Diagram of an experimental method for research 3D printing material [based on 6].

The results of the conducted laboratory tests confirmed that produced fresh geopolymer has properties, which are necessary for 3D printing application. In addition authors evidence that proposed criteria and mix design are suitable in practice. The open 3D structure using the optimum mixture, which based on fly ash, by a 4-axis gantry concrete was printed. The total printing time for this element was less than 20 min with a flowrate of 0.5 l/min and a printing speed of 80 mm/sec. The height was 60 cm, whereas width was 35 cm. This component comprised of 10 mm thickness 60 layers [6].

Inherent problems with 3D printing concrete rely on low tensile strength and poor ductility due to non-reinforcement. These aspects greatly limit the application of 3D printing materials and structures. Ma and al. [25] formed a reinforced geopolymer composite by using a continuous micro steel cable (1.2 mm) during filaments (12 mm) deposition process. The composition of used geopolymer (in percentage of total weight) are F-class fly ash (0.64), silica fume (0.11), slag (0.25), silica sand with particle size ranging from 0.1 mm to 0.6 mm (1.2), sodium metasilicate pentahydrate powder (0.125), tap water (0.348) and also small dosage of polypropylene fibers (0.0056) to prevent shrinkage. Moreover to increase water-retention property in this mix also used appropriate viscosity modifying admixture (VMA, Hydroxyethyl cellulose). Figure 3 illustrates the schematic manufacturing of filament reinforced composite. The most important part of the printing process is e.g. the step motor-based active feed-system. An extruder repeatedly entrains the filament into the printing nozzle by a narrow transmit pipe. After that the filament is extruded equally with the deposition of geopolymer paste, forming a reinforced composite [25].
Figure 3. Schematic illustration of the 3D printing process of composite reinforced by a filament.

The results show that the 3D printed micro-cable reinforced geopolymer composite gains eight times higher value of flexural strength and seventy times higher deflection resistance than the non-reinforced one [25]. These performances were obtained when the filaments were deposited in an incline-crossed printing configuration.

Al-Qutaifi et al. [26] focused on studying some factors related to the impact on the structural buildability of layered objects. A special timber mold was prepared to simulate the layering process by extrusion. Three geopolymer mixtures were prepared and three-time gaps of 5, 10 and 15 minutes are used. Two-layered patterns were tested with 18 layered samples. In addition, the authors also assessed the impact of 3D printing on hardened mechanical properties of geopolymer concrete by using 9 control samples. Materials such as fly ash (class F), fine aggregate (sand), activators (the combination of 8M sodium hydroxide solution and D-grade sodium silicate) and reinforcing materials were used in the research. The weight ratio of sodium silicate to sodium hydroxide was 1, and the weight ratio of alkaline liquid to fly ash was 0.26. Mixes 1, 2 and 3 contained 0%, 1% steel fibers and 0.5% polypropylene fibers, respectively. Al-Qutaifi et al. examined the flexural strength of layered geopolymer elements. On samples carried out three 3-point bending tests for 27 samples after 12 days of curing at room temperature and 2 hours of curing in an oven at 70°C. The results show that through the use of 3D printing technology, the geopolymer-based material has adequate bending strength. Despite this, its strength is lower than after the casting process. This is due to the layering processes. The flexural strength of the geopolymer material decreases due to anisotropic phenomena resulting from the presence of empty spaces between successive layers. In contrast, the flexural strength can be improved by increasing the thickness of printed layers. Reducing the time intervals between layers also increases the flexural strength of the layered element. The authors found that the introduction of fibers into the material can reduce the bond strength between successive layers. This is due to the fact that the uneven distribution of fibers can hinder adhesion between layers. Steel fibers, compared with polypropylene fibers, had a higher decrease in bond strength. It is not recommended to use steel fibers as reinforcement during 3D printing, as this may hinder adhesion between successive layers.

Zhu et al. [27] carried out research aimed at developing 3D-printing engineered cementitious composites (ECCs) characterized by high tensile strain capacity. These composites, in principle, can be used for the digital construction of concrete structures, moving away from conventional methods that use steel fibers. In this study, the authors used cementitious binder materials that consisted of ordinary Portland cement, sulfoaluminate cement-based on 100% solid industrial waste and fly ash. Fine silica sand has also been used. However, to obtain the required fluidity, a superplasticizer based on polycarboxylate ether-based was introduced. Samples M1 and M2 were made to examine the
effects of adding HPMC (hydroxypropyl methylcellulose) and ANC (attapulgitenanoclay). While in order to strengthen the ECC matrix, various volume fractions of polyethylene fibers (1%, 1.5%, and 2%) were introduced into samples M2, M3, and M4. For each of the mixtures M1 and M2, a cylindrical model was printed, which consisted of 17 layers, the height of each layer was 13 mm. Sample M2 showed excellent buildability and shape retention due to the addition of HPMC and ANC. Although the M1 sample was not damaged, deformations of the printed layers and poor shape retention could be observed.

Moreover, Zhu et al. [27] examined also rheological properties, workability, uniaxial tensile strength, flexural and compressive strength as well as microstructure for ECC developed for 3D printing. For comparative purposes, the samples were also made using a conventional casting method. The results showed that the tensile strength, as well as deformation energy and the number of cracks, increased with the volume fraction of PE fibers in the material. ECC tensile strength depended on the fiber distribution and pore size distribution. The extrusion-based 3D printing process caused the fiber orientation to be parallel to the direction of the force. The flexural strength of 3D printed materials was higher than that of mold-cast ECCs. However, the compressive strength of printed ECCs was lower than that of mold-cast ECCs. The impact of fiber content on compressive strength was small.

4. The most interesting applications of 3D printing of concrete
The application of 3D printed concrete has become really popular nowadays, thus some structural components and also full-size buildings can now be printed. Unfortunately, many printed structures and buildings can’t be used, because of the unqualified safety requirements [1]. The first workable 3D printed building was created in Dubai in 2016. The cost of production this building was relatively modest - $140,000. This building is used as an office building. It was created with used a single 120 × 40 × 20 feet 3D printer.

The first 3D printed pedestrian bridge was built in 2017 by the Institute of Advanced Architecture of Catalonia (IAAC) in Spain. It has 12 m span and 1.75 m wide and it consists of eight separate components [1]. Every single component was built in the D-Shape printing system. In addition, Salet et al. [28] printed a bridge by CC printing system, which is located in the Netherlands. The authors of the project divided the bridge into six components and they printed them apart. This was caused by the span limitation of the printer.

5. Summary
The article provides a general view of knowledge related to 3D printing of geopolymers and concrete. Moreover, the article presents problems that arise during the additive manufacturing process. 3D printing technology was also compared to conventional methods. It was determined what properties the material obtained depending on the method of manufacture.

It was presented that, the success of using 3D printing technology is based on improving the relationship between design and production processes, but it also depends on the skills of engineers to design building components. The quality of the printed elements is also undoubtedly an important value, which is determined by the material efficiency and precision of production. The printability of concrete or geopolymers depends on the mechanical properties and workability that can be optimized by selecting materials and printing parameters. The technology of 3D printing of concrete and geopolymers brings low labor costs, less waste material, and high efficiency. Currently, some buildings have already been printed, but 3D printing technology for concrete and geopolymers still requires continuous development and optimisation.
References

[1] Zhanga J, Wanga J, Donga S, Yu X and Han B 2019 Compos Part A. 125 105533
[2] Li B, Weng Y, Li M, Qian Li B, Weng Y, Li M, Qian Y, Fai Leong K, Jen Tan M and Qian S 2019 Constr Build Mater. 207 477–490
[3] Xia M and Sanjayan J G 2018 Mater Lett. 227 281–283
[4] Hui Lin J, Panda B and Pham Q-C 2018 Constr Build Mater. 178 32–41
[5] Zhang D, Wang D, Lin X and Zhang T 2018 Constr Build Mater. 184 575–580
[6] Panda B. and Tan M J 2018 Ceram Int. 44 10258–265
[7] Xia M. and Sanjayan J 2016 MaterDesign 110 382–390
[8] Xia M., Nematoollahi B and Sanjayan J 2019 Automat Constr. 101 179–189
[9] Fantino E, Chiappone A, Roppolo I, Manfredi D, Bongiovanni R, Pirri C F and Calignano F 2016 Adv. Mater. 28 5712–17
[10] Buswell R A, Leal de Silva W R, Jones S Z and Dirrenberger J 2018 Cement Concrete Res. 112 37–49
[11] Sun J, Zhou W B, Huang D J, Fuh J Y H and Hong G S 2015 Food Bioprocess Technol. 8 1605-15
[12] Seol Y J, Kang H W, Lee S J, Atala A and Yoo J J 2014 Eur. J. Cardiothorac. Surg. 46 342-348
[13] Lowke D, Dini E, Perrot A, Weger D, Gehlen C and Dillenburger B 2018 Cement Concrete Res. 112 50-65
[14] Panda B, Unluer C and Tan M J 2018 Cement Concrete Comp. 94 307-314
[15] Panda B, Unluer C and Tan M J 2019 Compos Part B 176 107290
[16] Biranchi P, Suvash C P, Nisar A N M, Yi Wei D T and Ming J T 2018 Measurement 113 108-116
[17] Suvash C P, Yi Wei D T, Biranchi P and Ming J T 2018 Arch CivMechEng. 18 311-319
[18] Franchin G, Scanferla P, Zeffiro L, Elsayed H, Bariello A, Giacomello G, Pasetto M and Colombo P 2017 J Eur Ceram Soc. 37 2481-89
[19] Le T T, Austin S A, Lim S, Buswell R A, Law R, Gibb A G F and Thorpe T 2012 Cement Concrete Res. 42 558-566
[20] Suhendro B 2014 Procedia Engineer. 95 305-320
[21] Szeczyńska-Hebda M, Marczyk J, Ziejewska C, Hordyńska N, Mikula J and Hebda M 2019 Materials 12 2999; doi:10.3390/ma12182999
[22] Mierzwiński D, Lach M, Hebda M, Walter J, Szeczyńska-Hebda M and Mikula J 2019 J Therm Anal Calorim https://doi.org/10.1007/s10973-019-08471-7
[23] Łach M, Mikula J and Hebda M 2016 J Therm Anal Calorim 125 (3) 1035–45
[24] Gosselin C, Duballet R, Roux Ph, GaudillièrèN, Dirrenberger J and Morel Ph 2016 Mater. Design 100 102-109
[25] Ma G, Li Z, Wang L and Bai G 2019 Mater Lett. 235 144-147
[26] Al-Qutaifi S, Nazari A and Bagheri 2018 Constr Build Mater. 176 690–699
[27] Zhu B, Pan J, Nematoollahi B, Zhou Z, Zhang Y and Sanjayan J 2019 MaterDesign 181 108088
[28] SaletT, Ahmed Z, Bos F P and Laagland H L M 2018 Virtual Physical Prototyping 13 222-236