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Development of 3D Printing Technology for Geopolymers

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Abstract. *The article presents the first results of the project under the title: 'Development of 3D printing technology for construction and facade prefabricated elements made of concrete composites and geopolymers', grant no. POIR.04.01.04-00-0096/18, funded by the National Centre for Research and Development in Poland, within the framework of programme: 'Smart Growth Operational Programme 2014-2020, IV Increasing the research potential, 4.1.4: 'Application projects'. The main aim of the project is design and development of the innovative large-format printer using geopolymers for 3D printing for residential houses. It allows the development of a technology for the production of a universal residential building, with a construction that is easy to transport and fast to assemble, as well as with the possibility of simple and quick expansion depending on the needs of users. The article shows the main idea of the advanced large format 3D printing for geopolymers with using an ergonomic printing method as well as materials research in modern filaments in the form of geopolymers.*

Keywords: *Geopolymer, 3D Printing, Additive Manufacturing, Large-Format 3D Printer, 3D Printing in Civil Engineering.*

1 Introduction

Additive Manufacturing is a rapidly developing industrial sector and potentially a disruptive technology. It can provide new horizons in the construction sector, especially in terms of geometrical flexibility, reduction of labour costs, improvement of efficiency and safety, construction in harsh environments, and sustainability (Nematollahi *et al.*, 2019; Labonnote *et al.*, 2016; Panda and Tan, 2019; Soltan and Li, 2018). Unfortunately, the full exploitation of 3D printing processes is currently limited due to the in-process and in-service performance of the available materials' sets, especially in application in construction industry.

Nowadays, the using geopolymers for 3D printing in the large-format printer is a great challenge. It offers a new perspectives for the construction industry, but the development of this technology is slowed down by a lot of barriers. The article shows the possibility of development the 3D printing. The main idea of development the advanced large format 3D printing for geopolymers is using an ergonomic printing method as well as materials research in modern filaments in the form of geopolymers. The article is focused on problems that appear during the first trials of development 3D printing technology.

The first research were connected with basic properties of the materials – key factors of effectiveness 3D printing process, such as: viscosity and time of bonding (Labonnote *et al.*, 2016; Rahul *et al.*, 2019). This basic properties are related with the thixotropic, and allow to understood as high yield strength and low viscosity behavior of the materials, including (Labonnote *et al.*, 2016; Panda and Tan, 2019):

- pumpability - reliability with which material is moved through the delivery system,
- extrudability - depositing material through a deposition device,

- buildability - resistance of wet material to deformation under loads,
- and open time - period during which the aforementioned properties remain consistently within acceptable tolerance.

The basic challenge in 3D printing is received the material that is sufficiently fluid and at the same time has sufficient viscosity to retain its shape after the printing process (Panda and Tan, 2019; Panda *et al.*, 2018). Moreover, not only the material properties decided about the possibilities of effective process. The other elements associated with technology are also important. All of this factors happen that there is only a limited understanding of the material requirements for 3D printing technology (Labonnote *et al.*, 2016; Rahul *et al.*, 2019).

2 Materials

The samples for small scale prototyping were prepared with metakaolin with pigment addition. The samples for large scale were prepared as geopolymer concrete, based on:

- metakaolin and sand (ratio: 1:1),
- fly ash and sand (ratio: 1:1).

Both raw material, fly ash as well as metakaolin, were thoroughly investigated as a possible raw material for the production of the geopolymers. The chemical composition was determined by X-ray fluorescence (WD-XRF). They oxide composition is shown in Table 1.

Table 1. Oxide composition of fly ash and metakaolin.

	Oxide composition (wt.%)							
	SiO_2	TiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	Na_2O
Fly ash	55,9	1,09	5,92	23,49	2,72	2,61	3,55	0,59
Metakaolin	53,01	0,74	1,34	41,54	0,27	0,38	0,71	0,82

Geopolymers were made from fly ash from the metakaolin or fly ash and sand in ratio 1:1. The fly ash was delivered from the bituminous coal power plant ‘Skawina’. This power plant is located in Skawina in Lesser Poland region on the south of Poland. The fly ash is obtained as combustion by-product through the electrostatic precipitation of fine particles from the exhaust gases from coal-fired furnaces. The chemical composition of this fly ash is relevant for the geopolymerization process – it is typical for class F (Łach et al., 2016). The detailed oxide composition is presented in Table1. This raw material contains less than 5% of unburned material and less than 10% of iron compounds. Additionally it has low amount calcium compounds. The amount of the reactive silica in the material is ca. 36%. Moreover, it has physical parameters relevant to geopolymers manufacturing, especially it contains a lot of spherical particles and has good workability (Łach et al., 2018) as well as large amount of amorphous phase (Łach et al., 2016). The process of activation has been made by 10M sodium hydroxide solution combined with the sodium silicate solution (the ratio of liquid glass - 1:2.5).

3 3D Printing of Small Scale Elements

Samples were prepared using sodium promoter for activation the metakaolin with some pigment addition. The trials has been made on the laboratory 3D printer for concrete – WASP 2040 with pneumatic feeder.

The samples some multilayers plate have been prepared using 3D printing method – Figure 1. The printed samples were characterized by different quality.

Figure 1. Page layout.

The most important problem was viscosity of the material. In the first trials the material was too solid and the process was impossible to print effectively (Figure 2b), but the layers in this case were created effectively. The samples had ratio between liquid and solid parts: c/s = 0.25. Because of the lack of possibility of printing the viscosity was regulated by ethanol addition. After receiving the required viscosity the main challenge was layer stability. The samples had ratio between liquid and solid parts: c/s = 0.3. This materials were very easy to printability, but the main problems was connected with lack of proper stiffness of the layers (Figure 2a), because of that the product loss they shape.

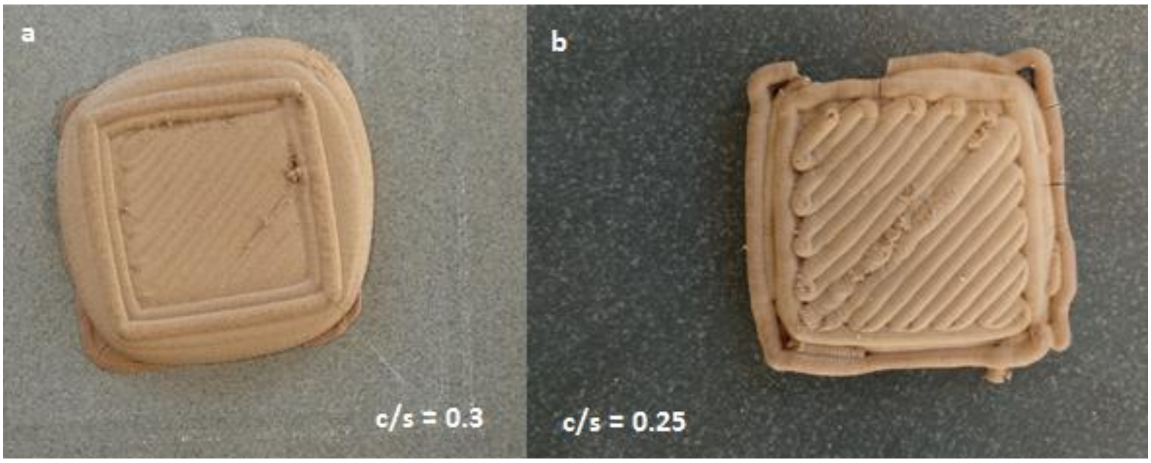

Figure 2. Samples after 3D printing with different liquid/solid ratio a) 0.3, b) 0.25.

The ratio between c/s required modification, but main problem is too long period for receiving the proper stiffness it must be analyzing once again and modify by proper addition on introducing some factors that accelerate the bonding such as additional sources of temperature (Bong *et al.*, 2019; Nematollahi *et al.*, 2019).

The other challenge was brittle material behavior after the curing time and cracking during the drying process (Figure 3).

Figure 3. Samples after drying with visible cracks.

The problem of the cracks required introducing the additives to the geopolymer. It could be for example fibers addition that reduced the brittle material behavior (Korniejenko *et al.*, 2018; Nematollahi *et al.*, 2018; Silva *et al.*, 2020).

4 3D Printing for Large-Scale Elements – Manual Prototype for 3D Printing Process

The other trials was performed on large scale samples made on the self-produced manual 3D printing machine (Figure 4). The construction given material using a rotating screw (own design for determining the optimal consistency and speed of material reproduction).

The samples were prepared using metakaolin and fly ash mixed with sand in ratio 1:1.

Figure 4. Self- produced manual 3D printing machine.

The trials were conducted on the large form with using different ratio liquid and solid parts – Figure 5.

Figure 5. Samples after 3D printing with different liquid/solid ratio a) 0.3, b) 0.25.

The achieved results did not fulfil the requirements. The samples produced with different kind of ratio were too liquid to application for building elements. The material need further modification.

5 Conclusions

The article is focused on problems that appear during the first trials of development 3D printing technology, especially materials issues. It shows similar problems that appeared for small and large scale elements as well as for different raw materials used. The most important problem was viscosity the material. It was regulated by ratio between liquid and solid parts and additives such as ethanol. This problem was partly solved, but after receiving the required viscosity the main challenge was layer stability. There are planned further work on material stabilization.

The other challenge was brittle material behavior after the curing time and cracking during the drying process. The solving of this challenge required further works, especially connecting with design of proper curing process.

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