

Comprehensive Review of 3D Concrete Printing by Using Ground Granulated Blast-Furnace Slag

Nur Syahera Jamalulail¹, Norhafizah Salleh^{1,*}.

¹Faculty of Civil Engineering and Built Environment,
Universiti Tun Hussein Onn Malaysia, Batu Pahat, Johor, 86400, MALAYSIA

*Corresponding Author Designation

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Abstract: 3D building printing is a technology for producing 3D models of an object to build any shape or size in layers by using computer software. The development of 3D printing was going to be more famous and commercial in the future to reduce the construction cost and labor demands, sustainability, and to the greenest way. Concrete is the mixture that consists of the ingredients of water, binder (cement) and aggregates (rock, sand, gravel). The productions of Portland cement in construction leads to the emissions of carbon dioxide (CO₂) gas into the air. Waste material has been used as cement replacement in this research study to reduce carbon dioxide (CO₂) gas emissions. This research study was going to evaluate the viability of concrete for 3D printing and printing emphasizing the impact on potential opportunities of this innovative industry. The behaviour of 3D concrete printing and potential of modified mortar in 3D concrete mix design by using Ground Granulated Blast-Furnace Slag (GGBS) is used to evaluate the potential uses of GGBS in concrete mixture for 3D building printing. This research study involved the review of concrete compressive strength and workability of 3D concrete printing with the control aspect during process manufacturing. The result shows that the mix design of 3D concrete printing with 30% and 40% produced concrete strength of 47.33MPa and 47.67MPa respectively. Furthermore, control aspect requirements of concrete for 3D printing were discussed in the field extrudability, flowability, buildability, strength between layers, aggregates, and water-cement ratio. Throughout this study, the manufactures of 3D building printing materials using environmentally friendly elements can contribute effectively create a sustainable environment automatically.

Keywords: 3D Printing, Ground Granulated Blast-Furnace Slag, Portland Cement

1. Introduction

Adaptive technologies have opened up new possibilities for many rapidly emerging industrial manufacturing sectors. Thanks to the flexibility factor, 3D printing has taken technologies to a new level they are also commonly used in building. Special fine-grained concrete (mortars) are necessary for the construction of real buildings and structures using 3D printing, which can ensure the safe use, robustness and resilience of buildings [1]. Concrete was the essential materials used in building construction works. Ground Granulated Blast-Furnace Slag (GGBS) have potential to replace the Portland cement as reported in many researchers. GGBS is an alternative to Portland cement for sustainable building. The substitution of GGBS with Portland cement can lead to a reduction in the production of carbon dioxide gas which can be used to substitute up to 80% of ordinary Portland cement [2]. Portland cement has usually been used in a concrete mixture as cement. The use of GGBS as waste material in concrete mixture in this research study will be carried out either for 3D building printing processes or not. Also, this research paper overlooks the participation of the numerous research institutes and concrete experts in 3D building printing. In this research reviewing the possible uses for the future use of 3D printing will be briefly studied. It explains the possibilities of innovation and advantages of mortar 3D construction printing to save money and time for future construction project technologies.

In 2014, a new chapter in construction technology began a real revolution in the construction industry as the first house was printed [3]. Today, the construction industry faces a variety of significant challenges, such as low labour productivity, a high statistical rate of construction site emergencies, and the complications of building process control. Besides, one of the largest users of non-renewable natural resources is the building industry. The use of Portland cement in the construction systems of concrete technology results in the release of carbon dioxide (CO²) gas into the air [1]. The increase in emissions of CO² gas causes warming, degrading the quality of human life. Overall, the world's production of Portland cement adds 1.6 million tonnes, or around 7%, of CO² to the atmosphere. For every 1000 kg of cement made, 900 kg of carbon dioxide is released due to the high energy output of Portland cement [4]. The invention of green concrete materials is important to minimise the use of cement. In addition to the design of the structure, in order to process the 3D building printing, the Ground Granulated Blast-Furnace Slag (GGBS) will be substituted as a Portland cement in the concrete blend (mortar).

The objectives of this study are to study the behaviour of concrete on 3D printing and potential of modified mortar in 3D mix design by using Ground Granulated Blast-Furnace Slag (GGBS). Besides, to evaluate the viability of concrete for 3D printing and printing emphasizing the impact on potential.

2. Concrete 3D printing Mix Design

The amount of GGBS is an estimate based on mix design ratio before preparing the concrete mixture. The amount of cement in concrete mixture is mix according to the different percentage to get a good quality of concrete mixture for 3D printing. The strength and workability of the mix design should be relevant and follow the criteria. Table 1, Table 2, Table 3, Table 4 and Table 5 shows the mixture of Portland cement with varying percentage of GGBS according to the different researchers.

Table 1: Mixture of Portland cement and GGBS in percentage [2]

Portland Cement	GGBS	Total cement
%	%	%
100	0	100
90	10	100
80	20	100
70	30	100
60	40	100

Table 2: Mixture of Portland cement and GGBS in percentage [4]

Portland Cement	GGBS	Total cement
%	%	%
100	0	100
70	30	100
50	50	100
30	70	100

Table 3: Mixture of Portland cement and GGBS in percentage [5]

Portland Cement	GGBS	Total cement
%	%	%
100	0	100
80	20	100
65	35	100
50	50	100
30	70	100

Table 4: Mixture of Portland cement and GGBS in percentage [8]

Portland Cement	GGBS	Total cement
%	%	%
100	0	100
70	30	100
60	40	100
50	50	100

Table 5: Mixture of Portland cement and GGBS in percentage [9]

Portland Cement	GGBS	Total cement
%	%	%
90	10	100
80	20	100
70	30	100
60	40	100
50	50	100
40	60	100
30	70	100

To get a good quality of concrete mixture, the consistency of cement should be checked through compressive strength and workability of the mix design [5]. The concrete mix must be included the characteristic of 3D printing of extrudability, flowability and buildability.

In mix design of this research study, it is focusing on the percentage of GGBS uses in the concrete mixture to build the 3D building printing [6]. Based on the literature review that has been interpreted, the percentage of GGBS uses in the concrete mixture to replace the Portland cement according to a past case study can be 10% until 90%. But, the researchers of the past case study mentioned that the 30% until 40% replacement is highly recommended in concrete mixture to achieve a good strength and workability in 3D building printing.

According to Chandra Thakur & Kumar [7], the observation compressive strength of concrete of partially replaced Portland cement with GGBS decreases at 3 days and 7 days while at 28 days, it increases giving the optimum at 40% replacement. Shreyask [2], and Talib Khalid et al. [8], believed

that at 30% - 40% replacement by GGBS, the level of compressive strength is higher than other concrete mixture. Besides, Zhou et al. [4], found that 30% replacement by GGBS gives the maximum compressive strength value. It can be proved in the Table 6 that the compressive strength at 40% replacement takes the higher strength compared to the others. Table 6 show the comparison compressive strength according to a percentage of GGBS replacement [9]. Figure 1 shows the graph of compressive strength through 3 days, 7 days, and 28 days of the concrete mixture respectively. It can be seen that the compressive strength of concrete mixture at 40% replacement was higher compared to the other concrete mixture.

Table 6: Comparison of compressive strength according to percentage of GGBS replacement [9]

Portland Cement %	GGBS %	Compressive strength (N/mm ²)		
		3 days	7 days	28 days
90	10	21.00	34.00	45.67
80	20	20.33	33.33	46.00
70	30	19.00	31.67	47.33
60	40	17.33	30.67	47.67
50	50	16.33	29.67	47.00
40	60	14.33	27.00	45.67
30	70	12.67	24.00	45.00

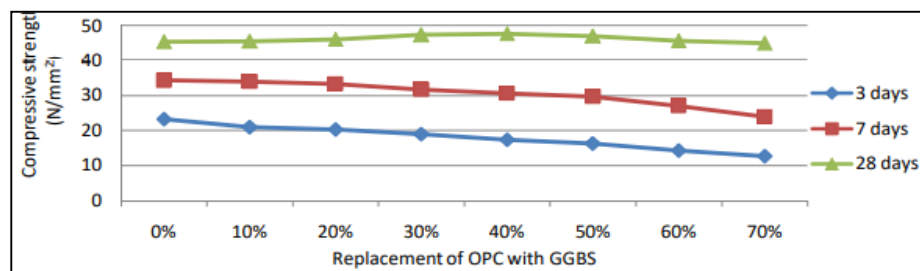


Figure 1: Graph compressive strength (N/mm²) against replacement of Portland cement with GGBS in percentage [9]

3. Concrete 3D Printing Laboratory Testing

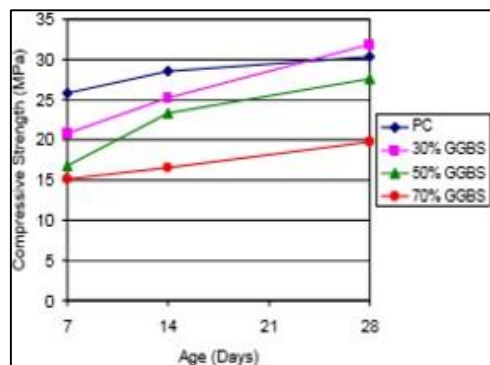
Laboratory testing for 3D concrete printing experimented by previous researchers with various types of mix design suitable for concrete mixtures. Laboratory testing on concrete mixture includes compressive strength test and workability. In order to get good concrete mixture for 3D printing, the testing that needs to be highlight for concrete mixture needs to be analysed. The behaviour of concrete strength was usually is tested by using compressive strength test to find out the workability of concrete mixture in 3D printing. The compressive test is important to find out the characteristic of concrete mixture in accordance with the criteria. All the experiments need to figure out the behaviour of concrete mixture either it is suitable or not for 3D printing.

Workability of concrete is very important because the optimum strength cannot be attaining if the concrete is not placed properly. Moreover, improper compaction and due to improper placement also can be a reason for low workability of the concrete. The workability of concrete will increases with the increase of GGBS replacement level [6]. So that the GGBS may be used to replace Portland cement which will reduce the cost and also reduce the consumption of Portland cement. The workability of concrete mixture for 3D printing will determine by slump test, flow table, Vicat test, and extrusion test. Table 7 show compressive strength according to mix design regarding different researchers.

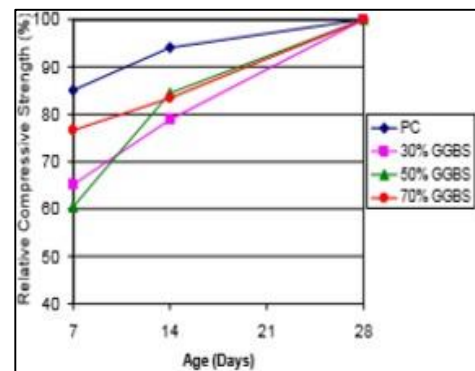
Table 7: Compressive strength according to mix design regarding to different researchers

Researcher	Mix design	Compressive strength (N/mm ²)		
		7 days	14 days	28 days
Shreyask [2]	40% GGBS + 60% Portland cement	15.70	18.25	26.45
Zhou et al. [4]	30% GGBS + 70% Portland cement	21.00	25.50	33.22
Barnett et al. [5]	35% GGBS + 65% Portland cement	16.72	23.44	48.00
Talib Khalid et al. [8]	30% GGBS + 70% Portland cement	14.23	30.06	45.10
Chandra Thakur & Kumar [9]	40% GGBS + 60% Portland cement	17.33	30.67	47.67

Based on previous studies on the use of GGBS in concrete mixture, Zhou et al. [4], have stated that GGBS possessed lower compressive strength than Portland cement at an early age but 30% of replacement GGBS in the mixture are slightly higher than Portland cement mixture. Another researcher, Talib Khalid et al. [8], stated that 30% until 40% replacement of GGBS got higher compressive strength in concrete mixture. However, the value of compressive strength getting lower when the replacement of GGBS in the mixture increase [8]. Figure 2 proved that the compressive strength of 30% replacement of GGBS is higher than the Portland cement mixture. Figure 2 show compressive strength GGBS mixture which (a) absolute strength; (b) relative strength [4].



(a)



(b)

Figure 2: Compressive strength GGBS mixture (a) absolute strength; (b) relative strength [4]

The extrusion test is usually conducted by using extrude machine which a prototype printing system with a chosen diameter nozzle, for linear extrusion as well as the base where the nozzle prints the layers of the mixture. By applying this method, the printability and buildability of the concrete mixture are going to determine as a characteristic of 3D printing process whether the mixture accepted or not. Figure 3 show the typical extrusion nozzle of 3D printing [7].

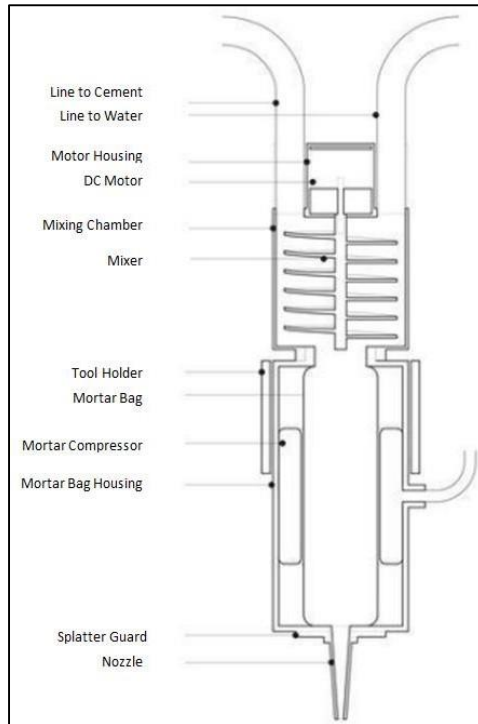


Figure 3: Typical extrusion nozzle of 3D printing [7]

4. Control aspect of 3D concrete printing

Control aspect is important to effectively print 3D printing structures, the main properties of concrete mixture needs to be considered are extrudability and flowability, buildability, strength between layers, aggregates, water-cement ratio. To achieve a stable foundation, the concrete needs to be bound within the layers when stacked on top of each other. The concrete should not be in a hardened condition, so as the concrete is placed on the surface of the previous layer, hydration of the concrete should be in progress. This factor is often linked to the workability and setting time of concrete for 3D building printing. Besides, the shape of layers of mortar should be considered to preserve the integrity of the structure and to ensure strong bonding between the layer [7]. Figure 4 show the layer of 3D printing extrusion model [7].

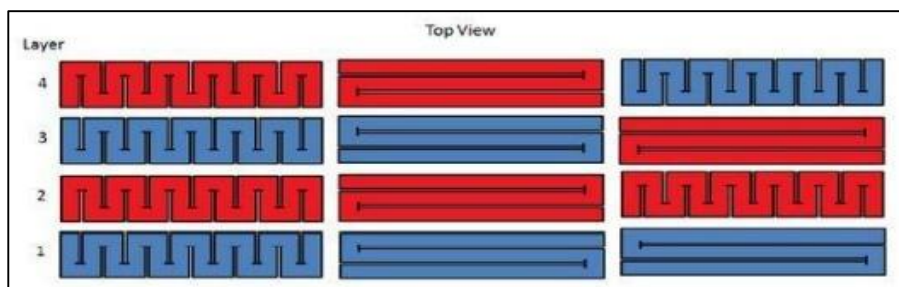


Figure 4: The layer of 3D printing extrusion model [7]

Talib Khalid et al. [8], mentioned that the mixture containing GGBS is required less water compared to mixture without GGBS. In a real application, the workability of 3D concrete printing is prone to even small variations of environmental conditions such as temperature, humidity, moisture of raw materials and others. Buswell et al. [10], mentioned that 3D construction printing a part that allows the extrusion to follow a finite path that places the material deposited, and is also repeated to create vertical height at each layer.

Other than that, Garg and Kapoor [11], also mentioned that GGBS has good effects on the workability as the water binder ratio decrease. With the content of GGBS replacement in the mixture increase, the workability of concrete will be increasing too. Table 8 show the criteria for accepting concrete mixture as printable or not [11].

Table 8: Criteria for accepting concrete mixture as printable or not [11]

Characteristic of 3D printing concrete	Accepted	Not accepted
Printability	1. The mixture is extruded through the nozzle. 2. Good printing quality meaning no voids, no dimensional variations of extruded material.	If 1 or 2 do not apply
Buildability	3. Five layers of printing material can be achieved without collapse. 4. Height of first layer versus height of fifth layer.	If 3 or 4 do not apply

The layered extrusion of concrete components allows the freshly printed material to have some unique rheological properties to successfully utilize the physical or mechanical properties of 3D printed concrete objects. The control aspect for extrudability, flowability and buildability are given in Table 9 below [11].

Table 9: Control aspect in concrete 3D printing [11]

Control aspect	Limitation
Extrudability	The capability to be extruded properly through the printing nozzle with a continuous material flow.
Flowability	The capacity to be worked and moved to the printing nozzle through a pumping system throughout a given time interval.
Buildability	The capacity to both remain stacked in layers after extrusion and sustain the weight of the subsequent layers that are deposited by the printing process.

5. Conclusion remarks

Through the case study, this research paper begins with an introduction to the assorted of 3D concrete printing technologies that are practice with waste materials which Ground Granulated Blast- Furnace Slag (GGBS). It can be inferred that the mix template for 3D printing uses 30% to 40% GGBS substitute for Portland cement. This is because many researchers typically use the compressive strength and workability of the concrete mixture with 30% up to 40% in 3D printing constructions. The technology has demonstrated its ability for 3D building printing and will become successful if the tools are applied further. Leading to the use of waste material as a cement substitute and the elimination of carbon dioxide gas emissions, the workability of the concrete mixture by using a partial percentage of GGBS is certainly recommended. In the future, the competition within contractors will increase due to demand in cheaper building and market will gradually grow the 3D building printing industry.

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