Recent Trends in Civil Engineering and Built Environment Vol. 3 No. 1 (2022) 1567-1576
© Universiti Tun Hussein Onn Malaysia Publisher's Office

RTCEBE

Homepage: http://publisher.uthm.edu.my/periodicals/index.php/rtcebe
e-ISSN :2773-5184

Comprehensive Review of Geopolymer Concrete For 3-D Building Printing

Ain Nadrah Abdul Aziz[1], **Norhafizah Salleh**[2]*

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

*Corresponding Author Designation

DOI: https://doi.org/10.30880/rtcebe.2022.03.01.175
Received 4 July 2021; Accepted 13 December 2021; Available online 15 July 2022

Abstract: The major goals for creating 3-D printed buildings are design flexibility, modification, efficiency, waste reduction, decreased workforce, and manufacturing complicated structures with less expensive materials. The most crucial features of a good 3-D printing are the fresh qualities of concrete. To sustain the succeeding layers of 3-D printing, concrete must have a high workability for extrusion, an optimal open time, and a high early strength. After a review that had been done, based on the results, there are a lot of components that affecting geopolymer concrete properties such as the amount of activator and water-to-solid ratio. Geopolymer concrete were resulting more compressive strength at 8% activator content than in 10% activator content. The highest compressive strength can go up 26.30% times more than 25 grade concrete which was only 31 MPa with Fly-ash content 30% of the mixture. The workability of geopolymer concrete was also founded that the factor of activator concentration and water/ash ratio affecting the workability. Its result based on water/ash ratio, the flow can go up to 120% with 0.16 water/ash ratio. While the higher the NaOH concentration, the lower the workability. Extrudability, flowability, buildability, strength between layers, aggregates, and the water-cement ratio were all considered as control aspects of concrete for 3-D printing. Manufacturers of 3-D building printing materials that use ecologically beneficial ingredients can automatically contribute to the creation of a sustainable environment, according to the findings of this study.

Keywords: 3-D Printing, Geopolymer Concrete, Ground Granulated Blast-Furnace Slag, Fly Ash

1. Introduction

By utilizing advanced displaying and innovation to fabricate freestyle building parts, 3-D printing of development materials can possibly challenge set up building measures. Enormous scope, concrete based added substance fabricating techniques, otherwise called 3-D substantial printing (3DCP), have been being worked on throughout the previous ten years, with in excess of 30 exploration associations overall currently included. By precisely keeping, or solidifying, specific amounts of material in successive layers utilizing a PC controlled situating measure, 3DCP disposes of the requirement for

---

*Corresponding author: nhafizah@uthm.edu.my

customary molds [1]. 3-D substantial printing is another structure innovation that has demonstrated to be useful as far as development speed, cost, plan adaptability, and blunder decrease, just as being biologically amicable. It's anything but a predesigned compositional part in 2-D layers on top of one another, with the redundancy bringing about a 3-D model. Concrete poured from a printing spout doesn't need any formwork or resulting movement [2].

Concrete is one of the world's most established and most broadly utilized structure materials, attributable to its minimal expense, wide accessibility, long solidness, and capacity to withstand cruel climate conditions. Other structure materials, like steel and polymers, are, then again, more expensive and less pervasive than concrete. Concrete is a fragile substance with solid compressive however poor elasticity. Accordingly, supporting of cement is important to permit it to withstand ductile strains. Steel is commonly utilized for such building up [3].

In this research paper, geopolymer concrete will be reviewed and researched in order to find out the usage and suitability of geopolymer concrete in 3-D building printing. It will be reviewed about the properties of the geopolymer concrete itself. For this research paper, the binder for geopolymer will be using fly-ash, granulated blast furnace slag and silica fume. It will be showed the usage of the activator to activate geopolymer concrete properties.

2. Geopolymer concrete mix design

Guidelines, laws, and codes for making a geopolymer concrete mix are still being created, however this study article may be able to glean some suggestions from the literature based on previous research efforts by other researchers. The mix percentages used by various research are shown in Tables 1, Table 2, Table 3, and Table 4, which assists in understanding the ratios in which the components can be mixed. Fly ash to GGBS ratios vary from 9 to 4, while Na2SiO3 to NaOH ratios range from 2 to 2.5, with 2.5 being the optimum ratio. elasticity.

An appropriate and acceptable mix design is required to provide the requisite strength and workable GPC. Due to the influence of numerous variables such as alkaline content, curing time and temperature, water to solid ratio, pH and molarity of activators, aluminosilicate composition and type, aluminates to silicate ratio, and silicate to hydroxide ratio in the geopolymerization process, GPC mix design is a complicated process [8].

Table 1: Geopolymer concrete mix in mass [4]

Material	Mass (kg/m³)	
Fly ash	360	320
GGBS	40	320
Na_2SiO	106.7	114.3
NaOH	53.3	45.4
Water	-	-
Superplasticizers	0	0
Coarse aggregates	1209	1209
Sand	651	651
Concrete mass (kg/m³)	-	-

Table 2: Geopolymer concrete mix in mass [5]

Material	Mass (kg/m³)	
Fly ash	408	404
GGBS	-	-
Na_2SiO	103	102
NaOH	41	41

Water	26	16.5
Superplasticizers	6	6
Coarse aggregates	1202	1190
Sand	647	640
Concrete mass (kg/m^3)	2433	2400

Table 3: Geopolymer concrete mix in mass [6]

Material	**Mass (kg/m^3)**
Fly ash	408
GGBS	-
Na_2SiO_3	103
NaOH	41
Water	15
Superplasticizers	5.6
Coarse aggregates	1202
Sand	647
Concrete mass (kg/m^3)	-

Table 4: Geopolymer concrete mix in mass [7]

Material	**Mass (kg/m^3)**
Fly ash	408
GGBS	-
Na_2SiO_3	103
NaOH	41
Water	22.5
Superplasticizers	6
Coarse aggregates	1294
Sand	554
Concrete mass (kg/m^3)	2428.5

3. 3-D printing

In recent years, many 3-DCP technologies have been developed to apply AM in concrete buildings. The cornerstones of these technologies are extrusion-based and powder-based technologies. These methods, as well as the already existing 3-DCP technologies, including the powder-based 3-DCP utilizing geopolymer developed by the authors of this study, are addressed in the following sections. The similarities and differences, as well as the benefits and drawbacks of various 3-DCP systems, are highlighted.

According to Panda and Unluer et al. [9], using River Sand with a fineness module of 2.75 resulted in mortar mixes that included one of the binder compositions investigated in that study (F90G5S5). A sand/binder ratio of 1.5 was used to make these combinations [10]. In the printing process, a 4-axis gantry concrete printer with an output speed of 80 mm/sec was employed. The geopolymer mortar was collected from a screw pump at a flow rate of 0.5 l/min. A circular 10 mm nozzle with a cross-sectional ratio (i.e., nozzle/shoe) of 0.16 was attached to the portal printer's extruder. After 7 days, the pressure force of a printed 400 x 60 mm (length x width) block was measured. Three samples were collected [11].

According to Ngo [12], the geopolymer paste was produced on a small scale using a 3-D Bioplotter inkjet printer from imagine TEC, as shown in Figure 1. The nozzle used had an internal diameter of 1.65 mm. After 5 minutes of stirring in a big Hobart mixer, the liquid was poured into special plastic syringes. This printer extrudes materials from the nozzle using a controlled pneumatic pressure at the back of the syringe. The horizontal speed of the printer's head may also be modified. The thickness of the printed layer is governed by a combination of horizontal speed, pressure, and nozzle size, in addition to the rheology of the mixture. As the 3-D printing input CAD file, Solidworks generated a 50 x 50 mm rectangular hollow column. The wall thickness was 3.5 mm, which was nearly twice the diameter of the nozzle (in order to accommodate to layers side-by-side).

Figure 1: The inkjet 3-D printer [12]

According to Malaeb et al. [13], the machine was designed to print a specimen consisting of a 77 cm 10 cm structural wall, with the objective of printing larger sections as the experiment continued. The wall was printed in two parallel lines, each having a length of 77 cm and a width of 2 cm, spaced 10 cm apart. As a consequence, the nozzle should be able to print one line parallel to the first on the longitudinal axis (x-axis) and then proceed down the perpendicular axis (y-axis). Finally, it must be able to travel along the z-axis to print layer after layer and complete the 3-D design.

4. 3-D printing Laboratory Testing

Previous researchers experimented with several sorts of mix design suited for concrete mixes in the lab for 3-D concrete printing. The following are examples of laboratory testing on concrete mixtures:

Compressive tests are used to evaluate a material's behaviour under load. The maximum stress that a material can sustain over time (constant or progressive) under a load is determined. Compression testing is commonly used to determine if a break (rupture) or a limit has occurred. Break detection may be adjusted based on the type of material being examined while doing a break test. A load limit or a deflection limit is used when executing a test to a limit.

The workability of fresh concrete was assessed using a rotating rheometer, a flow table test according to EN 1015-3 (1999), and a Vicat device according to EN 196-3 (2005). All of these tests were done out 0, 15, and 30 minutes after mixing to determine the rate at which the chosen 3-D printing system's workability declines [14]. However, a significant amount of material must be withdrawn from the printing system in order to conduct these tests, and results are obtained after the required testing period. Furthermore, the workability of 3D printing concrete in real-world applications is susceptible to even slight variations in ambient conditions (temperature, humidity, moisture of raw materials, and other).

5. Results and Discussion

5.1 Results

Mechanical properties such as compressive strength must be acceptable for a structure, in addition to the novel geopolymer mix features necessary for efficient printing. The compressive strength of geopolymer concrete can be impacted by a variety of variables. Such as the binder-to-activator ratio, the water-to-solid ratio, and so on.

Based on Nath & Sarker [15], GGBFS was introduced to a mixture of unmodified alkaline activator (40%) and an SS/SH ratio of 2.5, and the strength increased significantly after 3 days. The strength of concrete mixes containing 10%, 20%, and 30% GGBFS of total binder was 33 percent, 74%, and 110 times higher at 28 days, respectively, than the strength of the control geopolymer mixture (no slag). In other words, the 28-day compressive strength increased by about 10 MPa for every 10% increase in slag concentration. The results are depicted in the Figure 1 below. The quantity of slag content has an impact on the compressive strength.

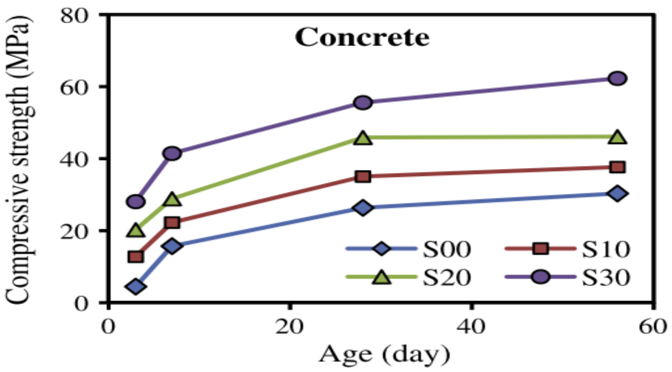


Figure 2: Compressive strength based on amount of slag content [15]

Based on Ngo [12], Different amounts of activator and water-to-solid ratios influenced the concrete's compressive strength. Figure 3 shows the compressive strength of geopolymer mixes with various quantities of activator and water-to-solid ratios after 21 days. The samples with a lower percentage of the activator (8 wt.%) were stronger than those with a greater percentage of the activator (10 wt.%).

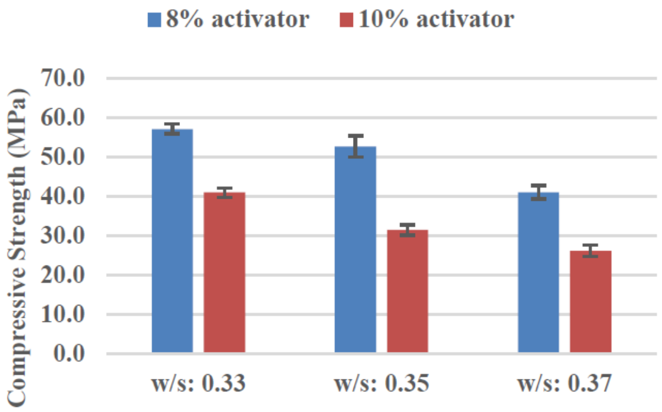


Figure 3: Compressive strength based on amount of activator and water-to-solid ratio [12]

Based on Nath & Sarker [15], GGBFS was introduced to a mixture of unmodified alkaline activator (40%) and an SS/SH ratio of 2.5, and the strength increased significantly after 3 days. The strength of concrete mixes containing 10%, 20%, and 30% GGBFS of total binder was 33%, 74%, and 110% times higher at 28 days, respectively, than the strength of the control geopolymer mixture (no slag). In other words, the 28-day compressive strength increased by about 10 MPa for every 10% increase in slag concentration. The results are depicted in the Figure 2. The quantity of slag content has an impact on the compressive strength.

Based on Phul et al [16], the compressive strength of GGBS and Fly Ash was tested at 3, 7, 14, and 28 days, as shown in Figure 4. It shows the compressive strength values obtained by changing the partial percentages of GGBS and Fly Ash on 5%, 15%, and 30%, respectively. When compared to the controlled group, the results indicated that the strength increased with time in a consistent manner with all partial percentages. In comparison to the control, the compressive strength improved as the curing days increased from SF1 to SF9 (OPC). SF9 also had a 26.30 percent higher compressive strength than the control, with a target strength of 31 MPA on 25 grade concretes. SF7, SF8, and SF9 all comfortably outperformed the necessary compressive strength.

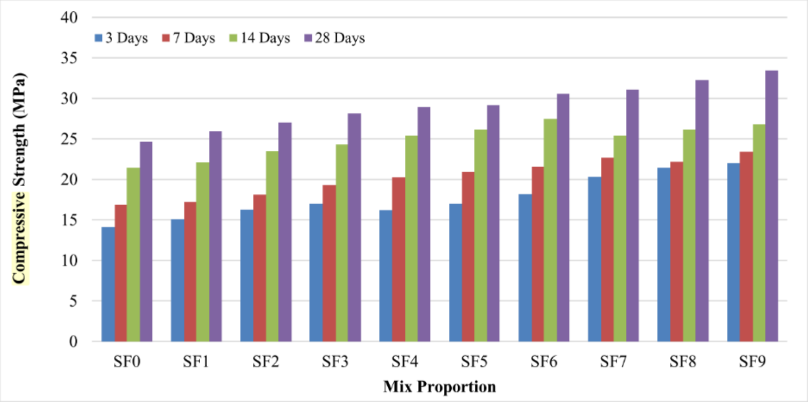
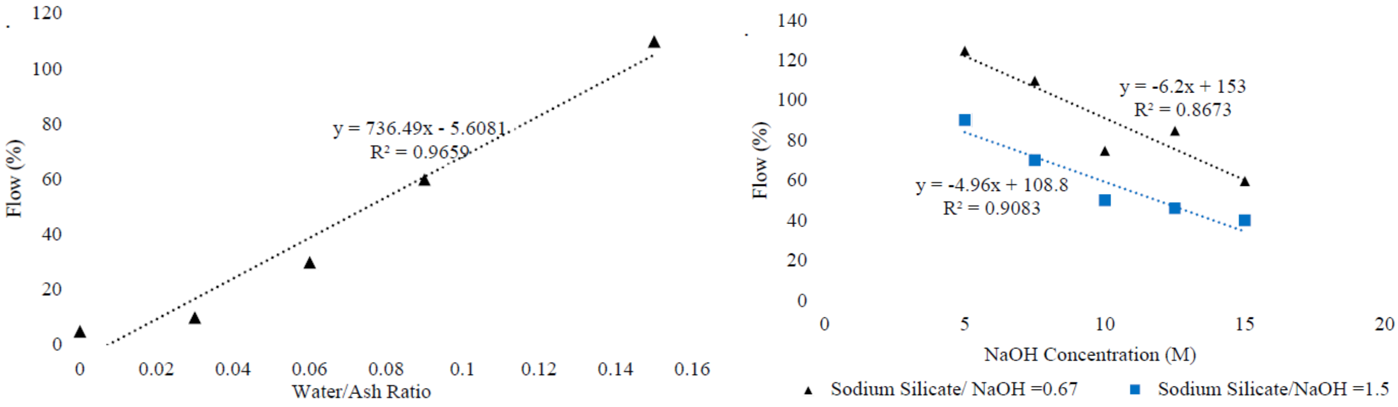


Figure 4: Compressive strength based on the percentage of the binder [16]

Flowability controls the workability of geopolymer mortar in general. The practical flow varies from 110 to 135 % (mm) depending on the concentration of activators and their respective ratios (mm) [8]. The ratio of fly ash to alkaline solution, as well as the Na_2SiO_3/NaOH ratio, impact flowability. When the viscosity of Na_2SiO_3 increases, the required ratios will require more water to produce a viable combination [17]. It was also discovered that GPC with NaOH as an activator works considerably better than mixes with NaOH and Na_2SiO_3 [18].

Several researchers looked at how superplasticizers and nanoparticles influenced geopolymer paste workability. According to Rangan et al [19], it was observed that adding a naphthalene-based superplasticizer to an FA-based geopolymer enhances its workability. It was also observed that adding silica nanoparticles decreases slump value due to a quicker reaction time and higher nanoparticle demand [20]. Based on figure shown, it shows how the concentration of activator and the water-to-ash ratio affect geopolymer sample flow. Figure 5 (a and b) shows that when the water-to-ash ratio rises, the workability rises as well, but as the NaOH concentration rises, the workability decreases due to an increase in viscosity [8]



(a) (b)

Figure 4: Flowability (a)water/ash ratio; (b) : NaOH concentration [8]

5.2 Control aspect in geopolymer concrete in 3-D building printing

The major characteristics of the concrete mixture, such as extrudability, buildability, flowability, and open time, must be addressed in order to print 3D structures effectively.

Extrudability refers to the ability to transport fresh concrete through a mixer and pumping system to a nozzle where it must be extruded in a continuous thread. Knowing what flowability is, it's self-evident that, up to a degree, higher flowability leads to better extrudability, and vice versa. This means that whatever factors reduce flowability should also reduce extrudability. Preliminary trial tests were carried out in the initial step to assess the concrete's extrudability. It's worth noting that none of the other feature matter if concrete can't be extruded. Despite the fact that all of the criteria must be satisfied, a priority order must be observed. Concrete cannot be extruded unless it is flowable, cannot be constructed unless it is extruded, cannot operate well until it is built, and does not have an open time unless one of the criteria is met [2].

Given that buildability refers to the ability of concrete levels to support themselves as well as any future top layers, counting the number of buildable layers is one way to assess it. The greater the buildability, the more concrete layers that may be stacked on top of one another before the structure deforms or collapses.

Flowability refers to the ease with which concrete flows in a system under particular conditions. The slump flow test is used to assess a concrete mix's flowability. In this test, the mixture is poured out of an inverted cone, and the time it takes for it to spread to a particular diameter is calculated. After that, the concrete flow rate may be determined. The higher the flowability and workability of the mix, the easier it expands [2].

Open time is a necessary need due to the concrete printing technique. Concrete printing disregards the mix's initial and final setting times, which are more essential in traditional concrete pouring. Because printed concrete is not poured all at once like regular concrete, some of its properties are expected to change over time from the first to the last printed layer. As a result, keeping track of the open time gives a more realistic picture of how the workability of the concrete mix changes over time. The slump flow test is used to calculate open time and flowability over certain time intervals [21].

6. Conclusion

It is widely assumed that 3-D printing will be a transformative force in manufacturing, whether in a positive or bad way. Despite worries about counterfeiting, several firms are already employing the technology to create complicated components in a repeatable manner, such as in automotive and aerospace production. As 3-D printers grow more inexpensive, they will undoubtedly be utilised for local, small-scale production, obviating the need for many sorts of supply networks. Consumer units for home usage will even be possible, allowing end customers to simply download and print a design for the product they want. The traditional manufacturing industry will have significant problems in adapting to these developments. Moreover, geopolymer technology is a fantastic way to recycle industrial waste (waste). The chemical and physical properties of source materials, alkali activators, and curing conditions all impact geopolymer production and features. At various times, many models have been offered. The early mechanical strength of a geopolymer with a dense structure is strong, and it is resistant to adverse conditions. Predicting the polymerization process is difficult since the raw materials needed to produce geopolymers come from a variety of places and include a variety of impurities. However, it can be stated that a variety of elements can influence the characteristics and mechanism of geopolymer concrete. This is due to the fact that geopolymer concrete is extremely sensitive to any type of exposure. Extrudability and flowability, buildability are the key qualities of a concrete mixture that must be addressed for 3-D printing. To produce a strong foundation, the concrete must be bonded inside the layers when piled on top of each other. The concrete should not have set, so that when it is placed over the surface of the preceding layer, hydration of the concrete is still taking place. This is one of the reasons why geopolymer concrete is currently in the experimental stage. More investigation is necessary to find the best combination for 3-D building printing with geopolymer concrete. If the study is successful, not only will the cost of building be reduced, but pollution will also be reduced, and the binder materials used will be more environmentally friendly. The technological and technical prospects are certainly vast, and the creative possibilities in product design and printing material formulation are virtually limitless.

Acknowledgement

The study would not have been accomplished without the technical help and facilities provided by the Faculty of Civil Engineering and Built Environment at Universiti Tun Hussein Onn Malaysia (UTHM).

References

[1] Buswell, R. A., Leal de Silva, W. R., Jones, S. Z., & Dirrenberger, J. (2018). 3D printing using concrete extrusion: A roadmap for research. Cement and Concrete Research, 112(May), 37–49. https://doi.org/10.1016/j.cemconres.2018.05.006

[2] Malaeb, Z., AlSakka, F., & Hamzeh, F. (2019). 3D Concrete Printing. In 3D Concrete Printing Technology. Elsevier Inc. https://doi.org/10.1016/b978-0-12-815481-6.00006-3

[3] Li, Z. (2011). Introduction to Concrete. Advanced Concrete Technology, April, 1–22. https://doi.org/10.1002/9780470950067.ch1

[4] Nath, P., & Sarker, P. K. (2014). Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. Construction and Building Materials, 66, 163–171. https://doi.org/10.1016/j.conbuildmat.2014.05.080)

[5] Sumajouw, D. M. J., Hardjito, D., Wallah, S. E., & Rangan, B. V. (2007). Fly ash-based geopolymer concrete: Study of slender reinforced columns. Journal of Materials Science, 42(9), 3124–3130. https://doi.org/10.1007/s10853-006-0523-8

[6] Sarker, P. K. (2011). Bond strength of reinforcing steel embedded in fly ash-based geopolymer concrete. Materials and Structures/Materiaux et Constructions, 44(5), 1021–1030. https://doi.org/10.1617/s11527-010-9683-8)

[7] McLellan, B. C., Williams, R. P., Lay, J., Van Riessen, A., & Corder, G. D. (2011). Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. Journal of Cleaner Production, 19(9–10), 1080–1090. https://doi.org/10.1016/j.jclepro.2011.02.010

[8] Concrete, E. G., Imtiaz, L., Kashif, S., Rehman, U., & Memon, S. A. (2020). applied sciences A Review of Recent Developments and Advances in

[9] Panda, B., Unluer, C., & Tan, M. J. (2018). Investigation of the rheology and strength of geopolymer mixtures for extrusion-based 3D printing. *Cement and Concrete Composites*, *94*, 307–314. https://doi.org/10.1016/j.cemconcomp.2018.10.0

[10] Panda, B., & Tan, M. J. (2018). Author' s Accepted Manuscript. *Ceramics International*. https://doi.org/10.1016/j.ceramint.2018.03.031

[11] Panda, B., Paul, S. C., Mohamed, N. A. N., Tay, Y. W. D., & Tan, M. J. (2018). Measurement of tensile bond strength of 3D printed geopolymer mortar. *Measurement: Journal of the International Measurement Confederation*, *113*(April 2017), 108–116. https://doi.org/10.1016/j.measurement.2017.08.051

[12] Ngo, T. D. (2019). *Optimisation of Mixture Properties for 3D Printing of Geopolymer Concrete Optimisation of mixture properties for 3D printing of geopolymer concrete*. *July 2018*. https://doi.org/10.22260/ISARC2018/0037

[13] Malaeb, Z., Hachem, H., Tourbah, A., Maalouf, T., El Zarwi, N., & Hamzeh, F. (2015). 3D Concrete Printing: Machine and Mix Design. *International Journal of Civil Engineering and Technology*, *6*(April), 14–22. http://www.researchgate.net/profile/Farook_Hamzeh/publication/280488795_3D_Concrete_Printing_Machine_and_Mix_Design/links/55b608c308aec0e5f436d4a1.pdf

[14] Papachristoforou, M., Mitsopoulos, V., & Stefanidou, M. (2018). Evaluation of workability parameters in 3D printing concrete. Procedia Structural Integrity, 10, 155–162. https://doi.org/10.1016/j.prostr.2018.09.023

[15] Nath, P., & Sarker, P. K. (2014). Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. Construction and Building Materials, 66, 163–171. https://doi.org/10.1016/j.conbuildmat.2014.05.080

[16] Phul, A. A., Memon, M. J., Shah, S. N. R., & Sandhu, A. R. (2019). GGBS And Fly Ash Effects on Compressive Strength by Partial Replacement of Cement Concrete. Civil Engineering Journal, 5(4), 913–921. https://doi.org/10.28991/cej-2019-03091299)

[17] Jumrat, S., Chatveera, B., & Rattanadecho, P. (2011). Dielectric properties and temperature profile of fly ash-based geopolymer mortar. International Communications in Heat and Mass Transfer, 38(2), 242–248. https://doi.org/10.1016/j.icheatmasstransfer.2010.11.020

[18] Mehta, A., & Siddique, R. (2017). Properties of low-calcium fly ash based geopolymer concrete incorporating OPC as partial replacement of fly ash. Construction and Building Materials, 150, 792–807. https://doi.org/10.1016/j.conbuildmat.2017.06.06

[19] J Rangan, V. B., Hardjito, D., & Wallah, S. E. (2014). Studies on Fly Ash-based Geopolymer Concrete Studies on fly ash-bas ed geopolymer concrete. Geopolymer Chemistry and Sustainable Developmnet Solution, 133–137. https://www.researchgate.net/publication/43649864_Studies_on_Fly_Ash-based_Geopolymer_Concrete

[20] Deb, P. S., Sarker, P. K., & Barbhuiya, S. (2016). Sorptivity and acid resistance of ambient-cured geopolymer mortars containing nano-silica. Cement and Concrete Composites, 72, 235–245. https://doi.org/10.1016/j.cemconcomp.2016.06.017

[21] Rahimi, M., Khoshnevis, B., & Arhami, M. (2009). Contour Crafting : A ew Automated Construction Technology and its Benefits to the Environment. 1581–1587.