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Fresh Properties and Flexural Strength of 3D Printing Concrete Containing GGBS with Varies in Water-Cement Ratio

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Abstract: In the recent years of construction industry, the need of 3D printing technologies starts to booming throughout the global and significant progress has been achieved in the development of large scale of 3D printing industry. The use of 3D printing concrete to produce structural components and buildings is extremely feasible. Freeform of building is allowed in 3D printing concrete without the necessity of high cost of formwork, which has big advantage over traditional method of pouring concrete into formwork. The aim to conduct this study is to investigate the fresh properties flexural strength of 3D printing concrete containing Ground Granulated Blast Furnace Slag (GGBS) with varies in water-cement ratio. The percentage of GGBS that used to replace the Portland cement in this study is fixed at 30% because GGBS has various benefit compare to traditional cement. The main goal of this experiment is to determine the amount of water required for cement contained with GGBS as partial cement replacement which will benefit to the largescale of 3D printing technology. The water-cement ratio varied from 0.4-0.6 with 0.05 increment. The fresh properties investigated included buildability, extrudability and flowability. The findings of this study shown that the fresh properties of the mixture increased with the increment of water-cement ratio while the hardened properties, flexural strength decreased with the increment of water-cement ratio.

Keywords: 3D printing, GGBS, fresh properties, flexural strength

1. Introduction

3D printing is increasingly commonplace throughout the globalisation. 3D printing technology is increasingly being used for mass customization and manufacture of any type of open source design in the agricultural, healthcare, automotive, and aerospace industries (Zareiyan & Khoshnevis, 2017). According to Shahrubudin et al. (2019), 3D printing has the potential to revolutionise the industries and streamline industrial processes. The utilisation of 3D printing technology will reduce costs while speeding up manufacturing. Consumer demand, on the other hand, will have a stronger influence on production. Consumers have more influence over the final product and can request that it be created to their exact specifications. Meanwhile, 3D printing technology facilities will be closer to consumers, allowing for more flexible and responsive manufacturing as well as improved quality control. Additionally, the usage of 3D printing technology might change the logistics of the firm. Logistics departments in businesses may handle the

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entire process and provide more comprehensive and end-to-end services (Rahul et al., 2019). Despite the advantage of 3D printing concrete brings to the industry, Shahrubudin et al (2019) claimed that the application of 3D printing in the construction and manufacturer labour industry will greatly affect the economies of the country as low wage jobs will be disqualified and replace by machine. Furthermore, users can manufacture a variety of objects utilising 3D printing technology, such as knives and firearms as well as hazardous materials.

On the other hand, there is no formwork necessary to support the concrete layers in 3D Printing Concrete (3DCP) and material must be pushed to the nozzle head for extrusion, and therefore the rheology of the printed material's fresh characteristics becomes critical (Paul et al., 2018). One of the new qualities of printable materials is yield strength, which is responsible for shape stability and buildability. Following extrusion in 3DCP, considerable yield strength is required to sustain the successive layers. To improve yield strength and thixotropy, a study by Panda et. Al (2019) added a little amount of nano clay to the control mixed. Thixotropic behaviour, a rheological property, can also be used to describe the new paste's shape stability. According to Paul et al. (2018), thixotropic is also known as shear given to a fresh material which lead to reduction in viscosity and followed by a gradual recovery when the shear is remove. According to Zhang et al. (2019), using a unique type of nano clay can improve shape stability. Nano clay, on the other hand, is ineffective at raising the stiffening rate, which is a limiting element in large- scale 3D printing projects' constructability (Panda et al., 2019).

Besides yield strength and thixotropy, flowability, extrudability, buildability, and open time are examined as the main features of printing materials in the fresh condition in most available literature (Li et al., 2020). They claimed that the main properties used to measure the material flow behavior during the extrusion process is the flowability and extrudability of the concrete. Controlling flowability ensures that the paste is easy to pump in the concrete pump system and easy to deposit in the deposition system (Ma & Wang, 2018). The author also claimed that in most circumstances, superplasticizers are recommended to improve the cement paste flowablity and extrudability while maintaining equivalent or higher cement strength when water content is increased. However, a larger water to binding material ratio might increase the flowability of the concrete mixtures and creates lot of pore or air void, which reduces the mechanical strength significantly (Singh et al., 2015).

The smooth grading of materials is the key to controlling extrudability of concrete material for printing concrete. The shape of the concrete of alternative raw materials should be spherical, and the particles should be fine. According to Mastali & Dalvand (2016), using round form aggregates instead of angular aggregates would allow for greater extrudability control and reduced the amount of water needed for power ratio. Malaeb et al. (2019) had also recommended similar mixture for 3D printing systems. The particle grading is quite precise. Fine aggregate to cement mass ratio of 1.28 and to the ratio of sand mass 2.0 is suggested. The fine aggregates' largest size is limited to 1/10 diameter of the nozzle of the concrete pump.

2. Cement Replacement

Nowadays, 3D printing concrete technologies have developed various type of methods such as concrete printing, contour crafting and D-shape to produce bigger structures using cementitious materials, fine aggregate, and fiber reinforcement (Al-Qutaifi et al., 2018). The current traditional construction technique, in particular, has a slew of difficulties relating to the environment, health, economy, and quality.

Concrete production, for example, is not considered environmentally friendly because Portland cement is used as the primary binder (Gao et al., 2017). Ingredients such as mineral powders and geopolymer-based materials, were employed to make 3D printed concrete in order to follow the standard cement-based materials (Xia & Sanjayan, 2016). As a result of its accessibility, energy-efficient, environmentally friendly manufacturing process, superior mechanical properties, and long durability, geopolymer cement has recently gotten a lot of attention (Mucsi et al., 2015).

According to Zhang et al. (2019), the flexural strength of cement paste can be increased by 18.5 MPa/174.5% by adding 1 vol. percent carbon 84 fibers, while the compressive strength does not change much. Ladle Furnace Steel Slag (LFS) which is also a by-product of iron steel industry can use to replace 20% of the Ordinary Portland Cement, whereas Silica Fume, (SF) replaced 10%. The use of LFS others than replace the cement, it also lowered the construction cost and prevent the concrete from shrinkage which caused by the large cement paste quantities.

Concrete with particular properties is required for 3D printing concrete. Pumpability, extrudability and buildability are the three major material properties that are used to create such combinations. Pumpability, extrudability, and buildability are the ability to pump, extrude, and sustain load of consecutive printed layers without failure, respectively (Rahul et al., 2019). El Cheikh et al. (2017), claimed that the ratio diameter greater than 4.25 between the maximum particle diameter and the nozzle diameter prevents obstruction during extrusion. According to their findings, good printing resolution and enough extrudability selecting fine aggregates with a 2 mm maximum grain size for a tiny nozzle concrete pump with a diameter of 9 mm was a reasonable choice. It is worth noting that a small nozzle reduces construction efficiency and limits the usage of coarse aggregates. According to Malaeb et al. (2019), the maximum grain size of sand is 2 mm for a tiny nozzle of 9 mm. Besides that, they also shared the idea of a fine aggregate to sand mass ratio of 2.0 and the fine aggregate to cement ratio mass of 1.28. The maximum size of an aggregate is fixed at 1/10 of the printing nozzle's diameter. By mass, 70% of cement, 20% of fly ash and 10% of silica fume is suggested as the ideal binder mixture for a high-performance printing concrete. The 3:2 sand to binder ratio was also recommended.

3. Materials and Method

3.1 Material, Mixed Design and Methods

The material that were used in this research are cement with 30% of GGBS replacement, water, fine aggregates and superplasticizer. The mix ratio of cement and fine aggregates was 1:2 and varies with water-cement ratio. The size of the prism specimen was 40mm x 40mm x 160mm for flexural strength with the curing period of 7 and 28 days. The weight of materials after the replacement of GGBS by 30% is shown in Table 1 below.

Table 1 - Proportion of materials for 6 prism

The materials	Density, kg/m^3	Replacement volume, m^3	Weight, kg
Cement	1440	0.00054	0.77
Sand	1680	0.0015	2.58
GGBS	1200	0.00023	0.27

SP = 0.5% of the weight of cement.

Water-cement ratio played a major part in this experiment. Varies of water-cement ratio could directly affect the flexural strength of the prism concrete. The water-cement ratio is stated for the specimen for example S0.4 means specimens having a water cement ratio of 0.4 and so on. The numbers of specimen placed for curing period is 3 for each 7 days and 28 days to identify the flexural strength of the prism. Table 2 shows the specimen details for each mixed.

Table 2 - Proportion of materials for 6 prism

Specimen	w/c ratio	Curing Period	
		7 days	28 days
S0.40	0.40	3	3
S0.45	0.45	3	3
S0.50	0.50	3	3
S0.55	0.55	3	3
S0.60	060	3	3
Total		15	15

Flowability test also known as flow table test was done to determine the fluidity of the fresh concrete where the aggregates size is not more than 2mm. Indeed, the ideal of this test is to eventually build a slump and collapse it, the quality of a concrete concerning of consistency and cohesiveness is determined. The procedure and principle of flowability test is performed upon the BS EN 12350-5:2019 standard. The apparatus used was as shown is Fig. 1 below. Extrudability test was conducted in this experiment to identify the suitable water-cement ratio for concrete mixture design that able to be extrude the 20 mm diameter nozzle with smooth and undefected concrete mixture layer. The concrete mixture included all the materials such as cement, fine aggregates, water, superplasticizer and GGBS. The pump was filled up with the concrete mixture and extruded through the pump as shown in Fig. 2. Meanwhile, buildability test is a test to determine the deformation speed of the concrete mixture. The concrete mixture layer that had been extruded into 5 layers was evaluated by using measuring tape to determine the height of the first layer as shown in Fig. 3.

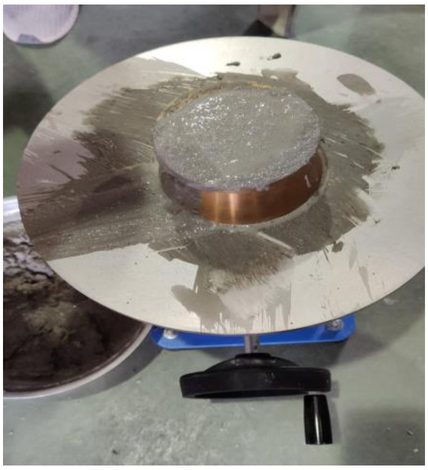

Fig. 1 - Flow ability test

Fig. 2 - Extruability test

Fig. 3 - Buildability test

4. Result and Discussion

4.1 Extrudability

Extrudability test had been conducted to determine the printing ability of the 3D printing concrete through the printing nozzle. Different water-cement ratio had shown significant different impacts on the extrudablity of the concrete. Below Fig. 4 below shown the outcomes of the test. Based on the extrudability test on 0.40 and 0.45 water cement ratio of 3D printing concrete, the mortar had failed to extrude out the nozzle even though the passing grades of fine aggregates had been reduced to 2 mm. The low water-cement ratio during the mixing process had lead the mortar to be too dry and unable to mix together between the materials which led to blockage in the nozzle. However, for the 0.50, 0.55, and 0.60 water-cement ratio, printing process was successfully carried out. For the 0.50 water-cement ratio, the mortar requires slightly higher force to extrude the mortar out of the pump and the shape also slightly inconsistent with slightly rough extrusion process. The 0.55 and 0.60 water cement ratio of the mortar are able to generate printing smoothly due to higher water content although with the same percentage of superplasticizer used in the concrete. The cohesion and viscosity of the concrete had been greatly improved by the additive of superplasticizer and the ratio of the water-cement. According to Panda et al. (2019), the author claimed that the main obstacle they had overcome was to extrude the concrete while having the ability to sustain the subsequent layer, hence they had chosen the 0.50 water-cement ratio as their control experiment. Hence, due to the extrudability outcome in the 0.50 water cement ratio, it had been selected to become the control experiment of this 3D printing concrete.

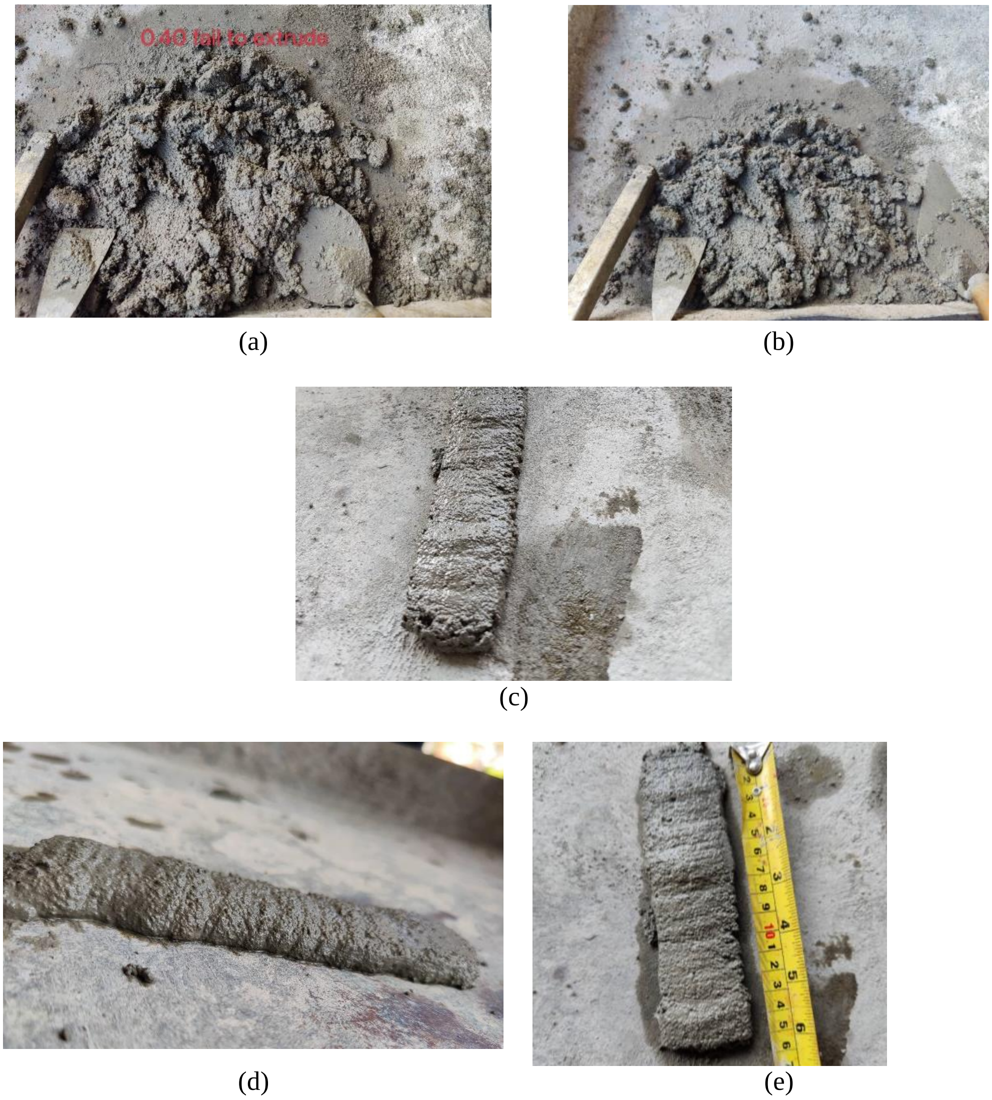

Fig. 4 - Extrudability test, (a) S0.40; (b) S0.45; (c) S0.50; (d) S0.55; (e) S0.60

4.2 Buildability

Buildability test had been carried out by evaluating the height of the 5 layers of concrete after extruded out the nozzle. According to Li et al. (2020), the author had also claimed that buildability is important as it must be sufficient to maintain the shape and the layers of the 3D printing concrete. Table 3 shows the buildability test result while Fig. 5 shows the height of initial layer for each stacking of layers of the 3D printing concrete. Based on Table 3 and Fig. 5, no data for water-cement ratio 0.40 and 0.45 because of the failure of the mortar to be extruded out of the pump. On the other hand, the 0.50 till 0.60 mixture had successfully printed the mortar out. From Table 3, it can be seen that the mixture 0.50 with an initial height of 16 mm had a total deformation height of 1.0 mm while for mixture 0.55 and 0.60, the total deformations were 1.5 mm and 2.5 mm respectively. It can be concluded that the higher the water-cement ratio, the higher the deformation of the initial layer due to the pressured by the stacking layer load. The higher water-cement ratio also indicates that the 3D printing concrete will have lesser cohesion properties, thus infect the buildability test of the result.

Table 3 - Buildability test result

Mixture (w/c)	**Height of the initial layer, h_1 (mm)**					**Deformation (mm)**
0.40	-	-	-	-	-	-
0.45	-	-	-	-	-	-
0.50	16	16	16	15	15	1.0
0.55	15	15	14	13.5	13.5	1.5
0.60	15	13	13	13	12.5	2.5

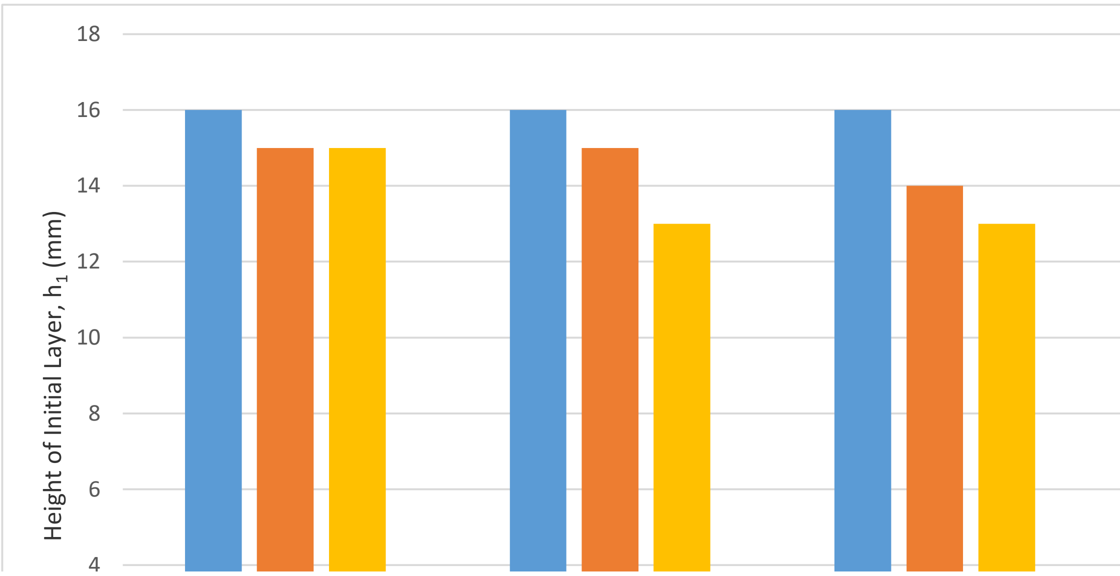

Fig. 5 - Buildability test result by layer

4.3 Flowability

Flowability is one of the most important fresh properties in the 3D printing concrete. It could be conducted by carry out the flow table test. The data and results of the experiment had been recorded in Table 4. Based on the Table 4, it had clearly shown that the flow percentage increased throughout the experiment when the water-cement ratio increase. The control experiment specimen 0.50 had gained the value of 85.0% of flow percentage. The highest amount of flow percentage in specimen 0.60 is 88.3% which is 7.3% higher than the lowest specimen, 0.40. It shows that the excessive amount of water in the mixture affect the bonding strength between the cement and the fine aggregates which make the materials easier to break off and loose. Higher moisture in the cement indicates in bigger space between the sand and the cement which also affect the flowability of the mixture.

Table 3 - Flow ability test result

Specimen	Diameter of the mixture (cm)		Flow value (cm)	Flow percentange (%)
	D1	D2		
S0.40	18.00	18.20	18.1	81.0
S0.45	18.70	18.35	18.53	85.3
S0.50	18.50	18.50	18.50	85.0
S0.55	18.80	18.70	18.75	87.5
S0.60	18.80	18.85	18.83	88.3

4.4 Flexural Strength

Flexural strength is one of the hardened properties of the 3D printing concrete and the data of the test was recorded in Table 4 and illustrated in Fig. 6. Flexural strength of concrete is also known as the ability of the concrete to resist the bending force applied by the load. There are two groups of data which is the 7 days and 28 days curing period for the 3D printing concrete. Flexural strength test results in Table 4 shows that the control specimen with water-cement ratio of 0.50 recorded 9.1 MPa at 28 days of curing. From Table 4 and Fig. 6, it was clearly seen that all specimen recorded higher flexural strength at 28 days compared with 7 days. Apart from that, the results also show that as the water-cement ratio increased, the value of flexural strength decreased. Similar trend was recorded for 7 and 28 days of curing period.

Table 4 - Flexural strength test results

Specimen	Flexural Strength (MPa)	
	7 Days	28 Days
S0.40	9.8	11.3
S0.45	8.7	9.8
S0.50	8.3	9.1
S0.55	8.1	8.9
S0.60	7.3	8.5

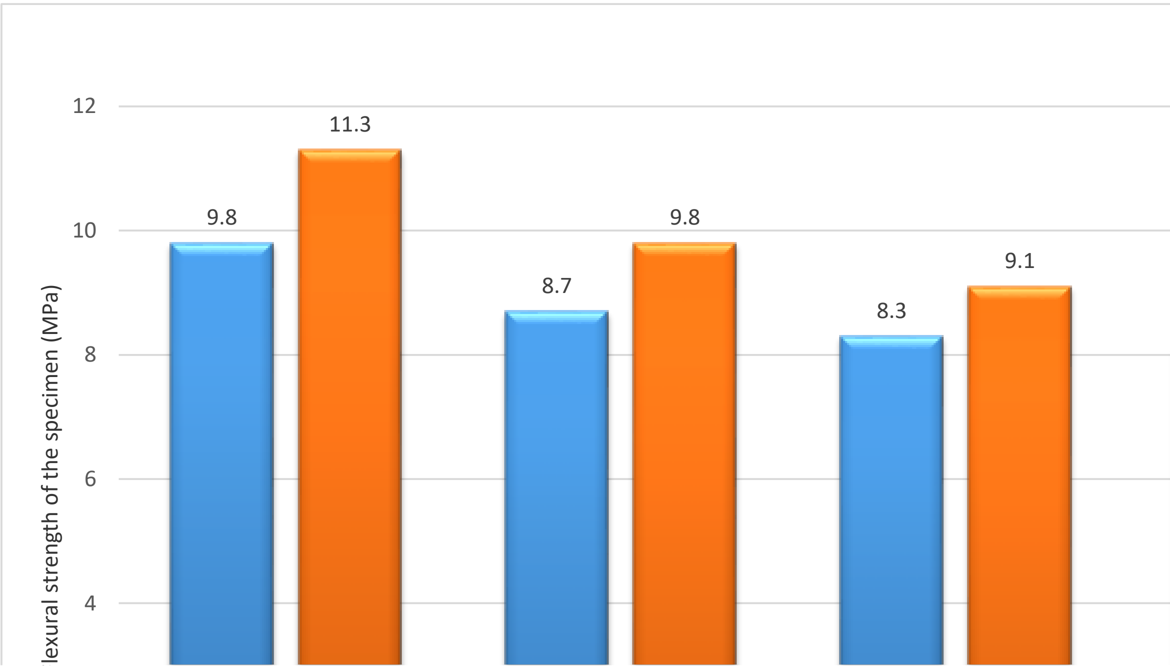

Fig. 6 - Flexural strength results

The findings of the flexural strength on the 7 days indicates that the flexural strength decrease with the higher water-cement ratio mixture. The highest value of strength is 9.8 MPa which for specimen with water-cement ratio of 0.40 due to the lowest porosity and less water to weaken the bond between fine aggregate and the cement as well as GGBS. The specimen of 0.60 water-cement ratio could only gain 7.3 MPa which is the lowest flexural strength compared with the other specimens due to the excessive amount of water in the mixture. Similar trend was recorded with the study conducted by Li et al. (2020), where the author pointed out that the lower water-cement ratio could improve the capacity of load which led to higher flexural strength. The optimum water-cement ratio of 3D printing concrete containing GGBS as partial cement replacement was chosen to be 0.50 because it recorded the highest flexural strength compared with the other specimen that able to be extruded out from the pump. Although specimen with water-cement ratio of 0.40 and 0.45 gains higher flexural strength compared with specimen 0.5, both specimens fails the extrudability test. Hence specimen with 0.50 water-cement ratio fulfil all the fresh properties and hardened properties criteria and it is the most suitable ratio for the 3D printing concrete.

5. Conclusion

The volume of water in the ratio of cement has a very big impact on the extrudability test in this 3D printing concrete experiment. The increment of water-cement ratio from 0.40 to 0.60 shows the capability of each mixture to be extruded out of the pump. The sand used which was sieved through 2 mm sieve size had also improved the extrudability of cement out the pumps. The findings in the buildability test also shown that the higher the water-cement ratio, the higher the deformation of the layers of the 3D printing concrete. Although the same dosage of superplasticizer was used, the deformation rate is still differed in each mixture. The control specimen of 0.5 water-cement ratio shows the least deformation compared with the others specimens and it had shown that it is more suitable to be used as 3D printing concrete. As for the flow table test, it had clearly shown that the higher the water-cement ratio, the higher the flowability of the mixture. This trend is due to the less cohesion between the mixtures. The overall fresh properties show that the increase in water-cement ratio also increased the fresh properties of the 3D printing concrete.

For the hardened properties of the 3D printing concrete, flexural strength test had been carried out by curing the specimens for 7 and 28 days. The data of the outcomes shows that as the curing period increased, the flexural strength also increased as predicted. The results also show that the higher the water-cement ratio, the lower the value of flexural strength. Overall, from the findings and the outcomes, the amount of water-cement ratio used significantly affected the fresh and hardened properties of the 3D printing concrete. Specimen with water-cement ratio of 0.5 gives the best performance compared with the other specimens when effects of both fresh and hardened properties was take into consideration without assessing them separately.

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