Recent Trends in Civil Engineering and Built Environment Vol. 5 No. 1 (2024) 205-215

RTCEBE

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

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

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DOI: https://doi.org/10.30880/rtcebe.2024.05.01.021
Received 23 June 2022; Accepted 01 January 2024; Available online 30 June 2024

Abstract: 3D printing is an advanced construction technology that utilizes the concept of replication material layer by layer through the nozzle head. Cement is one of the materials to produce 3D printing concrete. However, it requires concrete material to fulfill the requirement of fresh and hardened properties. The major issue that arises from this innovative technique lies in the preparation and optimization of concrete materials which possess favorable printable properties that are compatible with the 3D printer in printing. This present study evaluated the fresh properties and compressive strength of 3D printing concrete. Moreover, an optimum w/c ratio of 3D printing concrete containing 30% GGBS as partial cement replacement was determined. A series of tests such as flowability test, extrudability test, buildability test, and compressive strength test was conducted. There are 30 cube specimens under 0.4-0.6 w/c ratios were tested to obtain the compressive strength of the concrete. The flowability analysis revealed that the mixture with w/c ratio 0.5 achieved a flowability value of 204mm. In terms of extrudability, the mixture S0.50 exhibited the most satisfactory results as the printing layer achieved shape retention and extruded smoothly. The buildability of the mixture S0.50 was performed better with only 0.5mm deformation and the printed layer exhibited fewer voids and was smooth. The compressive strength of mixture S0.50 increased by 39% after 28 days of curing age. As a result, the optimum w/c ratio 0.5 was determined for the 3D printing mixture.

Keywords: 3D Printing, Fresh Properties, Water-Cement Ratio, GGBS

1. Introduction

The construction industry contributes approximately 13% of the global domestic product (GDP), making it one of the largest industries in the world. In the construction field, the building consumes 50% of the world's total resources and is the most resource-efficient industry in the world [1]. As of today,

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despite the evolution of technology until 4.0, general workers are still required in the construction field according to the perspective of the developer. A critical issue in the construction field is its aversion to change and stronghold on traditional values, along with weak demand for innovative construction methods and low productivity.

The involvement of the construction sector in the 3D printing business may be changed the image of the industry [2]. Additive manufacturing offers concrete and cement-based materials a whole new perspective. There are two types of technologies include power-based and extrusion-based additive manufacturing in the construction sector [1]. Additive manufacturing (AM) known as 3D printing prints the printable material into successive layers from a digital model [3]. In 1986, one of the earliest 3D printers, the stereolithography machine's patent, was issued to Charles Hull [4]. Since then 3D printing technology has been extensively utilized in various industries, for instance, manufacturing, aerospace, biomedical, and consumer industry [5]–[7]. It also contributes to the construction field as seen from the evidence of Canal House in Amsterdam, WinSum buildings, and Andy Rudenko's garden [8]. In addition, this technology has been adopted in many countries such as Netherland, Dubai, Saudi Arabia, and Spain [9]. Over the years, 3D printing has proved that provide massive benefits in terms of time and cost-saving, less human resources, and mitigating negative impacts on the environment. When 3D printing comes into the real life of the construction industry, the major issue that arises from 3D printing brings out different engineering challenges from the material standpoint. The issue lies within the design and preparation of printable material which possess favorable printable properties that are compatible with the 3D printer [10]. The printable material must fulfill the requirement of fresh and hardened states to ensure the printable mixtures able to travel to the delivery system and extrude from the printing nozzle. The printed layers must have adequate buildability to withstand the successive layers without deformation once the material extrudes out from the nozzle [11].

In 3D printing, Portland cement is the primary ingredient due to its inherent thixotropic property [12]. Due to escalating growth of cement production by 2.5% yearly, the amount of 2.55 billion tons in 2006 is expected to rise to 45-73% tons by 2050 [13]. Therefore, mineral additives incorporate silica fumes, fly ash, rice ash husk, and GGBS has been widely adopted as the substitution of cement with additional chemical admixture in the concrete [14]. Many types of research have been done by the researcher who reported that GGBS is a potential pozzolanic material to replace cement. The replacement of cement with GGBS can up to 80% which leads to a reduction in carbon dioxide emissions [15]. The extensive use of GGBS in Europe, United States, and Asia are due to its durability when mixed with concrete and the extended lifespan of buildings from 50 years to 100 years [16]

This study aims to investigate the fresh properties and compressive strength of 3D printing concrete containing GGBS as partial cement replacement. Besides, this finding also aims to evaluate the optimum water-cement ratio of 3D printing concrete containing GGBS as partial cement replacement.

2. Material and Method

2.1 Material Preparation

In this study, the materials used in the concrete mix design included Type 1 Portland cement, fine aggregate with a maximum size of 2mm, passing the sieving process according to BS 882:1992, fresh tap water as stated in BS EN 1008-2002, GGBS, and 0.5% superplasticizer. The preparation of the materials is illustrated in Figure 1.

(a) (b) (c)

Figure 1: (a) Portland cement, (b) Fine aggregate, (c) GGBS

2.2 Concrete Mix Design

In this experiment, the mix proportions were prepared according to the ratio of cement to sand which is 1:2. The density of cement used in the mixtures was 1440 kg/m^3 while the density of sand was 1680 kg/m^3. A fixed amount of 30% of the cement was substituted by GGBS and the density of the GGBS is 1200 kg/m^3. The replacement by weight of cement with GGBS which results in a fixed amount of 73.5g of cement and 31.5g of GGBS per cube specimen was used in this experiment as shown in Table 1. A small dosage of superplasticizers was added to enhance the performance of the mix design. The selection of the w/c used in the mixture is in the range of 0.4 – 0.6 with an increment of 0.05 as. There are 3 cube specimens with different w/c that were cured for 7 days and 28 days respectively. An average of compressive strength was calculated based on the results of the 3 specimens in each experiment. The dimension of the specimen was 50mm x 50mm x 50mm. An additional 50% to the total volume of the cube specimen to compensate for the loss of volume as some of the mixtures might stick to the tray during the mixing process and also the buildability test using the manual cement pump.

Table 1: Mix proportion of the 3D printing per cube

Mix Design	Cement (g)	Sand (g)	W/C ratio	GGBS (g)	Superplasticizer (%)
1	73.5	210	0.40	31.5	0.5
2	73.5	210	0.45	31.5	0.5
3	73.5	210	0.50	31.5	0.5
4	73.5	210	0.55	31.5	0.5
5	73.5	210	0.60	31.5	0.5

2.3 Flowability Test

In this study, the flow table test was selected to identify the flowability of the concrete in accordance with the BS EN1015-3:2004 standard. The concrete mixture used does not contain coarse aggregate. This test was conducted to identify the spread of mortar mixtures on a flat plate by determining the consistency of cement paste Before testing, the table, mold, and contact blocks must be cleaned. Then, the cone was placed centrally on the disc of the flow table. The cone was filled with mortar in two equal layers and each layer was tamped lightly at least 10 times. The flow table was then jolted 15 times constantly to allow the spread of mortar. By following the rules, the maximum horizontal concrete spread in the two directions, d_1 and d_2 were measured using a measuring tape as shown in Figure 2.

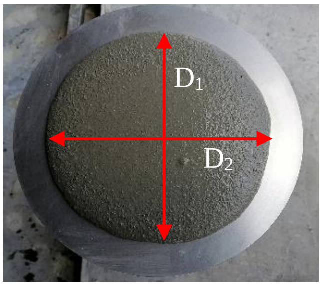


Figure 2: Dimension of the measurement of the spread

An average of flow value was calculated from the measurement of d_1 and d_2 directions and round off to the nearest 10mm. The flow value was determined by

$$f = \frac{d_1 + d_2}{2} \quad (1)$$

Where:
d_1 = maximum dimension concrete spread parallel to the flow table edge
d_2 = maximum dimension concrete spread parallel to the other flow table edge

2.4 Extrudability Test

Extrudability test was conducted to identify the ability of the concrete mixture design to be extruded out smoothly via the printing nozzle. Initially, all ingredients were mixed with the water with the addition of a small amount of superplasticizer. Then, the mixture was filled up the concrete manual pump by using the shovel and extruded out through the 15mm x 40mm rectangular nozzle as shown in Figure 3. The appearance of the printed mixture was visually examined.

Figure 3: Manual extrusion process using manual cement pump

2.5 Buildability Test

Buildability test was conducted to identify the number of printable layers that can withstand on top of each other before major deformation. This test was performed by using a manual cement pump to print the layers through the rectangular nozzle with the size of 15mm x 40mm. Initially, a mixing board was placed at the bottom before starting to print the layers. The length of the printed filaments was 150mm. The target stacking layer was set to 5 layers and the base of the layer was measured by using measuring tape after each layer deposition as shown in Figure 4.

Figure 4: Measurement of printed layers

The deformation of the base layer after each layer deposition is determined by

$$\Delta h = h_1 - h_5 \tag{2}$$

Where:
h_1 = The initial base height layer (mm)
h_5 = The base height layer after the 5th layer deposition (mm)
Δh = Deformation of the base layer (mm)

2.6 Compressive Strength Test

In this study, the compressive strength test was conducted to identify the strength of the cube samples by referring to BS EN 196-1:2016 standard. A total of 30 cube specimens with size 50mm x 50mm x 50mm were tested under different w/c. A total of 15 cube specimens will be subjected to curing in 7 days while another 15 cube specimens will be cured for 28 days respectively. The weight of each of the cube specimens will be recorded before testing. After that, the strength of the specimens was tested by using the universal testing machine. The results of the maximum load sustained by the cube specimens were recorded. The average compressive strength of the 3 cube specimens was calculated.

3. Results and Discussion

3.1 Flowability Test

The results of the flowability measurement with varying w/c ratio are presented in Table 2. The value of the diameter spread is in the range of 173.5 to 232mm. Based on Figure 5, Mixture S0.60 had recorded the highest flowability of 218mm while Mixture S0.40 had the lowest flowability of 173.5mm. A spread diameter of 186.5mm was obtained for Mix S0.45 containing a 0.45 w/c ratio. Next, the designated control mixture, Mixture S0.50 recorded a moderate flowable value of 204mm. As expected, the flowability of the mortar mixture increased with the increasing w/c ratio [17]. The researchers reported that the acceptable flow table value was between 150mm to 230mm[18], [19]. Therefore, the flow table readings obtained for all the mixtures were within the acceptable range of flowability.

Since extrudability and flowability are interrelated, therefore a good flowability mixture results in good extrudability [20]. Among the mortar mixtures, Mix S0.60 can be selected as the most extrudable mixture because it achieved the highest flowability characteristic which can be extruded through the nozzle smoothly and continuously. However, the previous research proved that the 3DPC mixture with the lowest and highest flowability is not suitable to be selected as 3DPC. The mixture with low flowability is hard to extrude as time passes because of the hydration reactions of cement which consumes the mix water and solidify the mixture [21]. Although the mixture is high in shape retention, it has more voids and a rough surface. Low flowability cement paste may form voids between filaments and cause poor adhesion between adjacent layers, resulting in poor mechanical properties [22]. Conversely, the mixture with high flowability is easy to extrude and has a smooth surface but shows low shape retention. Other than that, the mixtures measured in terms of buildability showed satisfactory results when the optimal flowable value was chosen by excluding the mixture with the highest and lowest flowability [20], [23]. As the result, the optimal flowable value is suitable to be selected as the 3DPC mixture. Therefore, Mixture S0.50 and Mixture S0.55 are suitable to be selected as the 3DPC in terms of flowability as the flowable value are not that much different.

Table 2: The relative flow table value for selected mixtures

Mixture	D_1 (mm)	D_2 (mm)	Average expansion (mm)
S0.40	172	175	173.5
S0.45	185	188	186.5
S0.50	202	206	204.0
S0.55	213	215	214.0
S0.60	231	233	232.0

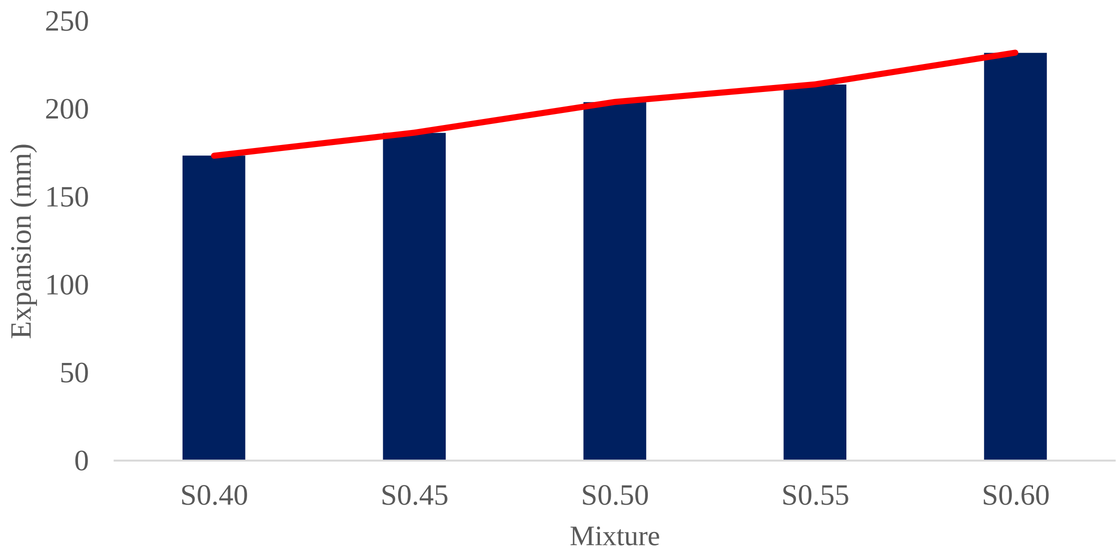


Figure 5: Flow table reading versus difference w/c ratio mixture.

3.2 Extrudability Test

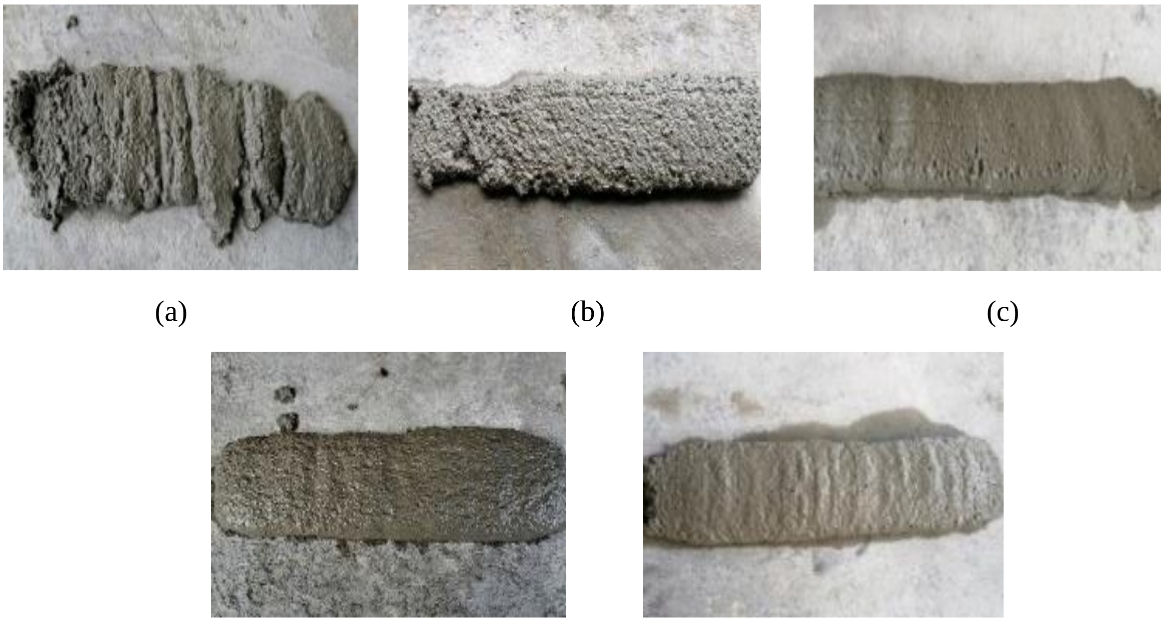
The extrudability test was conducted to identify the extrudability of the design mixture and also examined the shape of each sample through visual inspection to evaluate the printing performance using manual force. Table 3 and Figure 6 demonstrate the results and condition of the extrudable mixture.

The mixture S0.40 was tough to extrude out the nozzle because the amount of water added was insufficient to make the concrete flowable. The concrete mixture was too dried and sticky causing the friction generated between the mixture and the surface wall of the pump. Consequently, the mixture caused blockage at the nozzle even though the 2mm grain size of sand was adopted. The mixture was considered a discontinuous extrusion as many fractures were formed and blockage occurred during the extrusion process. Mixture S0.45 was managed to extrude a short distance but fracture formed in the end. The surface of the mixture was rough and consisted of voids. Therefore, it is also considered non-extrudable. Printable materials are considered extrudable if the extrusion is continuous without blockage or fracture while discontinuous extrusion is considered non-extrudable [24].

The dimension and shape of the printed sample are variable since there is no standard code to refer to for this experimental test at present [24]. Meanwhile, the mixture S0.50 to mixture S0.60 was able to extrude through the nozzle smoothly and continuously without any fractures or breaks to achieve the desired length of 15cm. In terms of extrudability, the results of mixtures S0.50, 0.55, and S0.60 fulfilled the requirement of 3DPC which is extrudable. However, mixture S0.55 and mixture S0.60 showed low shape retention due to high fluidity. The mixture with a high w/c ratio was too fluid and hard to achieve buildable though the mixture is easily extrudable [25]. Mixture S0.50 with an optimum w/c ratio of 0.50 exhibited the most satisfactory results as the printing sample achieved shape retention and the surface of the printed sample was smooth and contained fewer voids.

Table 3: Results of the extrudability test

Mixture	Results
S0.40	Non-Extrudable
S0.45	Non-Extrudable
S0.50	Extrudable
S0.55	Extrudable
S0.60	Extrudable



(a) (b) (c)

(d) (e)

Figure 6: (a) Mixture S0.40, (b) Mixture S0.45, (c) Mixture S0.50, (d) Mixture S0.55, (e) Mixture S0.60

3.3 Buildability Test

The buildability test was conducted to monitor the ability of the mixture to stack up to 5 layers. The physical appearance of the layers was identified and also the dimension of each stacked layer was measured and recorded. Table 4 illustrates the results of the buildability test while Table 5 demonstrates the results of the deformation of the base layer after each layer deposition.

Based on Table 4 and Figure 7, only mixtures S0.50, S0.55, and S0.60 were successfully stacked up to 5 layers without collapsing. Whilst, mixtures S0.40 and S0.45 failed in the extrudability test, thereby both mixtures were omitted in the buildability test. Based on Table 5, mixture S0.50 showed 0.5mm deformation during the 3rd layer deposition and remained constant till the last layer stacking. Meanwhile, the mixture S0.55 and S0.60 showed deformation upon the 2nd layer stacked on top of the 1st layer. Mixture S0.55 deformed by about 1.5mm during the 4th layer deposition whereas mix S0.60 achieved a total of 2.0mm deformation after the 5th layers were applied on it.

By analyzing the results, it can be identified that the mixture with a high water-cement ratio showed low shape retention due to high fluidity. Therefore, the mixture S0.60 showed the highest deformation among other mixes as the high w/c ratio was hard to achieve buildable. Overall, mixture S0.50 is selected as the suitable mix in 3DPC as it achieved the least deformation upon stacking 5 layers and is easily extrudable.

Table 4: Results of buildability test

Mixture	Ability to stack up 5 layers
S0.40	No
S0.45	No
S0.50	Yes
S0.55	Yes
S0.60	Yes

Table 5: Results of deformation of the base layer

Mixture	Height of the initial layer (mm)					Deformation (mm)
	1	2	3	4	5	
S0.40	-	-	-	-	-	-
S0.45	-	-	-	-	-	-
S0.50	11	11	10.5	10.5.	10.5	0.5
S0.55	11	10.6	10.2	9.5	9.5	1.5
S0.60	10	9	9	8.5	8	2.0

(a) (b) (c)

Figure 7: (a) Buildability mixture 0.50, (b) Buildability mixture 0.55, (c) Buildability mixture 0.60.

3.4 Compressive Strength Test

The compressive strength test was performed to identify the strength of the specimen under different w/c ratio conditions after 7 and 28 days curing period. Table 6 demonstrates the compressive strength of the cubic specimens while Figure 8 displays the compressive strength of the concrete against the curing period. Table 7 depicts the change in density of the concrete on different curing days.

The compressive strength for all the mixes showed an increment with the age of the curing period. Among all the mixes, S0.40 showed the best performance in terms of compressive strength of 45.3MPa after 7 days of the curing process, followed by S0.45, S0.50, S0.55, and S0.60. The strength improvement of the concrete was attributed to the low w/c ratio and curing period. As the water/cement ratio increased, many undesirable voids were created within the mass of concrete due to the exceeded amount of water. As a result, the strength of the concrete was reduced.

As for the results of 28 days of the curing period, S0.40 still recorded the highest compressive strength of 60.2MPa with an increment of 33%. Whilst S0.60 exhibited the lowest compressive strength of 46.3MPa with an increment of 39%. The increment in strength is because of the continued pozzolanic reaction with available calcium hydroxide to form extra dense C-S-H gels [26]. This is proved by the density of the specimens obtained in the experiment after 7 days and 28 days of curing period as demonstrated in Table 7.

The finding of this experiment shows that the compressive strength of the concrete increases as the water-cement ratio decreases. The highest compressive strength of concrete corresponds to a low w/c ratio and all the 3D printed mixture compressive strength exceeds 40MPa [25]. However, he furthered elaborate that flowability and buildability are the critical parameters in the 3D printing mixture.

Table 6: Compressive strength results of the specimens

Mixture	w/c ratio	Compressive strength (MPa)			Average strength (MPa)	Compressive strength (MPa)			Average strength (MPa)
		1	2	3	7 days	1	2	3	28days
S0.40	0.40	47.0	45.2	43.8	45.3	61.0	61.1	58.5	60.2
S0.45	0.45	41.7	39.6	44.1	41.8	57.3	59.7	52.8	56.6
S0.50	0.50	40.8	36.9	36.3	38.0	51.2	51.0	49.0	50.4
S0.55	0.55	34.9	36.5	33.7	35.0	50.7	49.0	49.3	49.6
S0.60	0.60	32.9	36.0	31.1	33.3	47.2	46.9	44.8	46.3

Table 7: Density results of the specimens

Mixture	w/c ratio	Density (kg/m^3)			Average Density (kg/m^3)	Density (kg/m^3)			Average Density (kg/m^3)
		1	2	3	7 days	1	2	3	28days
S0.40	0.40	2240	2240	2240	2240	2480	2480	2480	2480
S0.45	0.45	2240	2240	2240	2240	2480	2480	2480	2480
S0.50	0.50	2240	2240	2240	2240	2480	2480	2480	2480
S0.55	0.55	2160	2240	2240	2213	2400	2480	2480	2453
S0.60	0.60	2160	2160	2240	2187	2400	2480	2480	2453

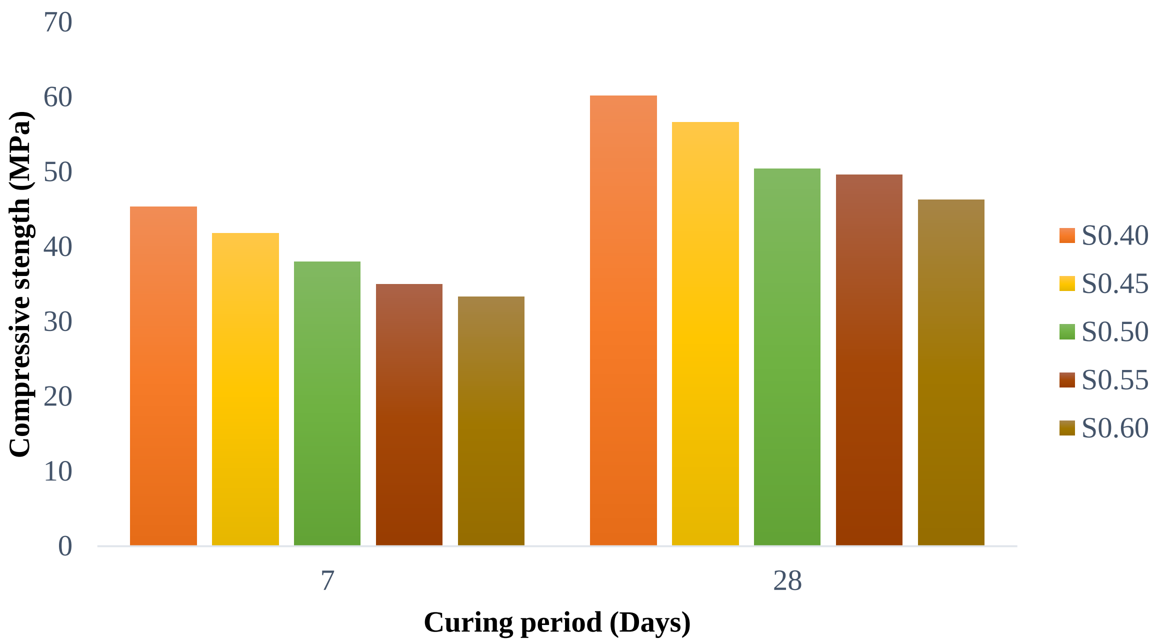


Figure 8: Compressive strength of the concrete versus curing period.

4. Conclusion

By referring to the objective of this research, all the objectives are achieved. For the flowability test, mix S0.50 had a recorded flowable value of 204mm while the flowable value of mix S0.55 was 214mm. The flowable value of both mixes was not that much different. It was proved that the mixture with optimal flowable value showed satisfactory results in terms of buildability and extrudability. Therefore, mix S0.50 and S0.55 were selected as a suitable mixture in terms of flowability. Next, the mixture S0.50 with an optimum w/c ratio of 0.50 was able to be extruded smoothly by using manual force among the mixture with low w/c ratio. Through visual inspection, the surface of the printed sample was smooth, contained fewer voids, and was able to achieve shape retention among all the mixes. Therefore, mixture S0.50 was selected as the suitable 3DPC mixture in terms of extrudability. Furthermore, mix S0.50 achieved the least deformation at 0.5mm upon stacking 5 layers among other mixtures. The stacking layers exhibited good shape retention and fewer voids which showed good buildable characteristics.

As for compression strength, all the mixes gained strength improvement from curing age 7 days to 28days and the compressive strength exceeds 40MPa. Thereby, the overall findings proved that the increment of the w/c ratio contributes to low-strength concrete. However, the optimum w/c ratio 0.50 was selected as the suitable mixture as it fulfilled the requirement of a 3DPC mixture in terms of flowability, extrudability, and buildability among all the mixtures. Overall, the experiment outcome that can be drawn from the experiment confirms the objective of the experiment.

Based on this research, several improvements can be done to obtain reliable results in future research. Firstly, the size of the fine aggregate can sieve below 2mm as the small size aggregate facilitates the flowability and extrudability of the mixture to avoid blockage to the nozzle. Next, replacing the manual cement pump with a 3D printing machine because the force applied during the extrusion process may vary with time and become inconsistent, thereby, it results in the non-uniform thickness of the extruded layer and affecting the results obtained in the buildability test. Furthermore, the flow table test can be conducted in 5, 15, and 30 minutes after mixing to identify the rate at which the flowability is lost for the given mixtures. Lastly, a study of replacement of GGBS with other SCMs materials such as pofa, fly ash, silica fume, and rice ash husk can be conducted in future studies to identify the fresh and hardened properties of the mixture.

Acknowledgement

The authors would also like to thank the Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia for its support.

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