

PAPER • OPEN ACCESS

## Investigation of the material mixtures and fiber addition for 3D concrete printing

To cite this article: A Antoni *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **907** 012011

View the [article online](#) for updates and enhancements.

The banner features a dark background with a vibrant, abstract image on the left side, showing a mix of purple, blue, and yellow colors. On the right side, the text 'IOP Publishing' is at the top, followed by 'ENVIRONMENTAL RESEARCH 2021' in large, bold, white and pink letters. Below this, it says 'A VIRTUAL CONFERENCE 15-19 NOVEMBER' in white and pink. On the far right, there are two circular buttons: 'FREE TO ATTEND' and 'REGISTER NOW', both in white text on a pink background.

IOP Publishing

**ENVIRONMENTAL  
RESEARCH  
2021**

A VIRTUAL CONFERENCE  
15-19 NOVEMBER

FREE TO  
ATTEND

REGISTER  
NOW

# Investigation of the material mixtures and fiber addition for 3D concrete printing

A Antoni<sup>1,2</sup>, A Agraputra<sup>1</sup>, D Teopilus<sup>1</sup>, A H Sunaryo<sup>1</sup>, M M Mulyadi<sup>1</sup>,  
P Pudjisuryadi<sup>1</sup>, J Chandra<sup>1</sup> and D Hardjito<sup>1</sup>

<sup>1</sup> Civil Engineering Department, Petra Christian University, Surabaya, Indonesia

<sup>2</sup> Corresponding author: antoni@petra.ac.id

**Abstract.** The era of Construction 4.0 is characterized by technological advances used in the construction industry. One of the advancements is the use of 3D concrete printing in construction. However, until now, the development of 3D concrete printing in Indonesia is still minimal. The main challenge is to determine the composition of the material mixtures for making the mortar, having good extrudability but still has sufficient strength. The rapid initial setting time required was also different for the concrete for typical construction. Our previous mixture composition incorporating calcium oxide to accelerate the initial setting time was adequate. However, the extrusion process was still not satisfactory. In this study, the effect of cement to sand ratio, sand particle size, and the addition of synthetic micro-fiber was investigated on the main properties of 3D printing materials, i.e., initial setting time, flowability, extrudability, and compressive strength. It was found that using smaller maximum particle size sand increases the initial setting time. The addition of synthetic microfiber reduces the strength and the workability of the mortar. However, fiber inclusion has advantages as it reduces the possibility of cracking in the printed concrete. The extruded concrete specimens were shown to have significant strength reduction due to lack of compaction, and it was affected by the direction of printing showing orthotropic properties of the 3D printed concrete.

## 1. Introduction

Amid fast-paced technological advances, the construction sector has begun to adopt current technology, which can increase the productivity and quality of the products produced. One of the technologies that are developing and used is additive manufacturing, or what is commonly known as 3D concrete printing. In Indonesia, 3D concrete printing technology is uncommon in construction activities, in contrast to the developed countries. Developments related to 3D concrete printing technology, both in terms of tools and materials, have enormous potential so that this technology can be used collectively in the future.

Over the last few decades, 3D printing technology has attracted the world's attention because of its ability to convert computer drawings into real objects [1]. The advantage of 3D concrete printing technology is that it can make concrete elements or structures without using formwork. The costs incurred can be more reduced, especially for high complexity and irregular shapes.

The characteristics that need to be considered for the 3D concrete printing materials are extrudability and buildability [2,3]. Extrudability is the material's ability to get printed out of the pump without obstruction and maintained a shape consistent with the shape of the nozzle. Buildability is the ability of a material to maintain its shape while withstanding the load of the subsequent layer. It is



necessary to have a collection of admixture and supplementary cementitious material so that the fresh and hardened characteristics of the concrete can be modified easily to achieve extrudable and buildable material.

In general, 3D concrete printing materials use a high cement to sand ratio, resulting in the concrete having excessive compressive strength and expensive costs. The previous study conducted by Antoni et al. [4] experienced several problems, such as unsatisfactory extrusion process and cracks in the 3D printing material. The cracks that occur were found in the second layer and so on. This could be due to the uneven surface of the previous layer. Cracks in hardened concrete could also be because of the higher shrinkage of the concrete due to high cement content.

In this study, the cement to sand ratio was reduced to reduce the cost of the material. Synthetic microfiber was used to reduce crack problems. This study aimed to investigate the effect of the cement-to-sand ratio, the maximum particle size of the sand, and the addition of synthetic micro-fiber on the fresh and hardened concrete. The tests that were carried out were workability, initial setting time, extrudability, and compressive strength. The compressive strength of the cube specimens was also compared to the extruded samples.

## 2. Materials and mixtures

The materials used were silica sand, calcium oxide (CaO), Portland cement, synthetic micro-fiber, and admixtures such as accelerators and superplasticizers. Portland composite cement (PCC) was obtained from Semen Indonesia. The PCC has a specific gravity of 3.15 measured based on ASTM C188 [5], and the normal consistency test of the PCC was measured at a water-to-cement ratio of 0.33 based on standards ASTM C187 [6]. The use of graded silica sand was intended to ensure consistent workability. In this study, two gradations of the silica sand were used, with a maximum size of 0.425 mm and 0.150 mm. The use of CaO was chosen to accelerate the initial setting time of the concrete. The silica sand and CaO was obtained from the Tuban quarry, East Java.

The addition of polypropylenes micro-fiber (diameter of 0.3 mm and length of 6 mm) was intended to reduce cracks in the extruded concrete. The fiber used was 0.3% mass of the total mixture. The admixtures used were superplasticizer (Sika Viscocrete 1003) and accelerator (SikaCim). The superplasticizer was added as much as 1% of the cement mass to obtain a flow diameter of 15 cm to 21 cm, based on Tay, Qian, et al. [8]. The CaO of 10% and accelerator of 4% of the cement mass are based on Antoni et al. [4]. The accelerator was used to increase workability and get a faster initial setting to get a better buildability.

The mix design is shown in Table 1. Notations "B" and "K" were for the maximum particle size of 0.425 mm and 0.150 mm. The following code was for the mass ratio of cement (C), sand (S), and also "F," denoting the addition of polypropylene synthetic micro-fiber in the mixture.

**Table 1.** Mix design for the 3D printed concrete for one cube specimen.

Mixture code	Max sand particle size	w/c	Cement (gr)	Sand (gr)	PP fiber (gr)	Sp (gr)	Cao (gr)	Accelerator (gr)
B_C3S2	0.425 mm	0.3	147	98	0	1.47	14.7	5.9
B_C3S2_F		0.3	147	98	0.9	1.47	14.7	5.9
B_C1S1		0.3	122.5	122.5	0	1.22	12.2	4.9
B_C1S1_F		0.3	122.5	122.5	0.9	1.22	12.2	4.9
K_C3S2	0.150 mm	0.3	147	98	0	1.47	14.7	5.9
K_C3S2_F		0.3	147	98	0.9	1.47	14.7	5.9
K_C1S1		0.3	122.5	122.5	0	1.22	12.2	4.9
K_C1S1_F		0.3	122.5	122.5	0.9	1.22	12.2	4.9

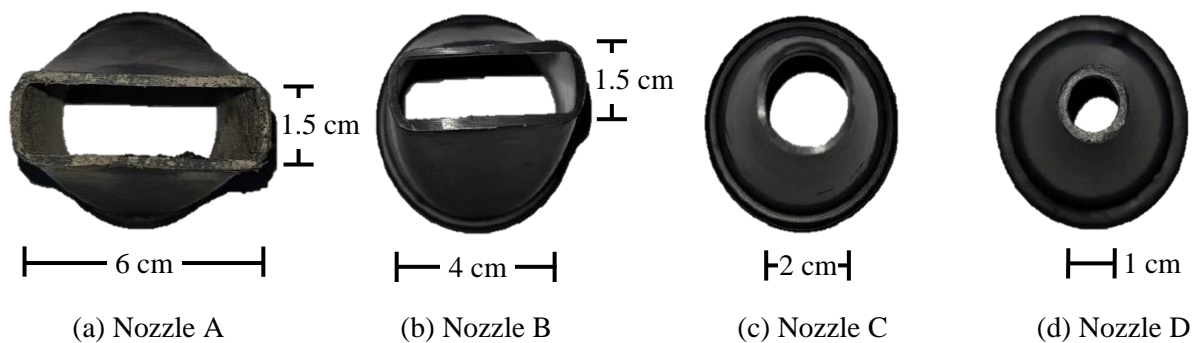
### 2.1. Equipment

The 3D concrete printing equipment in this research was modeled using a mortar extruder. The equipment for the material testing is shown in Figure 1. The plywood table was used to secure the concrete extruder, and the extrusion process was carried out from the top of the table. The moving bed consists of several multiplex stacks that can be adjusted in number to adjust the distance of the concrete printed from the nozzle and the printing bed itself. This simple contraption was used before using machine-controlled movement that was currently still in the construction process.

The concrete extruder uses a nozzle on its end with four types of nozzles (Figure 2). These nozzles have different hole areas, so differences in the extrusion process can be analyzed with different nozzle shapes and areas. The A nozzle has an opening area of  $9 \text{ cm}^2$  ( $6 \times 1.5 \text{ cm}$ ), the B nozzle has an opening area of  $6 \text{ cm}^2$  ( $4 \times 1.5 \text{ cm}$ ), the C nozzle has an opening area of  $3.14 \text{ cm}^2$  ( $\phi 2 \text{ cm}$ ), and the D nozzle has an opening area of  $1.57 \text{ cm}^2$  ( $\phi 1 \text{ cm}$ ).



**Figure 1.** 3D printing equipment model.



**Figure 2.** Nozzle size and shape for the extrudability test.

### 2.2. Mixing method

The mixing process was started by dry mixing the cement and sand evenly, and then water was poured into the mixture and then stirred using a handheld mixer. Accelerator and superplasticizer were added to the prepared mixture slowly while still stirring the mixture. Then, calcium oxide was added to the mortar mixture, and lastly, synthetic micro-fiber was added and mixed until homogenous.

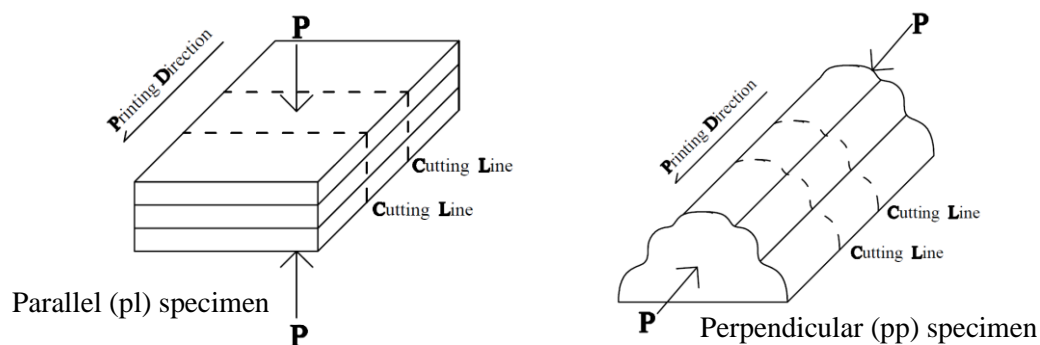
### 2.3. Testing

The initial setting time of fresh concrete using a penetrometer based on ASTM C403 [10]. The initial setting time suitable for 3D concrete printing is under 90 minutes [11]. The workability of the mortar was measured in the flow table test method based on ASTM C230 [12]. A recommended flow diameter for 3D concrete printing is between 13 cm to 21 cm [8]. The compressive strength test was

carried out on a hardened concrete cube with a 5 cm based on ASTM C109 [13]. The compressive strength tests were done on the 3, 7, 14, and 28 days with three replications.

An extrudability test was carried out to evaluate the process of printed concrete from the nozzle. The consistency of the extruded concrete through the nozzle and the hardened concrete was observed. This test was only done for the concrete mixture with the highest flow diameter but under 21 cm. In this study, the B\_C1S1 and B\_C1S1\_F mixtures were chosen for the extrudability test. The test was carried out with a constant distance of 3 cm between the nozzle and the printing bed.

The compressive strength test was also performed on the extruded samples by cutting them into several parts at 28 days. The given compressive load is divided into two directions, namely parallel to the cross-section of the layer (pl) and perpendicular to the cross-section of the layer (pp), as shown in Figure 3. This division was based on the surface of the layer. The flat surface was tested with load directed parallel to the cross-section of the layer. In contrast, the uneven or irregular surface was tested with load directed perpendicular to the cross-section of the layer. The compressive strength was calculated from the average value of the cut specimens.



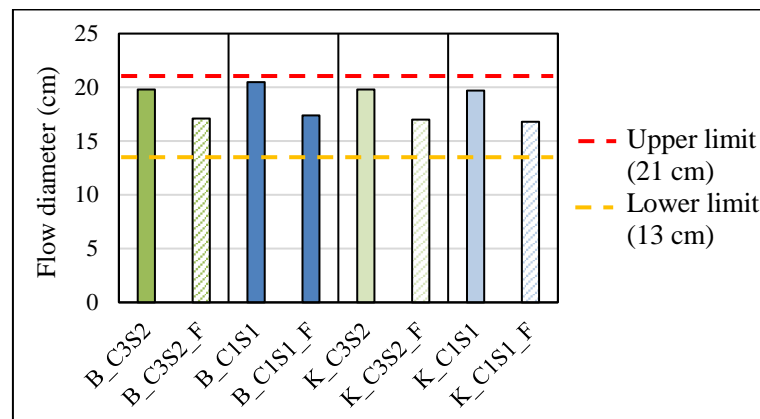
**Figure 3.** Compression load given directed parallel (pl) and perpendicular (pp) to the cross-section.

### 3. Result and discussion

#### 3.1. Workability

Workability test was done by testing the flow diameter of each mix design combination based on ASTM C230 / C230M-03 [12]. The larger the diameter of the flow, the higher the workability of the concrete, which means that the concrete will flow more quickly in the pump. The feasible flow diameter for the 3D concrete printing needs to be controlled to be between 13-21 cm. This limitation is determined so that the concrete mixture also has good buildability. The results of the flow table test can be seen in Figure 4.

From the test results presented in Figure 4, it is found that with the addition of the micro-fibers, the flow diameter of the mixture is reduced by an average of 2.8 cm, as in the example of B\_C3S2 compared to the B\_C3S2\_F mixture. The difference in sand particle size does not have a significant effect on the flow diameter. Finally, with the increasing cement to sand ratio, the flow diameter of the mixture decreases. The higher viscosity of the higher cement to sand ratio reduced the workability of the mixture. Less cement content in the mixture was still possible to obtain a cohesive mixture. However, the cement to sand ratio lower than one would cause separation of the extruded mixture, and an additional admixture to overcome segregation is needed. All mixtures investigated met the requirement for 3D printing according to Tay et al. [8], which proposed that a feasible flow diameter for 3D concrete printing is between 13-21 cm.

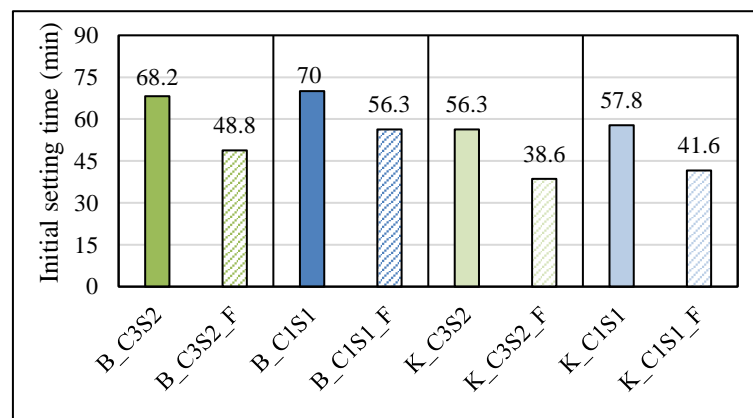


**Figure 4.** Workability of the mixture.

### 3.2. Initial setting time

The initial setting time test was carried out using a penetrometer based on ASTM C403 [10]. The test was done on the fresh mortar, and the initial setting time was calculated from the time for the penetrometer to reach 3.45 MPa (500 psi) of pressure for 25.4 mm insertion. The results of the initial setting time are shown in Figure 5. It was found that the addition of micro-fibers accelerated the initial setting time of the concrete. The result was consistent for all mixtures with a 20-30% reduction of the setting time when fiber was added to the mixture.

Furthermore, the smaller maximum sand particle size also had accelerated initial setting time, for example, the faster setting time for the K series compared to the B series. This condition could be due to the higher surface area of the sand particle, hastening the drying of the mortar. All mixtures met the initial setting time requirement for 3D concrete printing of under 90 minutes, according to Kim et al. [11].



**Figure 5.** Initial setting time for the mixture.

### 3.3. Extrudability

For the extrudability test, two mixtures were selected for testing, namely B\_C1S1 and B\_C1S1\_F. The B\_C1S1 was chosen due to its higher flow diameter than other mixtures, and the B\_C1S1\_F to show the influence of fiber in the extrusion process.

This test was carried out with three types of nozzles A, B, and C because the material cannot be extruded using nozzle D due to its small opening. Smaller nozzle opening required higher mixture workability and needs to be investigated further when fine printing resolution is needed. For the current testing, a larger nozzle area seems more suitable for the current mixture. The extruded concretes are shown in Figure 6 to Figure 11.



The tests conducted found that the mixture without synthetic micro-fiber has more cracks than the mixture that used synthetic micro-fiber. The cracks occurrence can be seen in Figure 6 (mixture B\_C1S1 without synthetic micro-fiber using nozzle A). It can be seen from the figure that there are quite a lot of cracks, while the extruded concrete was better in Figure 9 (mixture B\_C1S1\_F with additional synthetic micro-fiber using nozzle A). The extrusion process was not very smooth due to the manual setup. However, the process aims to examine the extrusion process, and it is equivalents to the real setup when using machine-controlled movement.



**Figure 6.** Mixture B\_C1S1 printed with nozzle A.



**Figure 7.** Mixture B\_C1S1 printed with nozzle B.



**Figure 8.** Mixture B\_C1S1 printed with nozzle C.



**Figure 9.** Mixture B\_C1S1\_F printed with nozzle A.



**Figure 10.** Mixture B\_C1S1\_F printed with nozzle B.



**Figure 11.** Mixture B\_C1S1\_F printed with nozzle C.

In the extrusion results, the average layer thickness was measured for every three layers. Table 2 shows the average thickness of the extruded layer. The measured thickness in hardened concrete showed the buildability of the concrete. However, the current setup cannot be used for the buildability examination due to the un-even extrusion process and difficulty in controlling the extrusion speed. The factors that may affect the extrusion process are the dimension of the nozzle, the speed of the horizontal motion in relation to the extrusion speed, the distance between the nozzle and the printing bed, and the constancy of the pressure applied on the concrete extruder.

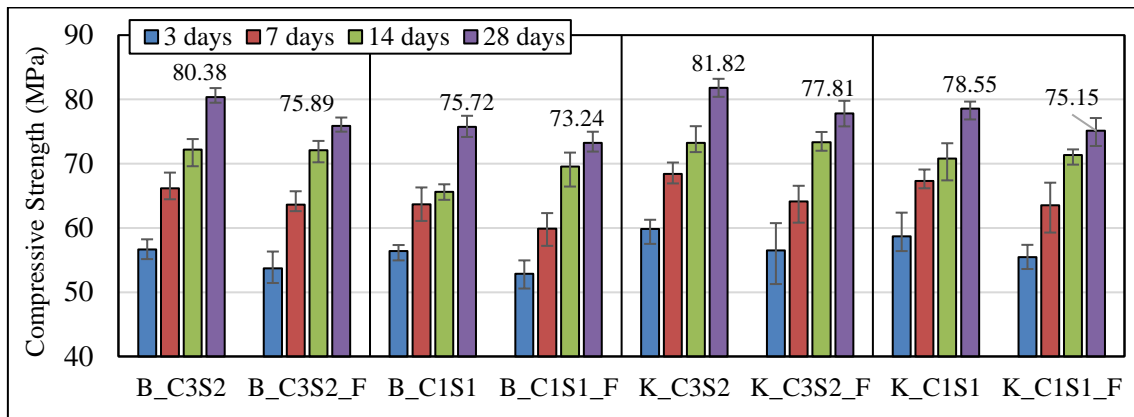
**Table 2.** The average thickness of 3 layers for each mixture.

Code	Nozzle type	The average thickness of 3 layers
B_C1S1	Nozzle A	1.5 cm
	Nozzle B	1.5 cm
	Nozzle C	1.6 cm
B_C1S1_F	Nozzle A	1.4 cm
	Nozzle B	1.4 cm
	Nozzle C	1.5 cm

### 3.4. Compressive strength

The results of the concrete compressive strength test for the cube specimens can be seen in Figure 12. Three replications were done for each testing date. Higher compressive strength was observed for the higher cement content and smaller maximum particle size in the mixture. Meanwhile, using synthetic micro-fiber in the mixture reduced the compressive strength by an average of 5.19% compared to one without micro-fiber. The addition of fiber tends to reduce the workability and increase the inclusion of air voids during the mixing process.

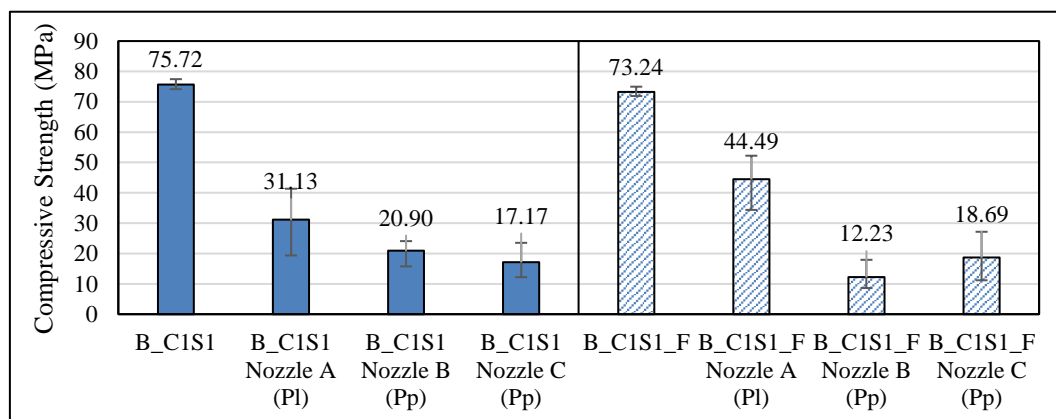




**Figure 12.** The compressive strength of the cube specimens.

Figure 13 shows the compressive strength of the extruded sample compared to the cube specimens. The results showed a very significant reduction of strength for the extruded samples. Strength reduction for the B\_C1S1 mixture with the compressive strength of 75.72 MPa was reduced to 31.13 MPa, 20.90 MPa, and 17.17 MPa when extruded using nozzle A, nozzle B, and nozzle C, respectively.

The strength reduction was less for the B\_C1S1\_F fiber mixture, showing a reduction of compressive strength of 73.24 MPa to 44.49 MPa, 12.23 MPa, and 18.69 MPa for the nozzle A, nozzle B, and nozzle C, respectively. Without compaction, the extrusion process would affect the hardened concrete drastically. The voids in the fresh mixture were extruded with the concrete and hardened as air void in the mixture.



**Figure 13.** Compressive strength of extruded specimen compared to the cube specimen.

The extruded concrete specimen loaded with a parallel (pl) compressive load to the specimen's cross-section has greater compressive strength than specimens with a perpendicular (pp) compressive load. The difference in strength showed that the extruded concrete has an orthotropic property depending on the extrusion direction and loaded surface. The parallel specimen was shown to have higher compressive strength when tested. The load applied perpendicularly affects the strength of the bond between the specimen layers, in contrast to the parallel load where the bond strength between layers is not reduced but improved.

#### 4. Conclusion

- The mixture with a higher cement-to-sand ratio has greater compressive strength and a smaller flow diameter because of the fresh mixture's higher compaction and high viscosity. The

increase in the cement-to-sand ratio also causes the concrete to have a slightly faster initial setting time.

- The use of sand with a smaller particle size could result in a faster initial setting time. The difference in sand particle size did not affect the compressive strength and workability of the mixture investigated in this study.
- The addition of synthetic micro-fibers accelerated the initial setting time, reduced the workability of the mixture, and decreased the compressive strength of concrete by 5.19% compared to the mixture without the micro-fibers. However, micro-fiber can be beneficial as it reduces microcracks that occur in the extruded concrete.
- The extruded concrete showed to have a significant strength reduction compared to the compacted cube specimen. Without compaction, the concrete could trap many air voids and was not freed in the casting process.
- There is an effect in the load direction on the compressive strength of the extruded concrete. The 3D printed concrete loaded parallel or perpendicular to its printing direction could have different compressive strengths. The bond between each layer, extrusion pressure from the subsequent layer, and the setting time of the mixture would play a significant role in controlling the compressive strength.
- All mixtures selected met the requirement in setting time and workability for the 3D concrete printing process. The B\_C1S1\_F mixture achieved the desired properties for the extrusion process. However, depending on the extrusion machine setup and nozzle size, the mixture needs to be readjusted to have the required workability.

### Acknowledgments

The authors are grateful for the funding provided by the Deputy for Research Empowerment and Development, Ministry of Research and Technology/National Research and Innovation Center, the Republic of Indonesia under PDUPT scheme no. 001/SP2H/LT-MULTI-PDPK/LL7/2021.

### References

- [1] Jo J H, Jo B W, Cho W and Kim J H 2020 Development of a 3D Printer for concrete structures: laboratory testing of cementitious materials *International Journal of Concrete Structures and Materials* <https://doi.org/10.1186/s40069-019-0388-2>
- [2] Khan M A 2020 Mix suitable for concrete 3D printing: a review. *Materials Today: Proceedings*. <https://doi.org/10.1016/j.matpr.2020.03.825>
- [3] Natanzi A S and McNally C 2020 Characterising concrete mixes for 3D printing in Bos F, Lucas S, Wolfs R and Salet T (eds) *Second RILEM International Conference on Concrete and Digital Fabrication* RILEM Bookseries vol 28. Springer, Cham. [https://doi.org/10.1007/978-3-030-49916-7\\_9](https://doi.org/10.1007/978-3-030-49916-7_9)
- [4] Antoni A, Widjaya D C, Wibowo A R K, Chandra J, Pudjisuryadi P, and Djwantoro Hardjito 2021 Using calcium oxide and accelerator to control the initial setting time of mortar in 3D concrete printing *Lecture Notes in Civil Engineering* Manuscript submitted for publication.
- [5] ASTM C188 2003 Standard test method for density of hydraulic cement (Reapproved 2003), *ASTM International* West Conshohocken, PA
- [6] ASTM C 187 2004 Standard test method for normal consistency of hydraulic cement *ASTM International* West Conshohocken, PA
- [7] Millán-Corrales G, González-López J R, Palomo A and Fernandez-Jiménez A 2020 Replacing fly ash with limestone dust in hybrid cements *Construction and Building Materials* <https://doi.org/10.1016/j.conbuildmat.2020.118169>
- [8] Tay Y W D, Qian Y and Tan M J 2019 Printability region for 3D concrete printing using slump and slump flow test *Composites Part B: Engineering* <https://doi.org/10.1016/j.compositesb.2019.106968>

- [9] ASTM C494 2015 Standard specification for chemical admixtures for concrete *ASTM International* West Conshohocken, PA
- [10] ASTM C403/C403M-99 1999 Standard test method for time of setting of concrete mixtures by penetration resistance *ASTM International* West Conshohocken, PA
- [11] Kim K, Park S, Kim W S, Jeong Y and Lee J 2017 Evaluation of shear strength of RC beams with multiple interfaces formed before initial setting using 3D printing technology *Materials* <https://doi.org/10.3390/ma10121349>
- [12] ASTM C230 / C230M-03 2003 Standard specification for flow table for use in tests of hydraulic cement *ASTM International* West Conshohocken, PA
- [13] ASTM C109/C109M 2007 Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens) *ASTM International* West Conshohocken, PA