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A Review of Fresh Properties of 3D Printing Construction Material

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Abstract: 3D printing in construction is a good approach as 3D printing concrete able to harden in short period of time after being produced and the use of formwork is not required. This situation will reduce the construction waste as well increase the efficiently of work. Therefore, the characteristics of 3D material in fresh state is important to fulfilled as printable material. This paper reviews the fresh properties of 3D printing in construction involving the flowability, extrudability and buildability. Any experimental testing related to the flowability, extrudability and buildability of 3D printing will be included as data for the fresh properties. The main objective of this paper is to conduct comprehensive review on fresh properties of 3D construction material for future researches. The findings indicate that the experimental tests that can be applied in determining the flowability of 3D construction material are slump test, flow table test and rheological properties of 3D products, involving the yield stress, plastic viscosity and green strength. Another experimental tests in determining extrudability and buildability were also discussed in this paper.

Keywords: 3D Printing, Flowability, Extrudability, Buildability

1. Introduction

3D printing has been used widely as an application to be applied in industry including construction industry. The idea to apply 3D printing in construction is to overcome certain problems occur in the construction such as time consuming, minimize construction waste and reduce labor cost. 3D printing will able to work longer than a person in building a structure as machine can operate longer than people and simultaneously reduce labor cost [13]. The operation of 3D printing machine is quite simple, setting up the machine, place the coordination to the machine and let it operate. 3D printing concrete will able to harden immediately after being produced and the use of formwork is not required. In normal

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construction proses, a formwork can only be use up to two and three times before being considered as a construction waste. Therefore, 3D printing production can minimize construction waste as it is not using formwork in produce of concrete. In order to obtain satisfied concrete produce by 3D printing, the characteristic of 3D printing such as fresh properties need to be studied. Buildability is one of the fresh properties that need to be acknowledge as important element in order to obtain the satisfied printing product. Another fresh properties, flowability and extrudability also need to be monitored as important pieces in the production of 3D printing.

This paper emphasizes on the three basic measurement for the fresh state of 3D construction material which are flowability, extrudability and buildability. Tests associated with every properties are presented and discussed in this paper. Experimental investigation conducted by previous researcher is used to support the test to obtain basic fresh properties of 3D construction material.

2. Flowability of 3D Material

Flowability is a critical property that evaluates the flow behavior of fresh materials in the pumping system and it also known as pumpability. The flowability of concrete mix usually measured by performing slump test, rheometer test and flow table method.

2.1 Slump test

Malaeb et al. [1] conducted a slump test, which measured the time for the mix to spread out to a specific diameter after the mix was poured out of a cone. Five samples of mixture were tested to the determine the flowability. The superplasticizer was used to improve the quality of the mix ranging from 0 to 1.3mL. Table 1 shows the flowability rate for the test. The result indicates that the flowability rate increases as the quantity of superplasticizer increased.

Table 1: Rate of flowability (Malaeb, 2019)

Sample number	Superplasticizer quantity (mL)	Rate of flowability (cm/s)
1	0.0	-
2	0.5	1.1
3	1.0	1.13
4	1.1	1.2
5	1.3	1.4

2.2 Flow table

The change in flow of 3D mortar made of various agent was studied by Marchment et al. [4]. The flow test method was conducted in accordance to ASTM C1437. Diameter of the flow was measured 3 minutes after all the materials were mixed. The change in flow diameter of the same mix was measured after 15 minutes. Table 2 shows the type of cement paste used in the study while Figure 1 shows the flow table test result.

Table 1: Type of paste (Marchment, 2019)

Type	Criteria
Mortar mix	Mix ratio of cement, coarse sand, fine sand and water, 1 : 1 : 0.5 : 0.36
OPC paste	Cement with 0.36 water ratio
Paste 1	Cement + retarder
Paste 2	Cement + viscosity modifying agent
Paste 3	Cement + slump retainer

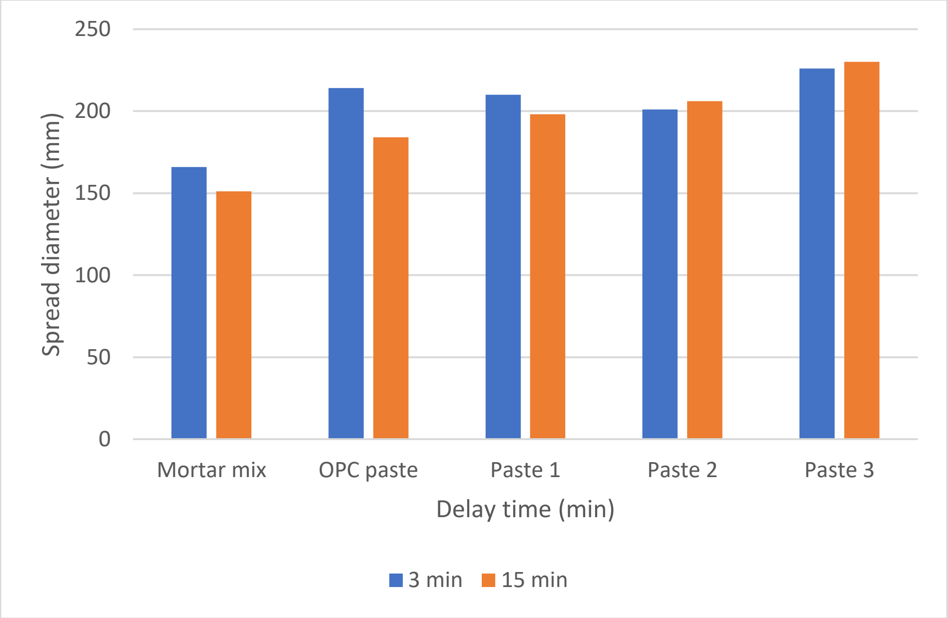

Figure 1: Flow table test results (Marchment, 2019)

It was observed that after 15 minutes, the OPC paste had a greater rate of stiffening compared to the other paste mixtures. The pastes which contained admixtures, showed minimal change in flow after the 15-minute period, depending on the type of admixture used in the mix. It still manages to slow the stiffening effects of cement in order to maintain a bond interface of the mortar.

2.3 Rheology

Weng et al. [2] conducted a rheometer test to determine the rheological properties of the mixture. A certain rheological requirement was observed by using different mixture as it highly affected by the gradation of aggregates. A set of test was conducted and the details is presented in Table 3 and the result also tabulated in Table 4.

Table 3: Mixture criteria (Weng, 2019)

Mixture	Description
A	Designed to achieve a continuous gradation system
B	Uniform gradation system mixture with sand 0.6-1.2mm
C	Uniform gradation system mixture with sand 0.15-0.25mm
D	Gap gradation with removal of sand 0.6-1.2mm
E	Gap gradation with removal of sand 0.15-0.25mm
F	Used natural sand river as raw material

Table 4: Rheological performance (Weng, 2019)

Mixture	Yield stress (Pa)	Plastic viscosity (Pa.s)
A	3350	16.65
B	2411	19.00
C	2107	21.81
D	3318	18.03
E	2693	33.31
F	1874	16.95

Based on the Table 4, mixture A has the highest static yield stress and the smallest plastic viscosity while mixture E possesses a highest viscosity. Among all the mixtures, it indicates that flowability of mixture E is the worst.

3. Extrudability

Extrudability can be defined as the capacity of fresh paste to pass through the printing nozzle as a continuous and intact filament. The extrudability can be determined by an assessment of printability which the paste can be extruded out without blocking, an extruder test and measurement of rheological properties.

3.1 Ranking

Le et al. [3] has conducted an assessment to measure the printability of the sand-binder mix and the details are presented in Table 5. The materials used for binder were cement, fly ash and silica fume. The mixture had to be printed to 9mm wide filament through 9mm nozzle.

Table 5: Mix proportions (Le, 2012)

Mixture	Description
1	75% sand + 25% binder
2	70% sand + 30% binder
3	65% sand + 35% binder
4	60% sand + 40% binder
5	55% sand + 45% binder

Table 6: Printability (Le, 2012)

Mixture	Printability
1	-
2	-
3	0.4 kg/m3
4	1.6 kg/m3
5	No data

Based on the results presented in Table 6, mixture 1 and 2 with the binder content 25% and 30% appeared to be insufficient to create suitable extrudability in the experiment. Meanwhile, mixture 3 and 4 could be printed out up to 0.4 kg/m3 and 1.6 kg/m3 respectively. As for mixture 5, the highest binder content in the experiment was not evaluated as the paste surely will able to pass through printing nozzle and mixture 4 was identified as optimum mix in extrudability and binder content.

3.2 Rheology

Suvash et al. [7] used rheological properties of three different mixture to measure the extrusion of printed concrete involving the static yield torque, dynamic yield torque and plastic viscosity. A rheometer apparatus was used to execute the testing and the materials composition was presented in Table 7 while Table 8 shows the rheological properties for the mixture.

Table 7: Materials composition (Suvash, 2018)

Mixture	Materials composition (kg/m^3)
Mix 1	Slag (39), fly ash (645), silica fume (78), sand (1168), actigel (8), bentonite (8), water (47), K2SiO3 (250), KOH (23)
Mix 2	Cement (290), fly-ash (278), silica fume (145), sand (1211), water (285), sodium lignosulfonate (7)
Mix 3	Cement (289), fly-ash (277), silica fume (145), sand (1209), water (284), sodium lignosulfonate (9), glass fiber (13.5)

Table 8: Rheological properties (Suvash, 2018)

Mixture	Static yield torque (N mm)	Dynamic yield torque (N mm)	Plastic viscosity (N s/m^2)
Mix 1	1370	358	186
Mix 2	1401	367	144
Mix 3	1763	303	113

From Table 8, it shows that mix 1 has a higher plastic viscosity value and it leads to a quicker shear stress development compared to others. Meanwhile, mix 3 produced a small value in both dynamic yield torque and plastic viscosity because of the inclusion of fibers.

4. Buildability

Buildability refers to the concrete itself in determining the ability of the layers to hold other layers above it without collapsing or failing. Moreover, the concrete must maintain a suitable compressive strength. Buildability can be determined by observing the number of concrete layers that could be hold on top each other before a deformation or collapse happened.

4.1 Number of layer count

Buildability is measured by counting the number of concrete layers that could be hold on top each other before a deformation or collapse. It also evaluates the amount of the layers that can allowed each mixture to stand without support while accepting the load applied by the top layers. To determine the buildability of 3D printing, Malaeb et al. [1] conducted experiment involving the number of layer count. The mixtures consisted of 125g of cement, 80 g of sand, 160 of fine aggregates and addition of superplasticizer. Table 9 shows the sample of mixture with various content of superplasticizer.

Table 9: Sample of mixture (Malaeb, 2019)

Mix number	Superplasticizer (mL)
1	0.0
2	0.5
3	1.0
4	1.1
5	1.3

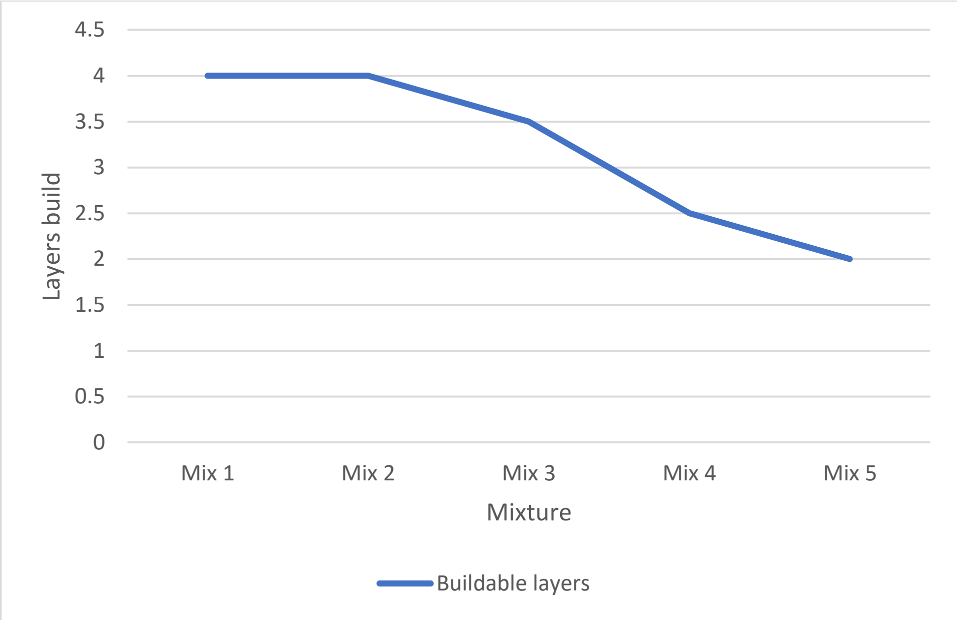

Figure 2: Buildable layers for the mixture (Malaeb, 2019)

Based on graph in Figure 2, it shows that as the quantity of superplasticizer increased, the number of buildable layers tend to be decreased. Mixes 2 and 3 showed appropriate result as they had the highest buildability while the value decreasing for mixes 4 and 5.

4.2 Workability

Lee et al. [3] adopted shear vane apparatus to measure the workability of the mortar. The mortar is subjected to shear strength of 0.3 kPa and 0.55 kPa, then measured the number of layers extruded from the nozzle.

Table 10: Number of layers build (Le, 2012)

Shear strength	Number of layer build	
	1 filament group	5 filament group
0.30 kPa	4	7
0.55 kPa	15	34

As presented in Table 10, the experiment indicates that at 0.3 kPa of shear strength, the concrete could not build a test sample because it was too wet or too stiff. At this stage, only 4 layers and 7 layers of layer can be built for 1 and 5 filament group, respectively. Meanwhile, at 0.55 kPa of shear strength, the concrete could build up to 15 layers for 1 filament group and 34 layers for 5 filament group.

5. Conclusion & Recommendation

5.1 Conclusion

There are a lot of approaches available in determining the fresh properties of 3D printing. The main fresh properties of 3D printing, flowability, extrudability and buildability are able to be determined by using suitable approaches. All of the experimental tests that have been reviewed in this study confirm that the tests are appropriate in determining the fresh properties of 3D printing concrete. Therefore, all of the testing will be accepted as a good approach in determining the fresh properties of 3d printing. The acceptable of testing that has been conducted are slum test, flow table, rheological properties involving static yield stress are suitable to determine the flowability of 3D printing concrete. As for the extrudability, the testing that had been conducted are by ranking, which involve an assessment of printability and rheological properties which observed the static yield torque, dynamic yield torque and plastic viscosity can be applied. Meanwhile, for the buildability, the number of layer count and workability measurement are the testing that are suitable for 3D printing. In addition, 3D printing in construction is a new approach in construction resulting a lot of study needed to determine the acceptable parameters to be apply in the construction.

5.2 Recommendation

In order to apply the use of 3D printing in the construction, the development of this approach still require a lot of researches. The condition and important parameter in operating a 3D printer for construction need an improvement to make sure it can be use as regular equipment in the construction. The experimental test that has been conducted by previous study surely can determine the fresh properties of 3D printing but, in order to get absolute data for the properties of 3D printing, a new or improve experimental tests are needed. These testing will contribute a lot for the 3D printing for the construction.

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