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3D printable concrete: Mixture design and laboratory test methods

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Abstract:

Experimental results of the mix design and fresh properties of a proposed concrete for 3D printing are presented in this paper. Layer-by-layer sample components were built by the designed concrete and extruded through a nozzle. The two most critical rheological properties of the designed mix are extrudability and buildability as they are both highly influenced by mix proportion and the presence of superplasticizers. Therefore, this study focused on mix proportion design approaches and laboratory test methods, which generally allowed access to the fresh concrete's printable properties. Because they are efficient and convenient in construction, materials including cement, fly ash, natural sand, and superplasticizer were selected for mixing proportion analysis. Slump-flow tests, V-funnel tests, buildability tests, and extrudability tests were also employed to access the printability of the proposed mixture in this study. This first analysis on the mixture design approach and laboratory test methods to evaluate the printable properties of 3D-printable concrete can be considered a reference and orientation to further develop 3D printing technology in Vietnam.

Keywords: **buildability test, extrudability test, slump-flow test, V-funnel test, 3D concrete printing technology.**

Classification numbers: **2.1, 2.3**

1. Introduction

Researchers worldwide have been paying attention to 3D printing, also known as additive manufacturing, for a few decades. The idea of 3D printing has also attracted the attention of engineers, architects, and investors because of its capability to transform a drawing into an object. Since the construction industry has adopted this new technology, its usage needs to be extended beyond making quick prototypes to the final production of structures. Since 2014, many well-known buildings, bridges, and architectural icons have been constructed on-site by applying 3D printing technology [1-5]. These achievements offer insights into the full potential that 3D printing technology can bring to the construction industry. However, there are only a few published documents about material requirements for 3D printability despite its rapid growth. In a successful process extrusion, i.e., in order to be extruded through the nozzle, the material must be flowable enough. Nevertheless, when a layer is extruded, it must have sufficient shear strength to resist deformation due to its self-weight and the weight of the layers printed above it. From a rheological aspect, while inside the pump and nozzle, the material must be liquid-like with low viscosity, but once printed out, it must transition into solid-like behaviour with enough strength to prevent deformation.

Fortunately, contour crafting (CC) and binder jetting are successful printing methods for cement-based materials [6, 7]. Moreover, attempts to develop appropriate printing methods for cement-based materials have been investigated by many researchers as well [8-13]. In this study, the authors employed the results of J. Jo, et al. (2020) [14] and C. Zhang, et al. (2019) [15] as basic directions to design the mix proportion of the tested concrete. The main constituents of the mixtures mentioned here are cement, sand, and fly ash, which has been selected by other authors as well. Then, V-funnel tests, buildability tests, and extrudability tests were carried out to reveal the printability of the concrete. The V-funnel and buildability tests are simple and relatively

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reliable tests [16]. This first analysis on the mixture design approach and laboratory test methods to evaluate printable properties of 3D printing concrete can be considered a reference and orientation to develop 3D printing technology in Vietnam.

In summary, this study suggests a mix proportion design approach and laboratory tests that access printable properties of fresh concrete with convenient applications.

2. Materials and process for printability

The sources of the materials used in this work can be found in previous research by the authors [17]. For the reader's convenience, the contents are briefly re-introduced. Cement Portland by Chinfon (OPC) and Fly-ash (FA) by Hai Phong Thermal Power Plant were used to form the binder component. A commercially available manufactured sand with a nominal maximum aggregate size of 1.25 mm was used. Superplasticizer SikaPlast-398 (SP) was used to adjust the workability of the fresh concrete. The constitutions of the concrete are presented in Fig. 1.

Compared to traditional construction, fresh concrete properties play an essential role in concrete development. Therefore, the printability of the concrete is firstly investigated in the process of 3D printing technology. The ability of the material and nozzle combination to produce a well-controlled filament is related to printability [19]. In this research, the ability of fresh concrete to (1) be extruded continuously, without surface fracture; (2) not cause jamming or clogging of the nozzle; and (3) build up with acceptable deformation before setting are all considered printability characteristics, which has also been explained in other words by authors [19-22]. These characteristics can also be considered as extrudability and buildability.

3. Mixture proportion design

Investigations on the effect of material composition on the properties of 3D-printability have been carried out by many other authors [10, 11, 18, 20, 21, 23-25]. While there is still limited research on mixture design approaches, some highlighted results can be found in

(A) Cement (B) Fly ash (C) Sand (D) Superplasticiser

Fig. 1. Constitutions of the proposed concrete.

other research [9, 14, 15, 26]. Among these advances, the results of C. Zhang, et al. (2019) [15] and J. Jo, et al. (2020) [14] were referred to when proposing the mix proportions.

Fresh and hardened concrete mechanical properties of a mix design are required to meet the performance, as shown in Fig. 2.

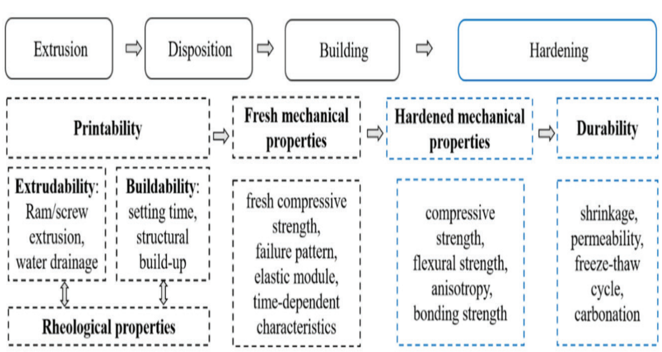


Fig. 2. The performance of 3D printing concrete during the printing and hardened processes [18].

According to J. Jo, et al. (2020) [14], the amount of sand can be determined based on the equation below:

$$S=0.4B \tag{1}$$

where B is the binder (mm); S is the amount of sand with a diameter smaller than 0.7 mm.

Following the authors, they added a sand with 0.7 mm maximum size to avoid bleeding or clogging while printing to produce a suitable mortar mixture. According to C. Zhang, et al. (2019) [15], the amount of sand can be determined based on the equation below:

$$m_{1.18}=4.22F+351 \quad (2)$$

Note: From natural sand by sieve of 1.18 mm square hole is fine sand; F is the flowability of cement paste (mm); $m_{1.18}$ is the amount of sand (gram/litre).

The research results of Eq. (1) and Eq. (2) help to quantify the ratio of binder and fine aggregate (sand). However, other factors used in this study including fly ash, superplasticizer ratio, water ratio, and sand diameter are different from the studies of the two above authors. Therefore, concrete with the mixture proportions designed in this study should be further evaluated for printability by the test methods presented in this study.

To calculate the amount of sand, the flowability test of the binder needs to be done for different values of slump flow. The test procedure can be referred to in Ref. [27]. To replace the maximum amount of fly ash to cement, but also while minimizing the effects on the compressive strength of the concrete, the ratio between fly ash and cement was determined to be 4:6. The water to cement ratio was 0.3 because the workability of the concrete was adjusted with a superplasticizer. The fine sand used in this study is from natural sand filtered through a 1.25-mm square hole sieve, which is much larger than that of Junho and only a little larger than that of Zhang. The flow slump value was then measured as 240 mm, as shown in Fig. 3.

Fig. 3. Flow-slump of the tested binder.

According to the Eq. (1) and Eq. (2), the amount of sand was calculated. However, the ratio of sand to binder by Zhang and Junho has a large gap, so the authors propose a range from 0.4 to 2.4 with specific values. Then, five initial mixes with different proportions of sand/binder were designed, as shown in Table 1.

Table 1. Concrete mixture proportion.

Mix label	Fly ash to cement	Water to binder	Sand to binder	SP to binder (%)
Z_2.4	0.667	0.30	2.4	1.2
J_0.4	0.667	0.30	0.4	0.2
M1_1.1	0.667	0.30	1.1	0.6
M2_0.8	0.667	0.30	0.8	0.4
M3_0.5	0.667	0.30	0.5	0.2

Note: Ratio by weight and to the binder.

4. Laboratory test methods and results

4.1. V-funnel test

The viscosity and the deformability of fresh concrete can be evaluated with the V-funnel test. After filling the V-funnel with the prepared fresh concrete, it was lifted and the concrete was passed through the opening well with no segregation or jamming. According to previous research, this value of time, V_t, falls within the typical range of 9 to 25 s [16]. The time (Vt) to empty the concrete was listed in Table 2 with the range of 15 and 25 s corresponding to Z_2.4 and J_0.4, respectively. The test was carried out as shown in Fig. 4.

Table 2. The time (V_t) of the V-funnel tests.

Mix label	V_t (s)	Description
Z_2.4	9	Segregation/jamming
J_0.4	25	No segregation/no jamming
M1_1.1	11	Segregation but no jamming
M2_0.8	14	Segregation but no jamming
M3_0.5	24	No segregation/no jamming

(A) Z_2.4 **(B) J_0.4**

(C) M1_1.1 **(D) M2_0.8** **(E) M3_0.5**

Fig. 4. V-funnel tests.

According to Table 2, with V_t = 9, 11, and 14 s, the three mix labels Z_2.4, M1_1.1, and M2_0.8 had segregation. Meanwhile, segregation did not occur with the mix labels J_0.4 and M3_0.5. In the V-funnel tests, only mix label Z_2.4 caused jamming.

4.2. Buildability test

The slump height remains of the concrete cylinder under the force of gravity can be used to evaluate the yield stress and the buildability of the tested concrete. The height and diameter of the cylinder mould were chosen to be the same value of 80 mm due to the previous research done by the authors [15]. Therefore, the buildability is assessed by the shape and the remaining height of the cylinder sample. If significant deformation is not observed after lifting the mould away, it can be concluded that the concrete has appropriate buildability.

The slumps of the mixtures are shown in Table 3. The concrete cylinder slump remained in a range from 8 to 22 mm, and the specimen did not deform after lifting the mould away, as shown in Fig. 5. These values mean that the concrete has enough solid ability.

Table 3. The slump of the samples in the buildability test.

Mix label	S (mm)	Description
Z_2.4	8	No deformation/appropriate buildability
J_0.4	22	Significant deformation/inappropriate buildability
M1_1.1	11	Lightly deformation/appropriate buildability
M2_0.8	12	Somewhat deformation/appropriate buildability
M3_0.5	13	A little deformation/appropriate buildability

(A) Z_2.4 **(B) J_0.4** **(C) M1_1.1**

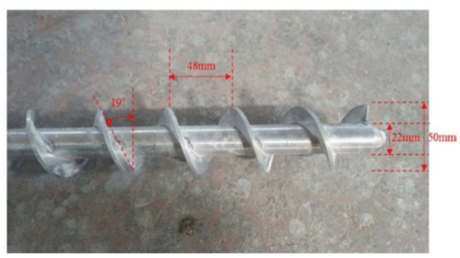
(D) M2_0.8 **(E) M3_0.5**

Fig. 5. The slump of the sample in the buildability test.

The concrete cylinder with mix label J_0.4 indicated an incapacity for buildability with a slump of 22 mm and unacceptable deformation. The four other mix labels, on the other hand, proved to be appropriate for buildability. The mix label Z_2.4 had a slump of the concrete cylinder at 8 mm with almost no deformation. On the other hand, the three mix labels M1_1.1, M2_0.8, and M3_0.5 demonstrated a modest deformation phenomenon with slumps of 11, 12, and 13 mm, respectively.

4.3. Extrudability test

The print system used in this study was designed and created based on the screw principle as presented in Fig. 6. The ability to transport the fresh concrete through a hopper and screwing system into a nozzle where it produces a continuous filament is considered extrudability. In this research, the extrudability was tested with filaments of 25 mm wide (printed from a 25 mm nozzle). The filaments must be homogeneous and continuously extruded without blockage, cracking, or segregation throughout the extrusion process. A printed sample, furthermore, must be well-shaped to retain its formation.



(A) Screw detail (used with permission from [14])

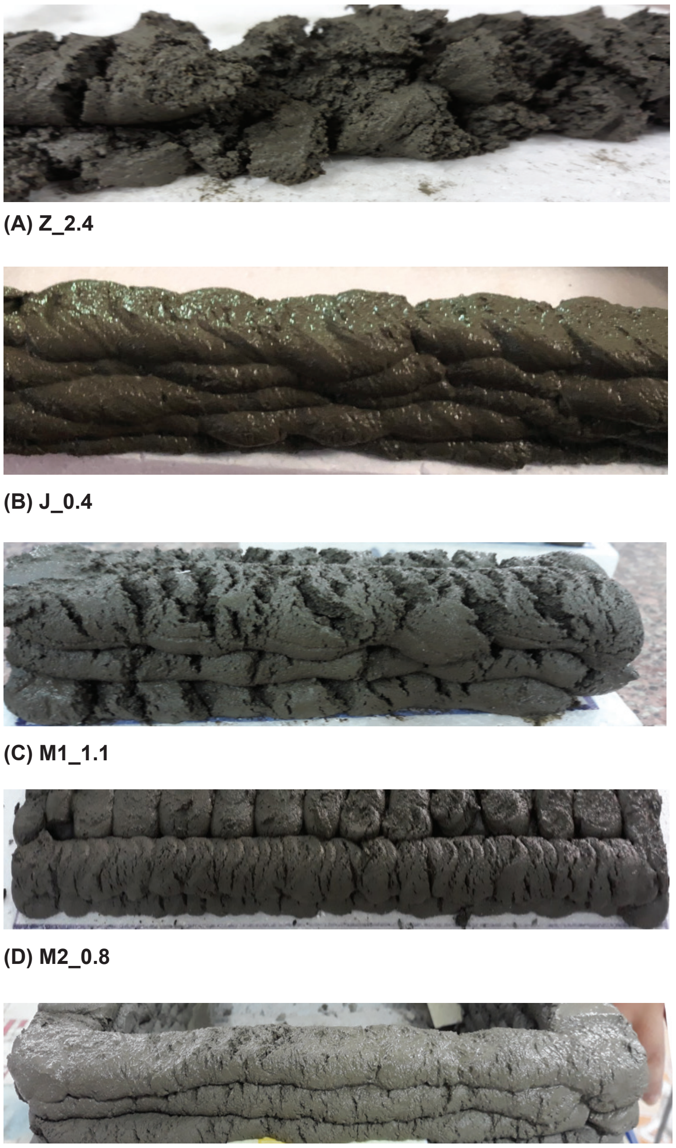
(B) Print-head system

Fig. 6. Screw and nozzle drive.

Table 4. Characteristics of printed mixtures.

Mix label	Extruded continuously	Blockage	Cracking/ segregation	Shape retention
Z_2.4	No	No	Seriously	Bad
J_0.4	Yes	No	No	Bad
M1_1.1	Yes	No	Yes	Acceptable
M2_0.8	Yes	No	Yes	Normal
M3_0.5	Yes	No	Yes	Good

In Table 4, the extrusion process was not continuous with only mix label Z 2.4, which had serous cracking and segregation without blocking resulting in poor form retention. Mix label J_0.4 failed to maintain good form despite a continuous extrusion demonstration that was free of blockage, breaking, or segregation. The three other mix labels M1_1.1, M2_0.8, and M3_0.5 were continuously extruded with satisfactory form retention and no blockage but did experience a breaking or segregation phenomenon as shown in Fig. 7.



(A) Z_2.4

(B) J_0.4

(C) M1_1.1

(D) M2_0.8

(E) M3_0.5

Fig. 7. Printed samples.

5. Results and discussion

Based on the investigation presented above, some highlighted discussions and suggestions can be given.

Firstly, a series of preliminary mixtures was tested to find out the maximum particle grading including sand, cement, and fly ash for extrudability. With the mechanics of the printing system as shown in Fig. 6, natural sand filtered through a 1.25-mm square hole sieve was available. Then, the mix of available particle combinations was experimented with the admixture dosages varied by 0.2-1.2% to approach the optimum flowability, buildability, and extrudability. Based on the present study, the authors developed a mix proportion design process as presented in Fig. 8.

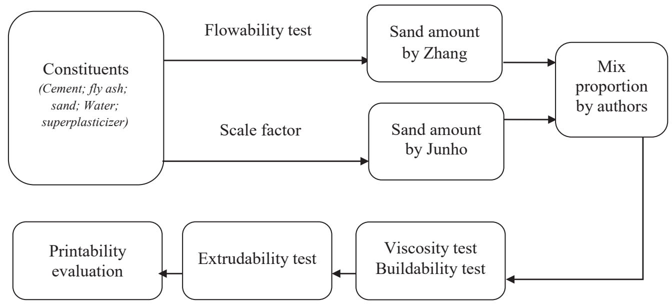


Fig. 8. Mix proportion design process proposed.

Secondly, the workability was significantly influenced by the dosage of the superplasticizer. In the series, increasing the superplasticizer dosage from 0.2 to 1.2% by weight of binder increased the workability, i.e., reduced V_t from 25 to 9 s (Table 2). The superplasticizer thus proved crucial for printing concrete to attain reasonable workability and high strength with a low water-binder ratio. However, ease of flow through the V-funnel does not equate to printability. In particular, the mix label Z_2.4 had a flow time of 9 s, but the printed concrete was too hard to guarantee the continuity of the printed filaments. The reason behind this is the amount of sand in this mixture was the largest.

Meanwhile, the printed pattern ensures continuity in the J_ model with a relatively long flow time of 22 s, but the printed filaments were seriously deformed. The reason is due to it having the least amount of sand and unreasonable additives. In the remaining samples, with a decrease in sand content and a corresponding decrease of superplasticizer, the flow time increased and the printability of the sample also gradually improved. This study found that assessing the workability of concrete through the V-funnel test is reasonable. However, the results of the flow time tests provide a relatively limited preliminary assessment of the printability of the concrete.

Thirdly, the qualitative relationship between buildability and extrudability is relatively straightforward. When the Z_2.4 mix produced a good result with an 8 mm slump, the extrudability test was a bit difficult to complete, and the printability test revealed that the sample did not satisfy the printable quality due to extensive cracking. Meanwhile, the extrudability test was easier to perform with the J_ 0.4 mix with a slump of 22 mm, but the result of the printability test showed that the sample did not meet the printable quality due to excessive deformation. The rest of the samples show an increasing slump, the extrusion test not difficult, and the print quality also improving. The mixtures M2_0.8 and M3_0.5 give the best print quality as captured in Figs. 7D, E.

Finally, owing to its great sensitivity to workability and extrudability, the ratio of sand to binder should not exceed 1.2, and the superplasticizer dosage should be tightly controlled.

6. Conclusions

Based on the test results of the first analysis on mixture proportion design approach, and the tests used to evaluate rheological properties for the 3D printing concrete in Vietnam, some conclusions and suggestions are given:

(1) The mix proportion design process suggested in this study is reliable and feasible.

(2) The mixture proportion design approach presented herein is appropriate and reliable.

(3) The V-funnel test and buildability test employed in this study are efficient for designing and evaluating concrete before printing.

(4) The ratio between sand and binder should exceed 1.2, and the superplasticizer dosage needs to be tightly controlled.

(5) The assessment of printability through the extrudability test may be different when using different printing nozzles.

(6) Increasing the number of extrusion experiments is necessary for the recommendation of an optimal concrete mix for the screw printhead as performed in this study.

CRediT author statement

Thi Loan Pham: Conceptualization, Methodology, Data Analysis; Xiao Jian Zhuang: Supervision; Thi Hoai Thu Nguyen: Writing - Original draft preparation; Phan Anh Nguyen: Laboratory test; Duy Thanh Trinh: Laboratory test; Trong Quang Do: Reviewing and Editing.

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COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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