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Experimental investigations on the rheological properties of the proposed 3D printing mortar

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Abstract:

After almost 30 years and many projects investigated all over the world, the full potential that 3D printing technology can bring to the construction industry has yet to be realised. There are many challenges that face the application of 3D printing technology to the construction field. Among these challenges, mixture proportion design is crucial for the preparation of 3D printing concrete. Therefore, this study focuses on mix proportion design approaches and tests, which access some rheological properties of the fresh mortar. Because they are highly practical and convenient in construction, materials including cement, fly ash, and natural sand were selected for mixing proportion analysis. Slump-flow tests, V-funnel tests, and buildability tests were also employed in this study. This first analysis on the mixture proportion and method to evaluate rheological properties of 3D printing mortar can be considered a reference and orientation to develop 3D printing technology in Vietnam.

Keywords: **buildability test, fresh properties, mortar, slump-flow test, V-funnel test, 3D printing.**

Classification number: **2.3**

Introduction

In order to explore the full potential that 3D technology can bring to the construction industry, considerable amounts of research have been carried out all over the world. However, compared to traditional construction, research related to the application of 3D printing in the construction industry is still in its infancy. Publications related to applying 3D printers in the construction field has become a hot trend in recent decades.

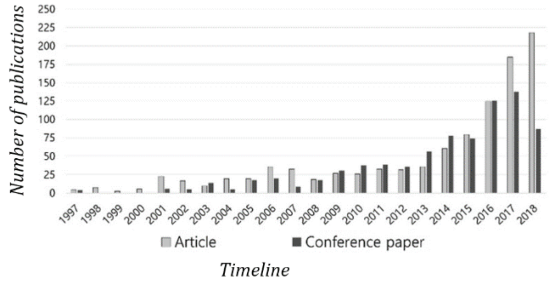

Fig. 1. Trend of publication output from 1997 to 2018 [1].

As shown in Fig. 1, since 2014 publications related to 3D printing technology has significantly increased. Many well-known buildings, bridges, as well as architectural icons, have been constructed on-site with applying 3D printing technology [2-6]. These achievements offer insights into the full potential that 3D printing technology can bring to the construction industry.

Along with these highlighted opportunities, there have been many challenges to applying 3D printing technology on-site such as mixture proportion design, printing of large-scale components, reinforcement, etc. [7]. Among these challenges, the mixture proportion design is crucial for the preparation of 3D printing concrete. Cement-based materials are the most common ingredient and has been applied in civil structures for centuries and maintain a significant role in modern buildings as well. Moreover, successful attempts to design appropriate printing approaches for cement-based materials have been investigated by many researchers as well [8-14]. In this study, the authors employed the mixture approach by C. Zhang, et al. (2019) [15] to design the mix proportion of the mortar.

Because they are highly practical and convenient in construction, the main constituents of the mixtures mentioned here are cement, sand, and fly ash, which have been selected by many other authors [15-17]. The reason for this is to support the application of 3D printing to large-scale and on-site buildings while strictly regarding extrudability, buildability, workability, and open-time as the key requirements for 3D-printable concretes [8].

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To respond to those mentioned requirements, concrete used for 3D printing technology must be as fluid as possible to be easily transported through printing system components such as pipes, nozzles, and extrusion through the printer head. Meanwhile, the concrete must be stable to prevent disunity or jamming during the flow. The fluid characteristics, setting behaviours, and viscosity performances are considered to be the most useful critical features that specify the printability and stability of concrete for 3D printing. Each behaviour can be detected and evaluated by one or more experimental methods. The slump-flow test, V-funnel test, and buildability test are simple and relatively reliable tests that are widely used [18]. Therefore, these three tests were employed in this study to evaluate the printability of the mortar.

In summary, this study suggested a mix proportion design approach and tests that access some rheological properties of the fresh mortar with highly practical applications.

Material preparation

In this research, ordinary Portland cement (OPC) by Chinfon and fly ash (FA) by Haiphong Thermal Power Plant were used to form the binder component. Table 1 illustrates the chemical composition of OPC and FA. According to ASTM C618, fly ash by Haiphong Thermal Power Plant is categorised as class F [19].

Table 1. Chemical composition of fly ash and ordinary Portland cement [20].

Chemical composition	Weight percentage (%)	
	Fly ash	*Cement*
SiO_2	45.56	22.45
Al_2O_3	23.04	5.42
Fe_2O_3	5.34	3.6
TiO_2	0.1	-
$K_2O + Na_2O$	7.44	1.1
CaO	1.08	61.75
MgO	1.29	1.15
P_2O_5	0.2	-
SO_3	-	2.18
MnO	0.1	-

A commercially available manufactured sand with nominal maximum aggregate size of 1.00 mm was used. The sand was quickly dried and stored in a closed plastic bag. Hence, the sand was considered as dry meaning the water content of the mixture does not contribute to the total water amount.

Superplasticizer SikaPlast®-398 SF (SP) was used to adjust the workability of the fresh mortar and its physical characteristics are given in Table 2.

Table 2. SikaPlast®-398 SF physical characteristics (SP) [21].

Physical characteristics	Test method	Test result	Specification
Specific gravity @20°C	SK-TM002	1.095	1.085-1.105
pH value @25°C	SK-TM003	5.610	4.500-6.500
Solid content @105°C	SK-TM004	30.600	29.500-31.500

Materials used for mixing mortar in this research is presented in Fig. 2.

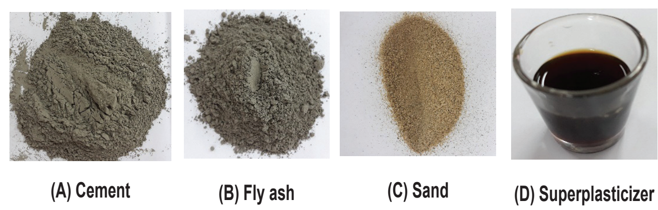

Fig. 2. Materials used for mixing mortar.

According to the successful investigations by previous authors, the authors take the water to binder ratio by weight to be 0.45. Cement and fly ash are considered as the binder. Then, the authors employed the formula of [15] to determine the amount of sand:

$$S=4.22F+351 \tag{1}$$

where: S is the amount of sand (gram/liter); F is the flowability of cement paste (mm); and fine sand is from natural sand by 1.00 mm square hole sieve.

The mixture proportion given in the Table 3 was prepared and then evaluated by the following tests.

Table 3. Mortar mix ratio.

Cement	Fly ash	Sand	Water	SP
0.5	0.5	2.58	0.42	0.12

Note: ratio by weight and to binder.

Results and discussion

Flowability test

The flowability of the binder is a critical parameter in this research. The flowability value, F, of cement paste is calculated using the sand content in Eq. 1 by C. Zhang, et al. (2019) [15].

According to the Chinese standard GB/T 8077-2012, the flowability of the binder is tested as described below [22]. Five-hundred grams of binder is prepared, and the total mixing time was five minutes. The mixing steps includes three steps as follows. Firstly, with a velocity of 140±5 r/min, the binder is dry mixed for 1 min. Next, mixing is continued for 1.5 min after adding water and superplasticizer. Finally, the binder is mixed for 2.5 min at high velocity of 285±10 r/min. After the mixing, the ready-mixed binder is poured into a truncated cone.

Then, the cone is vertically lifted and the flowability of the cement binder is measured immediately. The inner diameters of the top and bottom rims and the height of the cone are 36, 60, and 60 mm, respectively. The result of the flowability of the binder was 220 mm as captured in Fig. 3. The value of the flowability can range between 130 and 240 mm [15]. This value was taken to account for the amount of sand based on Eq. 1 and the result is presented in Table 3.

Fig. 3. Flowability of the tested binder.

V-funnel test

The viscosity and the deformability of fresh concrete is evaluated with the V-funnel test. The configuration of the V-shaped funnel used in this test is shown in Fig. 4. Firstly, the V-funnel is filled up with fresh mortar. Then, the funnel is lifted and the elapsed time between opening the bottom outlet and the complete emptying of the funnel without significant segregation and jamming through the narrow opening is defined as the V-funnel flow time (V_t). The mixing steps were like that of the paste for the flowability test.

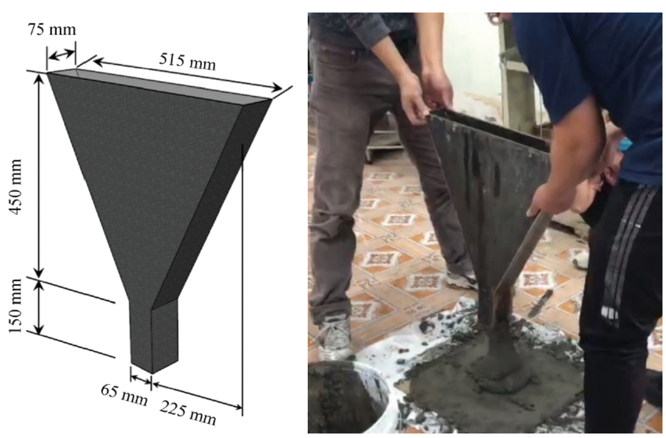

Fig. 4. Description of V-funnel test.

After filling the V-funnel with the prepared fresh mortar, it was lifted up and the mortar passed through the opening well with no segregation or jamming. The time (V_t) it took to completely empty out the mortar was 15 sec. According to previous research, this value of V_t falls within the typical ranges of 9 to 25 sec [18].

Buildability test

The remaining height of the slumped mortar cylinder under the action of gravity can be used to evaluate the yield stress and the buildability of the tested mortar. The height and diameter of the cylinder mould were 80 mm with reference to the previous experimental experience of the authors [15]. According to this reference, the buildability test procedure is as follows: initially, the cylinder mould is filled with mortar by three layers, where each layer is compacted by rodding 15 times. Then, the mould is vertically lifted, and 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 mortar has appropriate buildability. The mixing steps were like that of the paste for the flowability test.

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

The height of the mortar cylinder remained about 72 mm and the specimen did not deform after lifting the mould away as shown in Fig. 5. This means that the mortar has a solid ability but not enough viscosity.

Based on the slump-flow test, V-funnel test, and buildability test results, the mix proportion can be practically designed and initially evaluated by the proposed method in this study.

Conclusions

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

(1) Applying 3D printing technology in construction has inevitable trends in the near future.

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

(3) Slump-flow test, V-funnel test, and buildability test employed in this study are highly practical for designing and initially evaluating mortar used for 3D printing technology in the construction field.

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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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