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Study on flexural behaviour of printed concrete wide beams using polypropylene fibres

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Abstract:

Sustainability in building construction is an inevitable aspect of future construction projects. The justification of sustainability is highly appreciated by comparing 3D concrete printing technology with conventional construction. However, the 3D printing concrete system has limitations and challenges in industrial applications. The reason is that this process was initially used in small non-structural applications and is now being adopted for large-scale structures. Thanks to concrete printing machines, a wide variety of web frames are also available - something completely impossible to achieve using traditional formwork for pouring concrete. In this study, the girder web is designed in the style of truss beams. Three wide beams with different amounts of polypropylene (PP) fibre were printed, and 3-point loading tests were conducted. The failure mode, load-bearing capacity, and deflection were reported in this study. According to the results, applying concrete printing technology in civil and industrial construction is entirely feasible. The printing process successfully produced models with a nozzle diameter of 22 mm and layer height of 10 mm, ensuring sufficient adhesion force between the printing layers. Using a PP fibre content of about 0.25% yielded the best results in terms of concrete compressive strength and beams' flexural strength, while a PP fibre content of about 1.00% tended to increase the ductility of the member. Although the failure mode is brittle, the beams exhibited deflection before fracture far beyond the allowable deflection value of a flexural member. Therefore, the application of printed components to construction is feasible.

Keywords: **deflection, failure mode, flexural behaviour, load-bearing capacity printed concrete, polypropylene fibre, wide beam.**

Classification numbers: **2.1, 2.3**

1. Introduction

Sustainability in building construction is an essential aspect of future construction projects, making 3D concrete printing construction a standout advantage over traditional construction practices. The justification for sustainability becomes highly appreciated when comparing 3D concrete printing technology with conventional construction techniques, particularly due to the reduced labour requirement, absence of formwork, and decreased waste production. For example, the Dubai project (the United Arab Emirates National Committee) has reported labour cost reductions of 50 to 80% and a decrease in construction waste of 30 to 60% [1, 2].

In addition to the advantages mentioned above, a 3D printing concrete system carries some limitations and challenges in industrial applications. There is a lack of knowledge regarding the effects of different environmental factors on 3D concrete printed structures. Manipulating large-sized 3D printers at construction sites can be challenging. Higher capital investment is required for creating and developing digital models, which also requires skilled personnel and is especially limited in terms of design. Additionally, there is a lack of understanding about the behaviour of 3D concrete printed structures under different loading conditions. This knowledge gap stems from the initial use of this process in small non-structural applications and its subsequent adoption for large-scale structures. Therefore, research on the structural behaviours of printed components [3] or whole systems has been limited. By examining the progress of the development stages for concrete printing technology applications in the construction field, as shown in Fig. 1, we can reflect on past advancements and anticipate future ones.

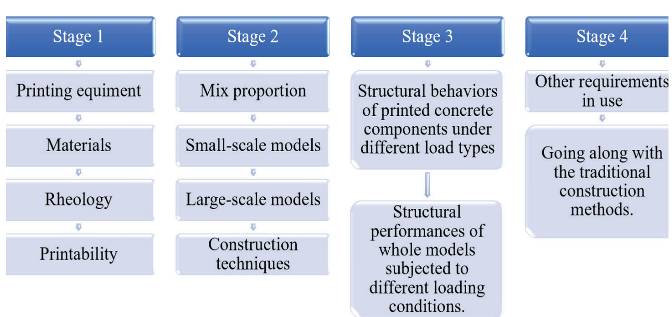

Fig. 1. Development stages of concrete printing technology applications in the construction field.

Stages 1 and 2 have been thoroughly researched and successfully published in recent years. Extensive literature reviews have been conducted worldwide [4-7]. Many researchers have investigated and designed effective printing

*Corresponding author: Email: loanpt297@gmail.com approaches for cement-based materials based on their experiments with printers [8-12]. One of the disadvantages of concrete printing technology is the use of rebars. To overcome this obstacle, reinforced concrete with random fibres such as PP fibres, glass fibres, steel fibre, palm fibre, and others have been explored [13-18].

Both small and larger-scaled models have been constructed using revealed construction techniques [19-22]. These achievements have significantly enhanced the application of concrete printing technology in the construction field.

Stage 3 is still in its initial steps, with some studies focusing on the structural behaviours of components such as panels [3], walls [23], and printed concrete specimens [24, 25]. From the authors' perspective and the experimental conditions at Haiphong University, research on the flexural behaviour of wide beams, including failure modes, moment resistance, and deflection of printed beams, has been carried out and analysed. The results obtained from this research will contribute to the success of Stage 3 and become an essential part of Stage 4 in the future.

Beams play a crucial role in the structural system of buildings, especially in frame structures. They support floors, walls, and connect columns to form the frame system. The most common cross-section for beams is rectangular, with simple construction and design processes that do not require complex or unique tools. Beams can be classified into high beams, wide beams, and typical beams based on the beam height and span ratio. Typical beams have a width-to-height ratio of about 0.5 to 0.75, while wide and typical beams have a span-to-height ratio greater than 5. The rest are considered high beams [26]. Typical and wide beams are widely used in all structural systems and are designed to withstand bending, shear, and deformation to ensure the work of the building. High beams are less commonly used as transfer beams to support additional columns. These act as girders in high-rise building systems, helping to increase the rigidity of the structural system and reduce the impact of lateral loads.

However, the presence of beams in the structural system of buildings often reduces the clearance height of floors. Therefore, there is a trend towards designing smaller height beams to optimise space utilisation, although this compromises the bearing capacity and deformation compared to conventional beam members with the same cross-sectional area. Nevertheless, the trend of choosing wide beams over traditional beams is increasingly popular as it serves two simultaneous goals: reducing building height and enhancing spatial aesthetics.

To meet the requirements of workability and the growing trend of using wide beams, studying the behaviour of this type of beam is indispensable. While wide beams are typically studied for shear strength in conventional reinforced concrete structures, beams produced by concrete printers exhibit a different failure mode. As wide beams made by concrete printers are designed without reinforcement, the development of web ribs becomes necessary. For wide beams fabricated by concrete printing machines, a wide variety of web frames are available depending on their requirements, thanks to the printability of the material - something that is completely impossible to achieve by pouring concrete using formwork. In this study, the girder web is designed in the style of the truss beams. Failure due to shear in inclined sections is avoided, and instead, failure on vertical sections caused by the concrete reaching its tensile strength due to moments induced by unreinforced beams is proposed. Therefore, this study focuses wide beams with flexural behaviour, rather than shear behaviour like conventional reinforced concrete beams, including analyses of failure modes and load-bearing capacity.

2. Materials and methods

2.1. Details of wide beams

The dimensions of length, width, and height of the beams are 1450, 450, and 150 mm, respectively. The thickness of the perimeter line is 40 mm, and the thickness of the girder web is 30 mm. Details of the printed concrete wide beams are shown in Fig. 2.

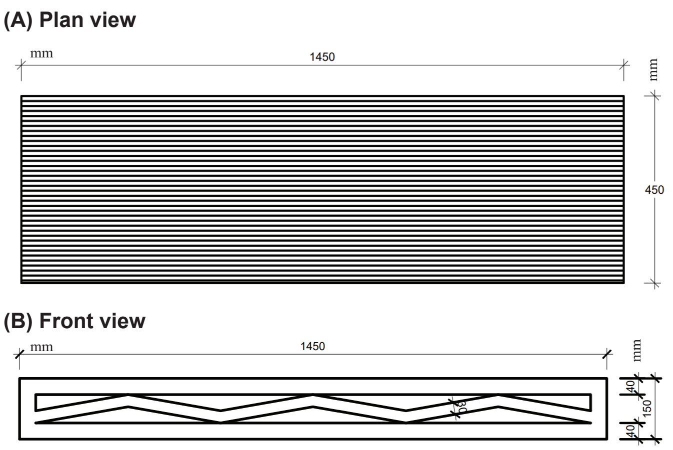

Fig. 2. Details of the printed wide beam. (A) Plan view; **(B)** Front view.

2.2. Materials and mix proportions

In this research, ordinary portland cement (OPC) by Chiffon PC40 and fly ash from Haiphong Thermal Power Plant were used to form the binder component, thanks to prior research on successfully applied cement-based materials

[9-12, 27, 28]. Table 1 illustrates the chemical composition of the OPC and fly ash. According to ASTM C618, fly ash from the Hai Phong Thermal Power Plant is class F.

Table 1. Chemical composition of fly ash and OPC [29].

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	-

Commercially available manufactured natural sand with a nominal maximum aggregate size of 1.5 mm was used. PP fibres were used to decrease the shrinkage of the printed concrete - the main properties of PP fibre are listed in Table 2.

Table 2. Properties of the PP fibre.

Tensile strength	500 MPa
Modulus	6000 MPa
Diameter	35+/-5 µm
Length	12 mm
Specific density	0.910 kg/l

Superplasticiser, namely Visconcrete 3000-200M, was used to adjust the workability of the fresh concrete. Materials used for mixing concrete in this research are presented in Fig. 3.

Fig. 3. Materials used for mixing concrete.

Based on the approaches and achievements of previous researchers, the authors highly value practical methods conducted in both laboratory and on-site settings. As a result, the authors propose the following mix proportion design process. In this method, the mix design incorporates coefficients and slump value approach, as shown in Fig. 4. To maximise the replacement of fly ash for cement but while minimising the impact on the compressive strength of the concrete, a fly ash to cement ratio of 1.0 was adopted. Additionally, the water-to-cement ratio ranged from 0.27 to 0.32. The workability of the concrete was adjusted using a superplasticizer. The fine sand used in this study was natural sand passed through a 1.25-mm square hole sieve. The mix proportions were designed based on the procedure proposed in Fig. 4 and are listed in Table 3.

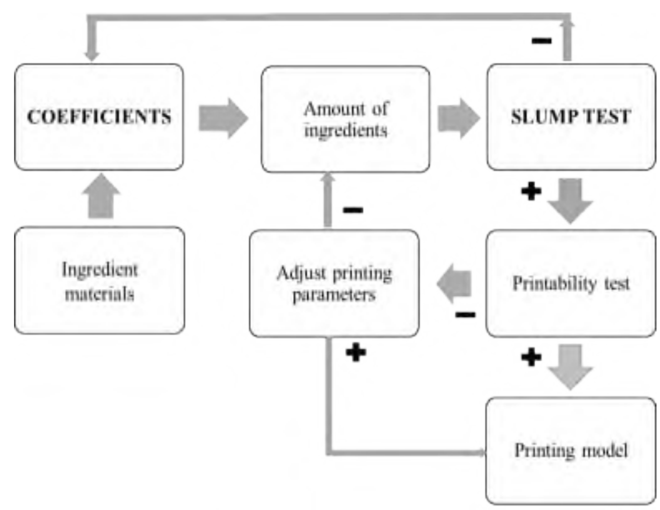

Fig. 4. Mix proportions design process [30].

Table 3. Mix proportions.

Beam label	Fly ash to cement	Water to binder	Natural sand to binder	PP fibre to binder (%)	SP to binder (%)
PB01				0.25	
PB02	1.00	0.27	1.00	1.00	0.40
PB03				1.50	

2.3. Printing process and fabrication

The process begins with a 3D CAD model of the object. Subsequently, slicing software is employed to create cross-sectional layers of the model, which are saved as a computer file and sent to the 3D printer. The 3D printer then fabricates the object by sequentially depositing each layer of material through the selective material placement. In this study, round-shaped nozzle with a diameter of 22 mm was used, and the model was sliced with a layer height of 10 mm. Fig. 5 visually depicts this process.

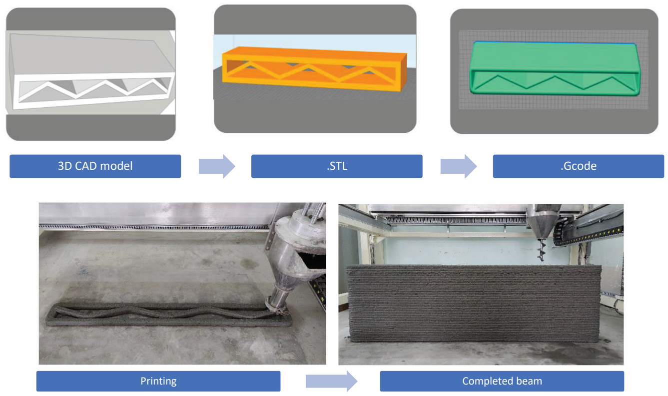

Fig. 5. Steps of the printing process.

2.4. Experimental program

2.4.1. Flexural test setup

A 3-point bending test was conducted on the experimental beams, which had a nominal length of 1350 mm. Each specimen was positioned on roller assemblies to accurately locate the supporting points. Linear variable differential transformers (LVDTs) were used to record the deflection based on the applied load. An LVDT was affixed at the mid-section of the beam specimen, precisely beneath the loading point. The test setup and instrumentation for tested specimens are shown in Fig. 6.

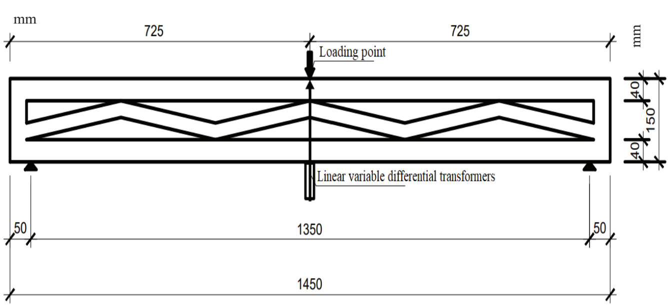

Fig. 6. Flexural test setup.

2.4.2. Compression test

Following the casting of the 10x10x10 concrete cubes, the concrete samples were cured under controlled humidity conditions. As a result, the testing procedure and loading protocol comply with TCVN 3118-1993 [24], as shown in Fig. 7.

Fig. 7. Compression test of concrete cubes.

3. Results and discussion

3.1. Failure modes

The failure patterns of the beams, as shown in Figs. 8-10 indicate that sudden failure of the concrete printed beams is characteristic of a brittle failure mode due to the absence of reinforcement. The inclusion of dispersed PP fibres did not result in a significant increase in the plasticity of the concrete. However, the failure mode of beam PB02 demonstrates a more extensive development of cracks in the concrete's tensile zone compared to the other two beams, PB01 and PB03.

Another noteworthy observation from these figures and the examination of the beam surfaces after fracture is the absence of delamination between the printed layers. This indicates that the adhesion force between the printed layers ensures the structural integrity of the entire system. Furthermore, the examination of the beam surfaces after failure reveals the solidity of the printed layers.

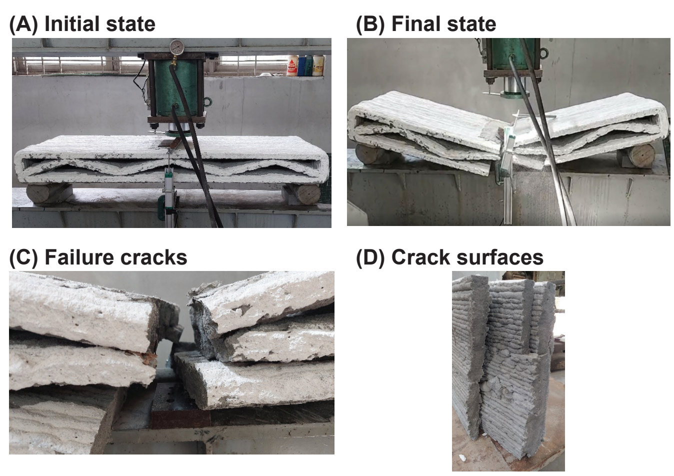

Fig. 8. The failure mode of PB01. (A) Initial state; **(B)** Final state; **(C)** Failure cracks; **(D)** Crack surfaces.

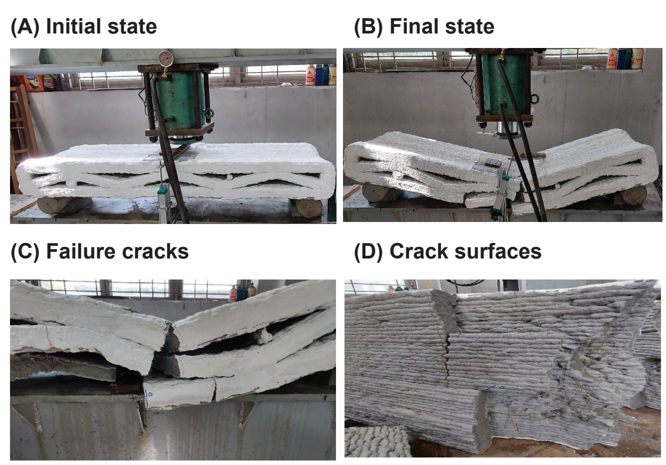

Fig. 9. The failure mode of PB02. (A) Initial state; **(B)** Final state; **(C)** Failure cracks; **(D)** Crack surfaces.

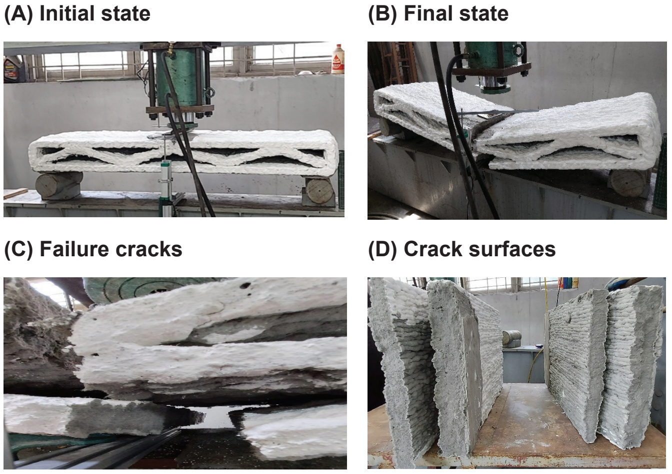

Fig. 10. The failure mode of PB03. (A) Initial state; **(B)** Final state; **(C)** Failure cracks; **(D)** Crack surfaces.

3.2. Loading capacity

The results of the force measurement and displacement meter on the bearing capacity of the beams are shown in Table 4.

Table 4. Load bearing capacity.

Beam label	Ultimate load (kN)	Deflection
PB01	24.74	16.17
PB02	19.84	24.73
PB03	20.87	17.78

The results indicate that the PB01 beam, corresponding to a PP fibre content of 0.25%, exhibits the highest bearing capacity among the tested beams. Additionally, an increase in PP fibre content tends to reduce both the flexural and compressive strength of the concrete, as shown in Table 5. This finding is consistent with the research results of other authors [16, 31, 32].

Table 5. The compression strength of printed concrete.

Beam label	Ultimate load (kN)	Dimensions (mm)	Coefficient α	Compression strength R_n (MPa)
PB01	525.64	100x100x100	0.91	47.8
PB02	256.46	100x100x100	0.91	23.3
PB03	285.15	100x100x100	0.91	25.9

Furthermore, the results table reveals that the PB02 beam, with a PP fibre content of 1.00%, exhibits the highest beam deflection. Notably, beam PB02 demonstrates a significant improvement in member ductility, as evidenced by a deflection value of 24.73 mm. This value is 35% higher than that of PB01 and PB03, respectively, by 35 and 39%, which is similar to results reached by other authors [33]. In addition, the failure of PB02, characterised by crack propagation as depicted in Fig. 9, shows a good agreement with the observed results. Although the failure mode is brittle, the deflection values prior to beam fracture far exceed the allowable deflection value of a flexural member of 9.00 mm (corresponding to 1/150 of the girder span).

4. Conclusions

Based on the combination of theoretical study and experimental research within the scope of this topic, the following conclusions can be drawn: 1) Concrete printing technology is feasible and can be successfully applied in the construction of civil and industrial works; 2) The adhesion force between the printing layers ensures the structural integrity of the printed components; 3) The flexural failure of all beams is characterised as brittle.

Furthermore, it has been observed that using a PP fibre content of approximately 0.25% yields the best results in terms of concrete compressive strength and flexural strength of the beams. On the other hand, a PP fibre content of around 1.00% tends to enhance the ductility of the member but leads to a reduction in the compressive strength of the concrete and the flexural strength of the beam. To further enhance the research and increase the reliability of the conclusions, the following points should be developed: It is recommended to use similar increments when adjusting the PP fibre content and conduct experiments with a larger number of beams. This will help determine an optimal value of PP fibre reinforcement for structural plasticity. Additional research should be carried out to investigate the influence of geometrical errors in the printed layers on beam workability. Further study is needed to explore the effects of different geometries of girder webs on the overall performance of the structures. By addressing these points, the research can be expanded, and the reliability of the conclusions can be improved.

CRediT author statement

Thi Loan Pham: Conceptualisation, Methodology, Data analysis; Duy Thanh Trinh: Laboratory bending test; Thi Hoai Thu Nguyen: Writing original draft preparation; Trong Quang Do: Reviewing and Editing; Phan Anh Nguyen: Laboratory printing test.

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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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