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The effect of printing direction on strength of 3D printed concrete

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KEYWORDS

3D printed concrete
Printing direction
Compressive strength
Flexural strength

ABSTRACT

This paper presents experimental results on the influence of printing directions on the strength of 3D printed concrete (3DPC) using materials available in Vietnam. The experimental results show that the printing direction has a significant influence on the strength of 3DPC with and without fiber, in which the X-direction printing samples has the lowest strength, only about 30 to 40% of the compressive strength and 20 to 30% of the flexural strength of the casted samples. However, the strength of the samples in the Y and Z directions is higher, for example, about 60 - 70% of the compressive strength and 40 to 50% of the flexural strength of the casted samples. The addition of fiber enhances the strength of 3DPC, especially with higher fiber contents, and reduces the anisotropy in flexural strength of 3DPC at a later age, i.e. 28 days.

1. Introduction

Nowadays, the 4.0 industry revolution has been a worldwide trend with outstanding achievements. In particular, 3D printing, one of the fundamental technologies of Industry 4.0, has been widely applied in many fields, especially potential for the construction industry [1]. Along with this inevitable development trend, the research and development of 3D printing technology in construction in Vietnam has been being implemented with the goal of producing 3D printed concrete components and construction works using materials available in Vietnam.

3D printing, also known as additive manufacturing, is a method of producing a three-dimensional component in layer-by-layer without formwork using a computer created design [1,2,3]. The additive process whereby layers of material are built up to create a 3D part, thus differently than the traditional construction method of conventional concrete (using formwork). The structure and properties of 3D printed concrete depend on the printability of concrete, which in turn depends upon the rheological properties of concrete, printing process parameters, and geometry of the target concrete structure. Le et al. [4,5] revealed that the material used for 3D printed concrete must have desired flowability and suitable open time to ensure the material can be extruded through the nozzle. In addition, the material must have sufficient buildability characteristics to enable it to deposit precisely, remain in position, be stiff enough to support upper layers without collapsing and yet still be suitable to provide a good interlayer bond strength. Besides, printing parameters, i.e., time gaps, nozzle standoff distances, printing speeds and nozzle type can also influence on the interlayer bond strength and resulting properties of 3D printed concrete.

Additive manufacturing (AM) method defined by the American Society for Testing and Materials (ASTM) as 'the process of joining materials to make objects from 3D model data, usually, layer upon layer' [6]. AM has become an integral part of modern product development [7] and the technology has been commercialized to the extent that machines are now affordable for home use [8-10]. Currently, there are 3 different 3D concrete fabrication methods based on the principles of AM method including Contour Crafting technology [11], D Shape [12]- using the principle of powder deposition and curing, and Concrete Printing [13] (technology of Loughborough University) – technology of extruding concrete layer by layer. The principle of the above methods is that materials are connected layer by layer to form the component to be machined from the 3D design model data.

Because the structure is created by printing successive layers (Figure 1), the internal structure of 3D printed products will always have voids formed between the filaments making it anisotropic. This weakens the interlayer bond strength between filaments as well as between layers, and leads a weakening of mechanical properties of the printed concrete components. Therefore, the understanding of the influence of voids and the bonding capacity of the printed layers in 3D printed concrete is very important in improving the mechanical properties of the printed concrete.

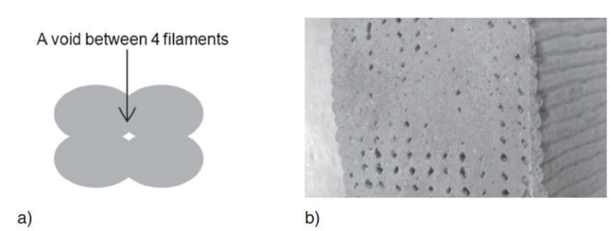

Figure 1. Voids formed between filaments resulting from a poorly executed printing process, a) Four filaments may form a void, and b) Poor printing example with obvious voids between filaments [14].

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Le T.T et al. [14] studied the effect of direction on mechanical properties of 3D printed concrete by printing slabs and cutting into 3 different directions (Figure 2). Authors reported that the anisotropy affecting the compressive, flexural strengths was caused by the void content of 3D printed concrete. For example, the compresive and flexural strengths can be achieved in the range of 75-102 MPa and 11-13 MPa, respectively, which is reduced up to corresponding 30% and 36% by testing in various directions. Moreover, the void content is different from three typical samples, e.g. 3.8% voids (0.2–4.0 mm size) in mould-cast specimens whilst 4.8% formed in the poorly printed concrete and only 1.0% voids in the well printed concrete (Figure 3).

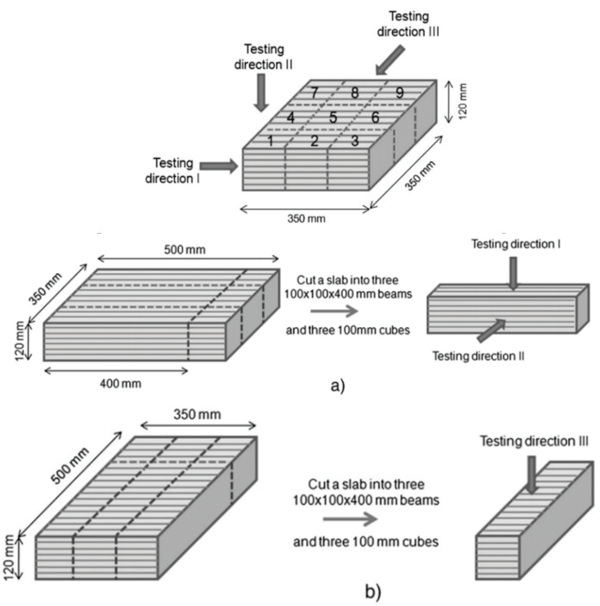

Figure 2. Diagram of cutting slabs and testing compressive strength and flexural strength [14] .

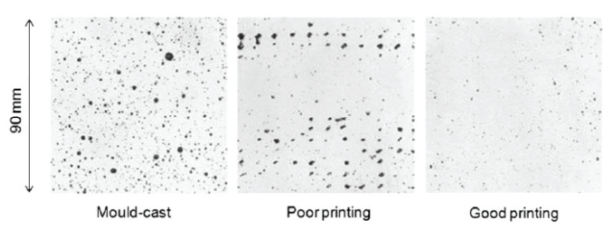

Figure 3. Three type samples for measuring the void content.

Besides, Rehman and Kim [15] reviewed rheology, mix designs, mechanical, microstructural, and durability characteristics of 3D concrete printing. Regarding the effect of printing direction on mechanical properties, the authors collected worldwide results on the strength of 3D printing concrete in different printing directions similar to the study of Le et al. [14]. The authors also concluded that each printing direction has an influence on the strength of the printed samples, in which the compressive and flexural strengths reduced about 50%, and even up to nearly 70% compared to those of casted samples.

From this analysis, in order to better understand the anisotropy of 3D printed concrete, this paper presents the influence of printing directions on compressive and flexural strengths of 3D printed concrete (3DPC) using materials available in Vietnam, especially in the case of adding fiber to improve its mechanical properties. The strength results were compared with those of casted samples with a designed compressive strength of 50 MPa.

2. Materials and methods

2.1 Materials

Portland cement PC50 Nghi Son (according to Vietnamese standard TCVN 2682 [16]), undensified silica fume (SF), and fly ash (FA) conforming to class F specified in ASTM C618 [17] were used for the binder of the 3DPC mixture with chemical composition and properties given in Table 1 and Table 2, respectively. Additionally, fine sand aggregate with maximum particle size of 2.5 mm and a density of 2.62 g/cm^3 was used for all mixtures (Table). To obtain reliable workability (flow value between 150 mm and 200 mm) of mixtures, a Sika Viscocrete 3000-20M superplasticizer was employed. Besides, polypropylene fibers with a diameter of 0.03 mm and a length of 6-7 mm were also used in this research.

2.2 3DPC mix proportions

In this research, the 3DPC mixtures were selected based on the studies of author Le et al. [4] with the binder including 70% cement, 20 % FA and 10 % SF. With the designed 28-day compressive strength of casted concrete greater than 50 MPa, the water to binder (W/B) ratio of 0.35 by weight was selected. Besides, the sand to binder (S/B) ratio of 1 by weight was fixed in this study. The supperplasticizer was used to control the flow value of mixtures in the range of 150-200 mm. The details of 3DPC mix proportions are given in Table 3.

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2.4 Methods

The printing process was performed by a 3D concrete printing system (Figure 4) with two main parts whose details are shown in Figure 5.

- Material preparation and mixing process
- Printing process and strength test

Note that the nozzle moves at a speed of about 1.35 - 1.8 m/min depending on the flowability of the material. An electronic rotation motor assembled on the nozzle head helps to extrude the material. The maximum extrusion speed of the helical screw motor is 3000 rpm. The extrusion speed can be varied from 0 to 100% of the maximum speed. The speed of the nozzle will be automatically calculated by the software in accordance with the rotation speed of the screw.

To evaluate the compressive strength of hardened 3DPC, a number of slabs with a size of 450 × 450 × 100 mm (Figure 6) was printed, then cut into 100 × 100 × 100 mm samples (Figure 7) and 100 × 100 × 400 mm (Figure 8) to test the compression and flexion complied with Vietnamese standards TCVN 3118:1993 and TCVN 3119:1993 in different X-Y-Z directions, respectively. Besides, cube and prism samples with the exact above sizes were cast for comparison with the printed samples.

Table 1. Chemical composition of cementitious materials.

Material	Chemical composition (%)									
	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	TiO_2	LOI
Cement	20.3	5.05	3.51	62.81	3.02	-	-	2.00	-	1.83
SF	92.3	1.91	0.86	0.32	0.85	0.38	1.22	0.30	-	1.68
FA	46.82	12.3	25.29	1.20	1.16	1.09	2.50	0.60	0.08	4.04

Table 2. Properties of cementitious materials.

Properties		Unit	Cement	SF	FA
Fineness (Blaine)		cm^2/g	4130	N/A	N/A
Mean particle size		µm	10.8	0.141	5.83
Density		g/cm^3	2.94	2.10	2.40
28-day strength reactivity index		%	-	110	85.4
Compressive strength	After 3 days	MPa	33.5	-	-
	After 28 days	MPa	55.4	-	-

Table 3. 3DPC mix proportions.

No	Mixture	W/B	S/B	SF (% wt. of binder)	FA (% wt. of binder)	Superplasticizer (% wt. of binder)	PP (% by vol. of concrete)
1	3DPC0	0.35	1	10	20	0.3	0
2	3DPC0.5	0.35	1	10	20	0.51	0.5
3	3DPC0.7	0.35	1	10	20	0.85	0.7

Figure 4. Structure of 3D printing concrete system.

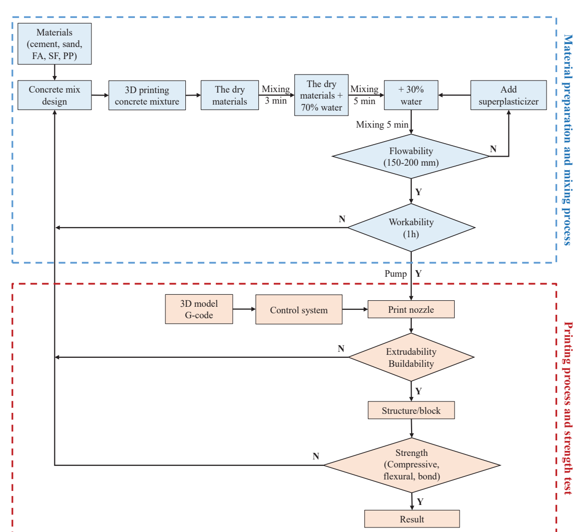

Figure 5. The printing process applied in this study.

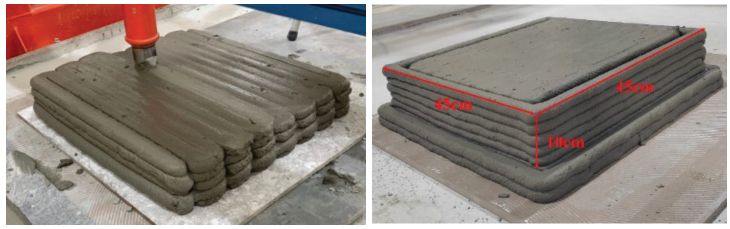

Figure 6. 3D printed concrete slab/block.

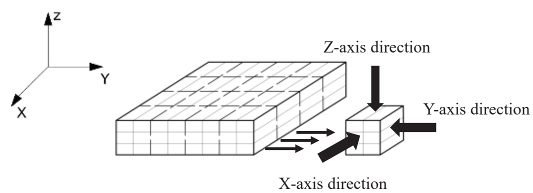

Figure 7. Cutting diagram and testing directions for 100 × 100 × 100 mm samples extracted from the 450 × 450 × 100 mm slab.

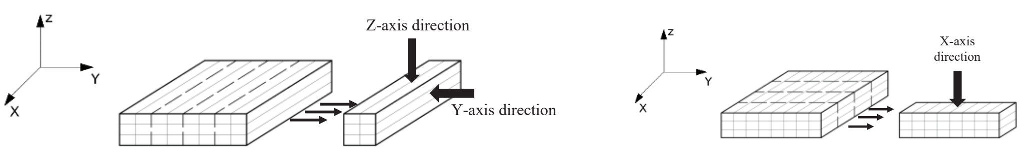

Figure 8. Cutting diagram and testing directions for 100 × 100 × 400 mm samples extracted from the 450 × 450 × 100 mm slab.

3. Results and discussions

3.1 Anisotropy in compressive strength of 3DPC

The compressive strength of casted samples and 3DPC samples with and without PP fiber at the ages of 3, 7, 28 days is shown in Table 4and Figure 9.

It can be seen that with the casted samples, the 28-day compressive strength of the control sample was reached over 70 MPa. However, the compressive strength of printed samples was significantly reduced and dependent on the printing direction where the compressive strength only in the Y direction can be obtained 57.8 MPa, and the other directions are lower than 50 MPa. This may be caused by the anisotropy due to voids created between the filaments (e.g. depicted in Figure 10a for X direction tests), and the bond between filaments is not in enough quality performance.

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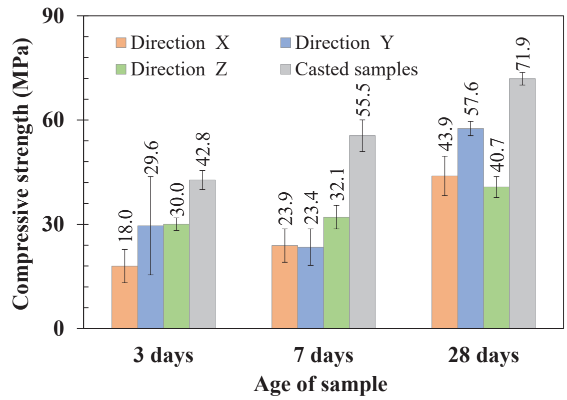
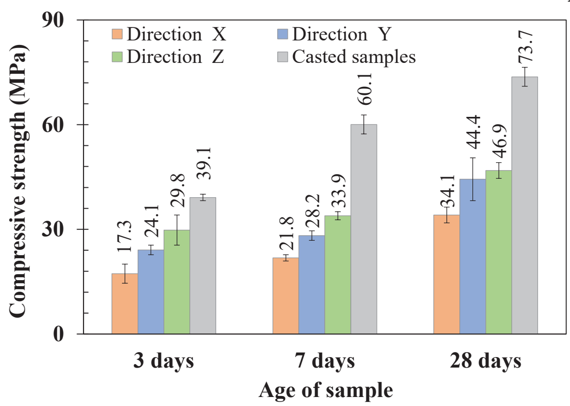
Table 4. Compressive strength of the casted samples and 3DPC samples with and without fibers

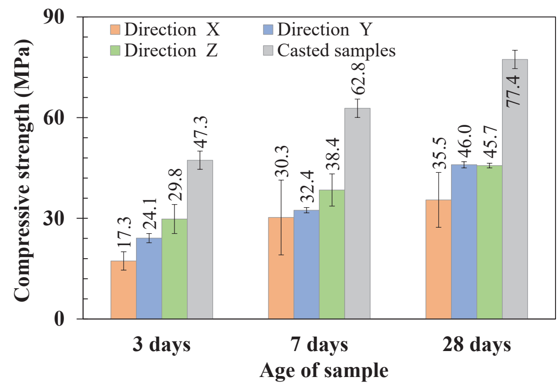
Age	Testing direction	Compressive strength of samples (MPa)					
		3DPC samples			Casted samples		
		3DPC0 sample	3DPC0.5 sample	3DPC0.7 sample	3DPC0 sample	3DPC0.5 sample	3DPC0.7 sample
3 days	Direction X	18.0	17.3	18.2	42.8	39.1	47.3
	Direction Y	29.6	24.1	25.5			
	Direction Z	30.0	29.8	30.7			
7 days	Direction X	23.9	21.8	30.3	55.5	60.1	62.8
	Direction Y	23.4	28.2	32.4			
	Direction Z	30.0	33.9	38.4			
28 days	Direction X	43.9	34.1	35.5	71.9	73.7	77.4
	Direction Y	57.6	44.4	46.0			
	Direction Z	40.7	46.9	45.77			



(a) Casted and printed samples without fiber



(b) Casted sample without fiber and printed samples using 0.5% fiber



(c) Casted sample without fiber and printed samples using 0.7% fiber

Figure 9. Compressive strength of the casted samples and 3DPC samples with and without fibers.

(a) (b) (c)

Figure 10. The damages of printed samples after compression tests with (a) X direction (without fiber), (b) Y direction (with fiber), and (c) Z direction (with fiber).

The addition of fibers, i.e., 0.5% and 0.7% by volume of concrete, improves the compressive strength of the printed samples, but not significantly. In addition, the compressive strength of printed samples is lower than that of casted samples, for example, obtaining 40-80% for printed samples using both 0.5% and 0.7% fibers.

It should be noted that the compressive strength of printed samples is the lowest for the X direction and highest for the Z direction, and the other two Y and Z directions have better strength compared with the X direction. The compressive strength of the direction X sample is about 10 MPa lower than that of the Z direction one, while the strength of the Z direction sample is insignificantly higher than that of the Y direction sample, i.e. about 2–5 MPa.

The results showed that the use of fiber improved the compressive strength of 3DPC but not significantly. The strength between different printing directions is still large, i.e. 15-20% depending the direction and the age of sample.

3.2 Anisotropy in flexural strength of 3DPC

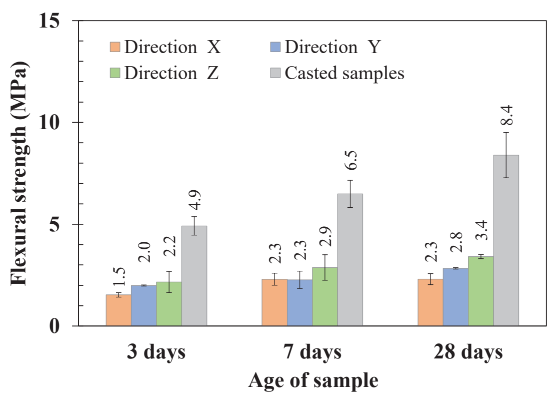
The flexural strength of casted samples and 3DPC samples with and without PP fibers at the ages of 3, 7, 28 days is shown in Table 5 and Figure 11.

The results from Figure 11a show that the flexural strength of casted samples without fiber ranges from 5-8.5 MPa, and this strength reduces about 60% for 3DPC samples. The highest and lowest strength can be achieved with Z direction and X direction, respectively.

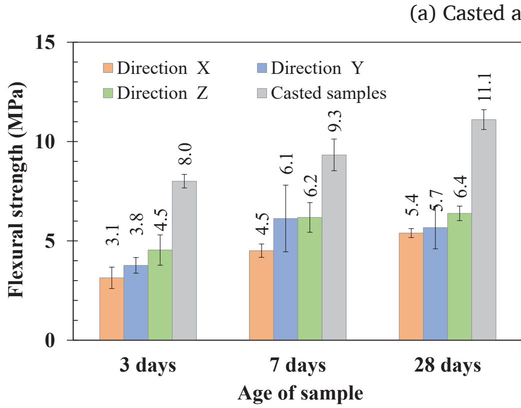
The addition of fibers enhanced the flexural strength of samples from 3 to 4 MPa and reached about 60% of the strength of casted samples. Besides, the flexural strength of samples with X direction was lower compared with that of Y and Z direction. These results agreed with other research authors [14,15]. This phenomenon can also be explained that the voids formed between the filaments making it anisotropic, which weakens the strength of samples with different printing directions. For example, it can be observed in Figure 12 that the sample with direction X contains a lot of voids between the filaments, while it does not happen with the sample in Z direction. In addition, note that the more the fibers were added, the higher flexural strengths were achieved. The flexural strength of samples using 0.7% fibers increased 3-4 MPa compared with that of samples using 0.5% fibers.

Table 5. Flexural strength of the casted samples and 3DPC samples with and without fibers.

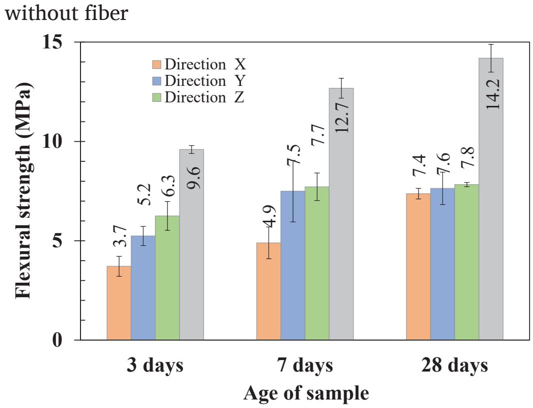
Age	Testing direction	Flexural strength of samples (MPa)					
		3DPC samples			Casted sample		
		3DPC0 sample	3DPC0.5 sample	3DPC0.7 sample	3DPC0 sample	3DPC0.5 sample	3DPC0.7 sample
3 days	Direction X	1.5	3.1	3.7			
	Direction Y	2.0	3.8	5.2	4.92	8.0	9.6
	Direction Z	2.2	4.5	6.3			
7 days	Direction X	2.3	4.5	4.9			
	Direction Y	2.3	6.1	7.5	6.49	9.3	12.7
	Direction Z	2.9	6.2	7.7			
28 days	Direction X	2.3	5.4	7.4			
	Direction Y	2.8	5.7	7.6	8.39	11.1	14.2
	Direction Z	3.4	6.4	7.8			



(a) Casted and printed samples without fiber

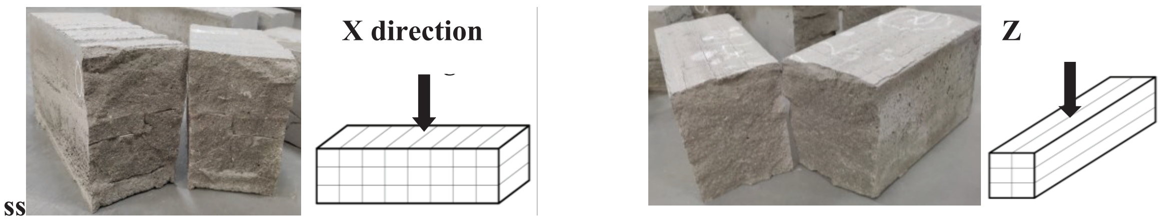


(b) Casted samples without fiber and printed samples using 0.5% fiber



(c) Casted samples without fiber and printed samples using 0.7% fiber

Figure 11. Flexural strength of the casted samples and 3DPC samples with and without fibers.



(a) (b)

Figure 12. The damage of printed samples using fiber after flexural tests (a) X direction, (b) Z direction

3.3 Effect of printing direction on strength of 3DPC

The influence of printing direction on the compressive and flexural strengths of 3DPC has been evaluated and shown in Figure 13 and Figure 14 respectively. These results were also compared with those from other research [14,15], and they were presented by a colour background area behind in the experimental points.

Regarding the compressive strength of 3DPC with different printing directions (Figure 13), it can be seen clearly that the compressive strength of printed samples achieves in a range of about 40 - 80% compared to the control samples. The X direction gives the lowest strength due to the weakened interlayer bond strength of filaments as mentioned above.

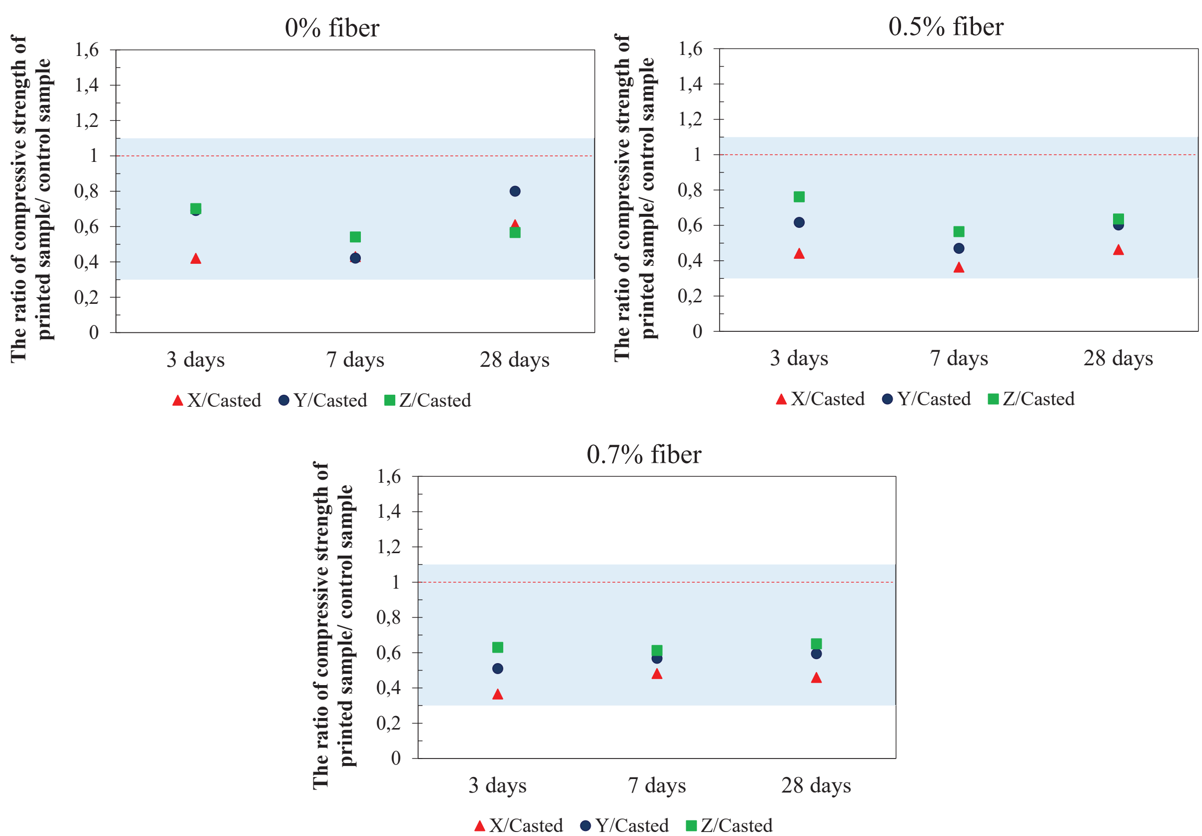


Figure 13. Ratio of compressive strength in different printing directions between printed and casted samples.

The same phenomenon can be observed in the flexural strength of 3DPC samples with different printing directions (Figure 14). The flexural strength of 3DPC samples was about 40 – 60% lower than that of casted samples. Some of the results obtained in this research are relatively low compared with the results of other authors [14,15], especially the strength with direction X. However, the difference in printing direction was not significant at the age of 28 days for samples using 0.5 and 0.7% fiber. This demonstrates that the addition of fiber reduced the anisotropy in the flexural strength of 3DPC.

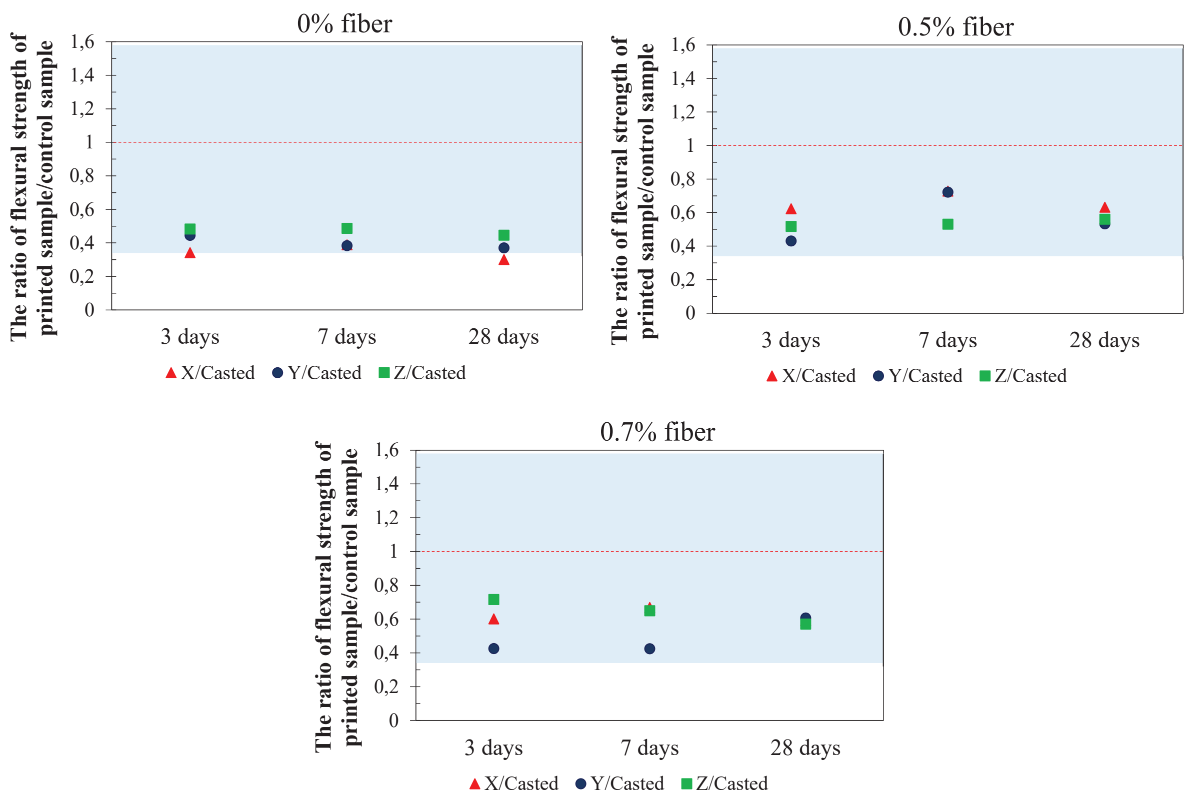


Figure 14. Ratio of flexural strength in different printing directions between printed and casted samples.

4. Conclusions

Print direction significantly affected the strength of fiber-free 3DPC, in which the X direction of the printed samples has the lowest strength (reaching about 30-40% of the compressive strength and 20-30% of the flexural strength of the casted samples), while the Y and Z directions could reach about 60-70% of the compressive strength and 40-50% of the flexural strength of the casted samples. This is probably due to the higher void content and lower interlayer bond strength, which weakened the strength of the X direction samples compared with that of the other direction samples.

The addition of fibers enhanced the flexural strength of 3DPC, especially with a higher fiber content, i.e. 0.7% versus 0.5% in this study. The addition of fiber also reduced the anisotropy in the flexural strength of 3DPC at a later age, i.e. 28 days. The strength values of the 3DPC samples were shown to be similar in different directions.

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