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Influence of polypropylene fibers and polyoxymethylene fibers on mechanical property and drying shrinkage of 3d printed concrete

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Abstract: The construction of 3D Printed Concrete (3DPC) structures, particularly in reinforced concrete, still poses challenges due to constraints in construction methods. Additionally, the unique mixture design of 3DPC typically results in noticeable drying shrinkage. Utilizing short fibers for fiber reinforcement is a reliable approach that may replace reinforcing steel and address the challenge of volume stability. In this study, polypropylene (PP) fibers and polyoxymethylene (POM) fibers were incorporated into the total volume of concrete at additional percentages of 0.5%, 1.0%, and 1.5% to printed the specimen. While ensuring printability, various experiment were conducted to evaluate compressive strength, flexural strength, anisotropy, and drying shrinkage,to ensure the impact of fiber type and content on the mechanical properties and drying shrinkage of 3DPC. The results indicate that 3DPC exhibits significant strength loss after fiber addition, with loss percentages approximately ranging from 5% to 55% for compressive strength and 9% to 57% for flexural strength. The extent of loss improves with increasing PP fiber content, while the strength of POM fibers continues to decline with increased usage. Furthermore, significant anisotropy is observed in 3DPC after fiber addition, with compressive strength relations appearing as $X > Y \approx Z$ in various directions, while flexural strength relations are demonstrated as $Y \approx Z > X$. Concerning drying shrinkage, the addition of 1.0% POM fibers proves most effective in inhibiting drying shrinkage, reducing shrinkage by approximately 6% at the age of 56 days. In contrast, the presence of PP fibers, regardless of quantity, adversely affects drying shrinkage.
Key words: 3DPC, Fiber, Mechanical Property, Drying Shrinkage

1. INTRODUCTION

3D Printing Concrete (3DPC) is gradually gaining attention worldwide, with the number of projects involving 3DPC experiencing exponential growth. The use of 3DPC technology eliminates the need for formwork, leading to shorter construction periods, reduced manpower requirements, and lower costs.

Currently, 3DPC has been successfully applied in the manufacturing of structures such as bridges, houses, and bus stations [1][2][3].

The majority of concrete applications require the use of reinforced concrete structures to meet performance requirements such as ductility, load-bearing capacity, and durability. However, in the 3D printing process of concrete, there are limitations due to the complexity of traditional rebar placement, posing significant challenges to the construction of reinforced concrete structures [4]. In addition, 3DPC typically involves the use of a higher proportion of cementitious material, making its volume more unstable [5].

In 3DPC, the use of short fibers is a reliable approach for improving mechanical behavior to address the challenge of replace reinforcing steel and volume stability[6].

However, the unique distribution of fibers may affect the mechanical behavior of fiber-reinforced 3DPC in specific directions, creating differences between 3DPC and traditional cast concrete [7][8] [9][10]. Additionally, fibers can form a bridging effect within the cement matrix to reduce the likelihood of shrinkage [11], but their ability to improve volume stability depends on the characteristics and quantity of the fibers.

This study employed polypropylene (PP) fibers and polyoxymethylene (POM) fibers, adding 0.5%, 1.0%, and 1.5% of the total concrete volume to printed the specimen. The evaluation included compressive strength, flexural strength, anisotropy, and drying shrinkage tests to assess the influence of different types of fibers on the mechanical properties and volume stability of 3DPC.

2. MATERIALS AND METHODS

2.1. Materials

The cementitious material used in this experiment are cement and silica fume, with their chemical composition shown in Table 1. The aggregate is quartz sand with a particle size ranging from 0.60 to 0.15 mm, a water absorption rate of 1.1%, and a specific gravity (SSD) of 2.67. The short fibers used include 6 mm polypropylene (PP) fibers and polyoxymethylene (POM) fibers, with their basic properties detailed in Table 2. Chemical admixtures such as superplasticizer (SP) and viscosity modifying admixture (VMA) are used to ensure the printability of 3D printed concrete.

Table 1. Chemical composition of cement and silica fume

Unit: %

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	LOI
Cement	20.12	4.79	3.24	64.56	2.33	2.07
Silica fume	90.80	-	-	-	-	1.90

Table 2. Basic properties of fibers

Material	Length (mm)	Diameter (μm)	Elastic modulus (GPa)	Ultimate tensile strength (MPa)
POM fibers	6	30	1.4	-
PP fibers	6	200	12	1200

2.2. Test Method

This study primarily explores the impact of fiber type and content on the mechanical properties and drying shrinkage of 3DPC while ensuring printability.

The compressive strength test follows ASTM C109, with specimen dimensions of 50 × 50 × 50 mm. The flexural strength test adheres to ASTM C348, with specimen dimensions of 40 × 40 × 160 mm, conducted at 28 days. The specimens are produced using a 3D printer to create larger samples, which are then cut to the specified dimensions using a cutting machine after a curing period of at least 7 days. The effect of printing direction on mechanical properties is considered for compressive and flexural strength tests, which are conducted in the X, Y, and Z directions, as shown in Figure 1. The coefficient of variation (CV) is used to assess the strength statistical dispersion in each direction, serving as an indicator of anisotropy, with a larger CV indicating more significant anisotropy. The formula for CV is provided in equation (1).

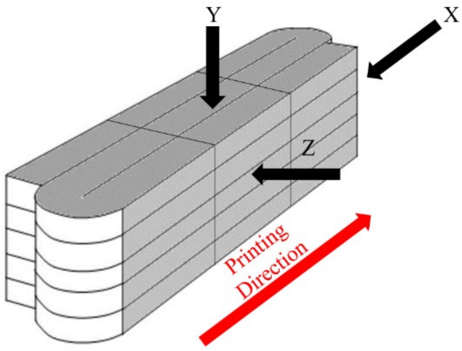

Figure 1. Illustration of different orientations of 3DPC specimens

$$\mathrm{CV} = \frac{\sqrt{\frac{\left(F_x - F_{avg}\right)^2 + \left(F_y - F_{avg}\right)^2 + \left(F_z - F_{avg}\right)^2}{3}}}{F_{avg}} \tag{1}$$

In this equation, Fx represents the test value of the load applied perpendicular to the X-direction of the specimen, Fy is the test value of the load applied perpendicular to the Y-direction of the specimen, Fz is the test value of the load applied perpendicular to the Z-direction of the specimen, and Favg is the average of Fx, Fy, and Fz.

Drying shrinkage tests were conducted following ASTM C596, with specimens measuring 25 × 25 × 285 mm. The specimens were demolded after 24 hours and placed in a curing chamber. After reaching an age of 3 days, the specimens were removed from the curing chamber, wiped dry, and their initial lengths were measured using a length comparator. Subsequently, they were air-cured, and the length changes of the specimens were measured until the age of 53 days of air curing.

2.3. Mixture proportions design

In the cementitious materials used in this study, the ratio of cement to silica fume is 7:3 by volume. The water-cementitious material ratio (W/C_M) is fixed at 0.3. The aggregate content is calculated as the volume percentage between the cementitious materials and aggregate (i.e., sand-cementitious material ratio (A/C_M)). The sand-cementitious material ratio in this study is fixed at 1.25. Chemical admixtures, including a siperplasticizer (SP) and a viscosity modifying admixture (VMA), were used to control the workability of the concrete and increase viscosity. The fibers used are polypropylene fibers (PP) and polyoxymethylene fibers (POM), added in extra percentages of 0.5%, 1.0%, and 1.5% of the total concrete volume. The mixture design is presented in Table 3.

Table 3. 3DPC mixture design.

Unit: kg/m^3

Mix ID	W/C_M	A/C_M	Cement	Silica fume	Fine aggregate	Fibers (%)[1]		SP	VMA
						PP	POM	(%)[2]	(%)[2]
NF	0.3	1.25	714	214	1081	-		1.2	0.5
PP0.5	0.3	1.25	714	214	1081	0.5	-	1.4	0.5
PP1.0						1.0		1.4	
PP1.5						1.5		1.6	
POM0.5	0.3	1.25	714	214	1081	-	0.5	1.2	0.5
POM1.0							1.0	1.4	
POM1.5							1.5	1.6	

[1]：The fibers are added as a percentage of the total concrete volume.

[2]：The quantity of SP and VMA is expressed as a weight percentage of the cementitious materials.

3. RESULTS AND DISCUSSION

3.1. Compressive strength test

Observing Figure 2, it is evident that the production of 3D printed concrete (3DPC) with PP (polypropylene) and POM (polyoxymethylene) fibers leads to a phenomenon of compressive strength loss. However, the extent of this loss can be reduced with an increase in the amount of PP fibers, while it tends to increase with the rise in POM fiber content.

In terms of PP fibers, the overall compressive strength of the PP0.5 mix exhibits a loss of approximately 31% compared to the control group NF. As the quantity of PP fibers increases, the compressive strength loss for the PP1.0 and PP1.5 mixes decreases to around 30% and 5%, respectively. Regarding POM fibers, the overall compressive strength of the POM0.5 mix shows a loss of about 33% compared to the NF control group. However, with an increase in the quantity of POM fibers, the compressive strength loss for the POM1.0 and POM1.5 mixes increases to 37% and 55%, respectively.

Additionally, it is noteworthy that the overall compressive strength of the PP1.5 mix, while showing some loss compared to NF, is mainly manifested in the Y and Z directions. The compressive strength in the X direction is closer to NF. The compressive strength in the X direction is closer to NF. The fiber content being the same at 0.5%, the order of compressive strength from high to low is NF ≈ PP1.5 > PP1.0 > PP0.5 > POM0.5 > POM1.0 > POM1.5.

Furthermore, through the calculation of anisotropy results (as shown in Table 4), it is observed that NF does not exhibit significant differences in test results in the X, Y, and Z directions, indicating no apparent anisotropy. This phenomenon is related to the shorter interlayer interval time during the printing process in this study. Shortening the interlayer interval time can prevent moisture loss from the surface of printed layers, effectively improving interlayer bonding, thereby reducing the formation of anisotropy[12][13]. However, after the addition of fibers, 3DPC shows significant anisotropy in compressive strength, with the relationship expressed as X > Y ≈ Z. This is associated with the arrangement of fibers parallel to the printing direction, where fibers arranged perpendicular to the loading direction may lead to the formation of weak planes inside the specimen, thereby affecting compressive strength test results.

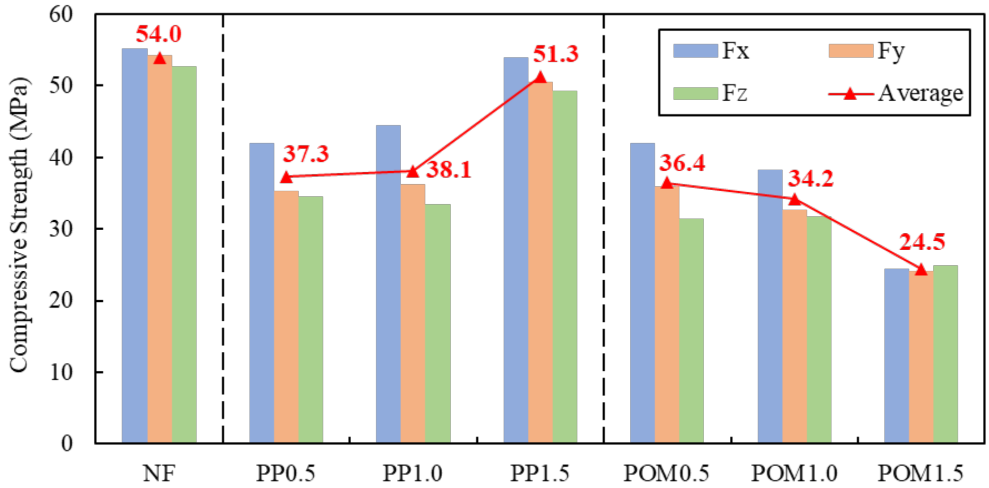

Figure 2. Compressive strength of 3DPC

Table 4. Anisotropy in the Compressive Strength of 3DPC

Mix ID	NF	PP0.5	PP1.0	PP1.5	POM0.5	POM1.0	POM1.5
CV	0.02	0.09	0.12	0.09	0.12	0.08	0.01

3.2. Flexural Strength Test

Observing Figure 3, it can be noted that the addition of fibers in the 3DPC shows consistent performance in both flexural and compressive strength.

For PP fibers, the overall flexural strength for the mixtures PP0.5, PP1.0, and PP1.5 exhibits losses of approximately 31%, 29%, and 9%, respectively, compared to the control group NF. On the other hand, in the case of POM fibers, the overall flexural strength for mixtures POM0.5, POM1.0, and POM1.5 shows losses of about 17%, 34%, and 57%, respectively, compared to the control group NF. Additionally, it can be observed that the overall flexural strength losses for mixtures PP1.5 and POM0.5 are mainly pronounced in the X direction, while the Y and Z directions are closer to NF. Therefore, the ranking of compressive strength from high to low is NF ≈ PP1.5 ≈ POM0.5 > PP1.0 > PP0.5 > POM1.0 > POM1.5.

Furthermore, based on the calculation results of anisotropy (as shown in Table 5), it is found that the anisotropic performance in flexural strength for each mixture is similar to compressive strength. Specifically, for NF, the test results in the X, Y, and Z directions do not show significant differences, but after adding fibers, a more pronounced anisotropy becomes evident. However, unlike compressive strength, in the case of flexural strength, the relationship in each direction can be expressed as Y ≈ Z > X. This phenomenon is due to the fact that when bending loads act in the Y or Z direction, the internal fiber arrangement is perpendicular to the loading direction, allowing it to better exhibit its characteristics. When the loading direction is in the X-axis, two possible scenarios may arise: (1) When subjected to bending loads on the printed specimen, fibers align parallel to the loading direction, resulting in the formation of a weak plane within the printed structure. (2) Bending loads act directly on the interlayer in the printed specimen. Both of the aforementioned scenarios are unfavorable for the development of bending strength. Simultaneously, a reasonable explanation can be provided for the greater loss of bending strength in the X-direction compared to the Y and Z directions.

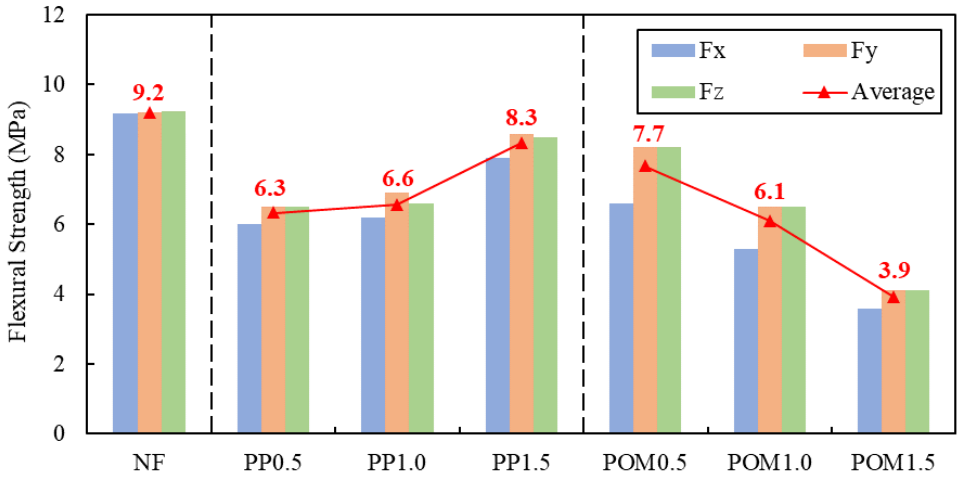

Figure 3. Flexural strength of 3DPC

Table 5. Anisotropy of bending strength in 3DPC.

Mix ID	NF	PP0.5	PP1.0	PP1.5	POM0.5	POM1.0	POM1.5
CV	0.00	0.04	0.04	0.04	0.10	0.09	0.06

3.3. Drying Shrinkage Test

The impact of different fibers on the drying shrinkage of 3DPC is illustrated in Figure 4. (a) and Figure 4. (b). It can be observed that the shrinkage increases with the age, and the stabilizes after the 18th day of the drying curing period.

Upon closer examination of the figures, it is evident that the addition of PP fibers leads to an increase in the shrinkage of 3DPC, and the extent of shrinkage rises with the increasing amount of PP fibers. The shrinkage for PP0.5, PP1.0, and PP1.5 at the 25th day of the curing period is approximately 7%, 14%, and 17% higher than that of NF (No Fiber), respectively.Furthermore, the addition of POM fibers proves effective in reducing the drying shrinkage of 3DPC. However, with the increasing amount of POM fibers, the shrinkage shows a trend of first decreasing and then increasing. Specifically, adding 1.0% of POM fibers achieves the most significant reduction in drying shrinkage. The shrinkage for POM0.5, POM1.0, and POM1.5 at the 25th day of the drying curing period is approximately 6%, 12%, and 4% lower than that of NF, respectively.

In summary, POM fibers exhibit a better inhibitory effect on the drying shrinkage of 3DPC, while PP fibers exacerbate its drying shrinkage performance. One possible reason for this phenomenon is that POM fibers exist as individual strands and are evenly dispersed in the cement mortar after thorough mixing, forming a network structure to resist the shrinkage behavior of 3DPC. On the other hand, PP fibers, due to their clustered form, tend to trap air during the mixing process, leading to the formation of more air voids, thereby increasing their shrinkage during the drying curing period and outweighing the inhibitory effect formed by the fibers. Additionally, the difference in elastic modulus between the two types of fibers may also contribute to the different drying shrinkage performances of 3DPC, with POM fibers benefiting from their higher elastic modulus, resulting in a greater inhibitory effect on the drying shrinkage compared to PP fibers.

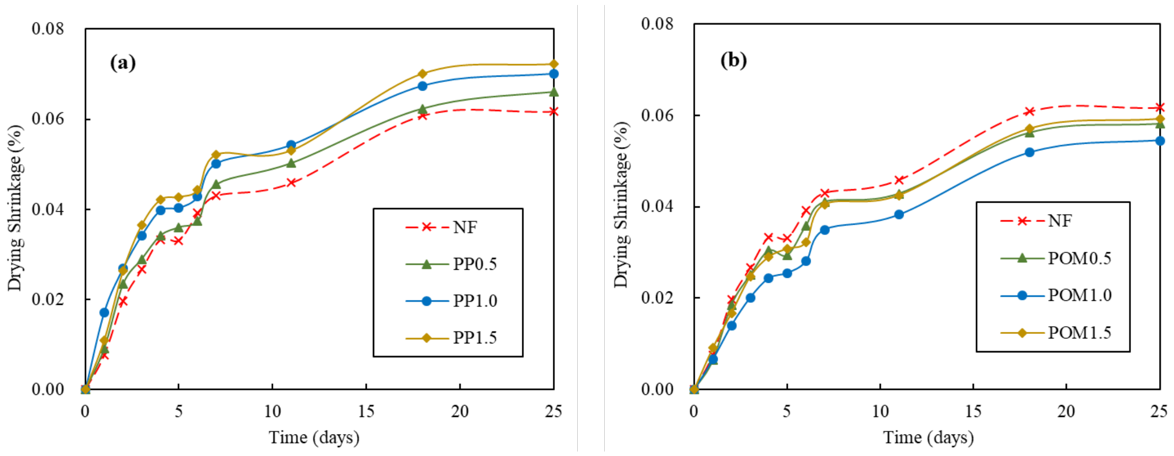

Figure 4. Drying shrinkage of 3DPC: (a) PP Fiber, and (b) POM Fiber.

4. CONCLUSIONS

1. The addition of fibers significantly impacts the compressive strength, flexural strength, anisotropy, and drying shrinkage of 3DPC.
2. The addition of PP fibers affects the compressive and flexural strength of 3DPC. However, the strength loss can be mitigated with increasing amounts of PP fibers, and the minimum loss occurs at a usage of 1.5%, with compressive and flexural strength losses of approximately 5% and 9%, respectively.
3. The addition of POM fibers affects the compressive and flexural strength of 3DPC, and the strength loss increases with the amount of POM fibers. The minimum loss occurs at a usage of 0.5%, with compressive and flexural strength losses of approximately 33% and 17%, respectively.
4. After adding fibers, 3DPC exhibits significant anisotropy, with the compressive strength relationship expressed as $X > Y \approx Z$, and the flexural strength relationship as $Y \approx Z > X$.
5. Regarding drying shrinkage, the addition of POM fibers effectively inhibits the drying shrinkage of 3DPC, with the most significant improvement observed at POM1.0, resulting in a reduction of approximately 12% in drying shrinkage at 25 days of curing (28 days of age). However, the addition of PP fibers exacerbates the drying shrinkage of the concrete.

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