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Effect of Metallic Fibers on the Print Quality and Strength of 3D Printed Concrete

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Abstract. 3D concrete printing is a promising technology in the construction field. Un-availability of standards/specifications related to certification of 3D printed structures and lack of reinforcement in printed concrete are the major factors behind the under-utilization of such innovative technology. Addition of fibers as reinforcement in the printable mix could be considered as viable solution to improve mechanical properties of printable mix particularly tensile strength. In this regard, recently carried out studies have used mostly non-metallic fibers with low modulus of elasticity and tensile strength. In this study, effect of adding flexible amorphous metallic fibers on the print quality and mechanical properties (flexural and direct tensile strengths) of resulting mixes has been investigated. Fibrous and non-fibrous mixes were designed. To prepare fibrous mixes, metallic fibers were used at dosage of 20kg/m^3, 30kg/m^3 and 40kg/m^3. Further, to study the influence of fiber length on the print quality and strength, fibers of length 5mm, 10mm and 15mm were used. Reference specimens for tensile and flexural strength tests were also cast in molds using all mixes used for printing. Results showed that addition of metallic fibers of length 10mm and 15mm exhibited detrimental effects on the print quality, however, strength values, particularly tensile strength of printed concrete were observed to be enhanced by the addition of these fibers. Although print quality of mix containing fibers of 5mm length was least affected, no positive impact of these fibers on the mechanical strength of printed concrete was noticed.

Keywords: 3D printed concrete, metallic fibers, print quality, mechanical strength, cast-in-mold concrete.

1 Introduction

3D printing of concrete is an emerging technique of construction which has attracted the attention of researchers in many countries on the globe. Unlike conventional construction technique, in 3D concrete printing, cement based material is extruded by a nozzle and deposited in layers without the use of any formwork to print structures. Comparing to in-situ and pre-cast construction techniques, architectural freedom, cost reduction through saving in material and labor, fast production and improved effi-

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ciency and safety are the main advantages of 3D concrete printing. However, lack of conventional reinforcement and certified standards has limited the benefits that this constructing technique could have been able to offer to modern construction industry [1]. In this regard, addition of fibers as reinforcement in the printable mix could be considered as viable solution to improve mechanical properties of printable mix particularly tensile strength. Recently, few researchers have attempted to add micro fibers in the mix before extrusion as well as adding steel reinforcement during the extrusion to improve the structural performance of printed elements [1-5]. In most of the recently carried out research studies, mainly non-metallic fibers with low modulus of elasticity and tensile strength were used. In this present study, effect of adding flexible metallic fibers on the print quality and mechanical properties (flexural and direct tensile strengths) of the mix has been investigated.

2 Materials and Methods

2.1 Materials

For this study, printable mortar mix was designed using CEM I 52.5 N cement (30% by weight of dry mix), limestone filler (10%), kaolin (10%), natural siliceous sand (50%), high rate water reducing (HRWR) admixture (0.4% by weight of cement) and flexible metallic fibers of three different lengths (5mm, 10mm and 15mm). The water to fines (cement + limestone filler + kaolin) ratio was kept as 0.31.

2.2 Printable concrete mixes

In total 10 concrete mixes were prepared: one control mix without fibers and remaining nine of metallic fiber-reinforced concrete. Flexible amorphous metallic fibers of 5, 10, and 15mm length (refer to Fig.1) were used to prepare fiber-reinforced concrete mixes. Amorphous metallic fibers are CE certified according to NF EN 14889-1 standard. For this study, three dosages of fibers; 20kg/m^3, 30kg/m^3 and 40kg/m^3 were investigated. Detail of all ten concrete mixes with respect to fiber length, dosage of fibers and mix designation is provide in Table 1, while properties of fibers are given in Table 2.

2.3 Printing process

U-shape objects were printed using a 3 degree of freedom printer (Delta WASP 3MTIndustrial 4.0). Printing speed was 25mm/sec. For each concrete mix, one object was printed. Information related to size of U-shape objects and test specimens saw-cut from printed objects for mechanical tests is provided in section 2.4. Circular nozzle of diameter 30 mm was used for printing. Due to very small settlement of material after extrusion, width of layer varied from 30 to 35 mm (see Fig.2), thickness of layer varied between 20 and 25 mm, while width of contact surface between layers varied from 22 to 28 mm as shown in Fig.2.

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5mm 10mm 15mm

Fig.1. Amorphous metallic fibers

Table 1. Detail of Concrete Mixes

Sr. No.	Mix designation	Fiber length (mm)	Fiber dosage (kg/m^3)
1	CONT	----	----
2	5FF20		20
3	5FF30	5	30
4	5FF40		40
5	10FF20		20
6	10FF30	10	30
7	10FF40		40
8	15FF20		20
9	15FF30	15	30
10	15FF40		40

Table 2. Properties of fibers

Property	**Value**
Length, mm	5, 10, 15
Width, mm	1.0
Thickness, μm	24
Equivalent diameter, mm	0.18
Number of fibers per kg	1100000, 580000, 385000
Specific surface (m^2/kg)	10
Density	7.2
Elastic modulus, GPa	140
Tensile strength, MPa	2000

2.4 Test Methods

Direct Tensile Strength: Displacement controlled direct tension tests were performed on printed and cast-in-mold specimens at 28 days after printing and casting, respectively. Both printed and cast-in-mold specimens were cured in air for 28 days. Loading rate was kept as 5μm/min for all direct tension tests. Printed test specimens of size

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10cm ×10cm × width (cm) according to layer width as shown in Fig.2 were saw-cut from the two sides [each of size 220x240 mm] of U-shaped printed objects as shown in Fig.4. Similarly, test specimens of cast-in-mold specimens of size 10cm x 10cm x 3cm were prepared as shown in Fig.3 and it is clear in this figure that a notch was provided at the center of each specimen. For each mix, two samples were tested and average value is reported in this contribution. Direct tension test in progress is shown in Fig.5.

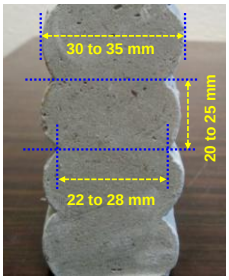


Fig.2. Layer dimensions



Printed Concrete



Cast-in-mold Concrete

Fig. 3. Test specimens for direct tension test



Fig.4. U-shaped printed objects



Printed Concrete Sample



Cast-in-mold Sample

Fig. 5. Direct tension test in progress

Flexural Strength: Displacement controlled three point bending tests were performed on printed specimens with three layers and on cast-in-mold specimens using all mixes prepared for this study. Loading rate was kept as 0.02mm/min up to 5% drop in the peak load value and then it was increased to 0.2mm/min. The printed samples for flexural strength test were also saw-cut from the central portion of size 400x240 mm of U-shaped printed objects as shown in Fig.4. For flexural testing, cast-in-mold specimens having standard size of 4cm × 4cm × 16cm were also prepared and cured in air for 28 days. The printed samples were tested for in-plane and out-of-plane

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bending strengths as shown in Fig.6. For each mix, two samples were tested and average value of flexural strength is reported here.

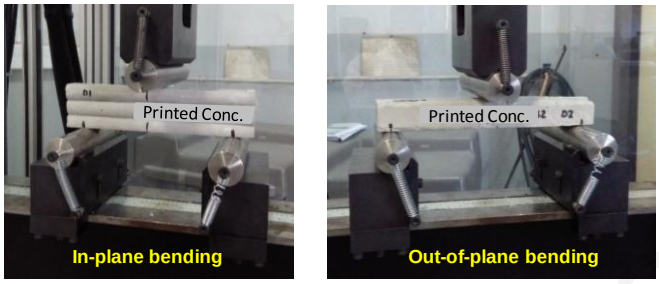


Fig.6. Flexural tests on printed specimens

3 Results and Discussion

3.1 Print Quality

To study the effect of adding fibers of different lengths at different dosages in the mix on the print quality, printing was done using nozzle of 30mm diameter. It was noticed that no significant change in the print quality occurred with the use of small length metallic fibers (i.e., 5mm) even up to dosage of 40kg/m^3. However, print quality was affected when fibers of 10mm and 15mm length were added in the mix. With the increase in the contents of these fibers from 20kg/m^3 to 40kg/m^3, the problem of poor print quality was observed to further aggravate. Discontinuity in the material within one layer was the major issue related to print quality. In general, no problem with respect to dimension conformity and consistency in the filaments printed using fiber reinforced concrete mixes made in this study was noticed. Layers printed with mix containing maximum dosage investigated in this study (i.e., 40kg/m^3) of 5mm, 10mm and 15mm long flexible metallic fibers are shown in Fig.7 where it is obvious that longer fibers severely affected the print quality of layer printed with 30mm diameter nozzle. In future, it will be interesting to study the relationship between fiber length and nozzle diameter on the print quality.

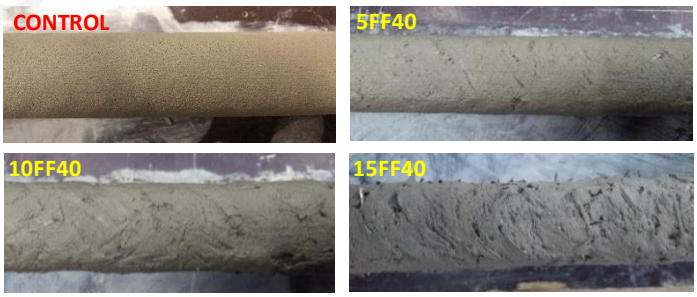


Fig.7. Effect of fibers on print quality

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3.2 Direct Tensile Strength

Tensile strength was calculated in each test using the maximum experimental force obtained divided by the average contact surface area between layers. For this purpose, after completion of each test on printed concrete, length and average width of failure surface of each specimen was measured to get the value of contact area as shown in Fig.8, where W1, W2 and W3 are widths at different locations which were used to get average width of contact surface. In case of cast-in-mold samples, surface area after providing notch was measured and used to calculate the tensile strength.

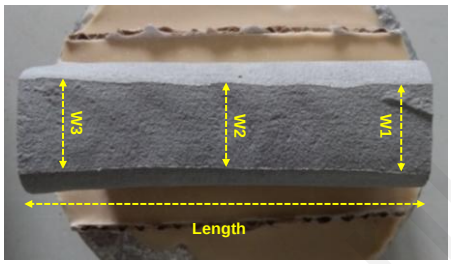


Fig.8. Contact surface area in printed sample

Tensile strength results are presented in Fig.9 where the tensile strength value of each mix is average of two samples tested for this purpose. The tensile strength results indicated that addition of 5mm long fibers in concrete at dosages of 20kg/m^3, 30kg/m^3 and 40kg/m^3 resulted in decrease in average tensile strength of printed element by 3.3%, 25% and 19.7% in comparison of control mix, respectively. However, presence of 10mm and 15mm long fibers in the concrete resulted in enhancement of tensile strength when compared to control mix. Fibrous mixes containing 10mm long fibers at dosages of 20kg/m^3, 30kg/m^3 and 40kg/m^3 resulted in increase in average tensile strength of printed element by 6.5%, 34% and 20% in comparison of control mix, respectively while for mixes containing 15mm long fibers at dosages of 20kg/m^3, 30kg/m^3 and 40kg/m^3 resulted in increase in average tensile strength of printed element by 17.9%, 26% and 28.5% in comparison of control mix, respectively. Since numbers of 5mm long fibers per kg are significantly large [refer to Table 2], presence of large numbers of fibers in horizontal direction (parallel to layer) as observed at failure surface during testing [see Fig.12] reduced the contact area of cement matrix between two layers which resulted in less bond strength in case of mix containing fibers of 5mm length. However, it was noticed during printing process that although print quality was adversely affected by 10mm and 15mm long fibers, part of few fibers coming out of the surface of already printed layer as shown in Fig.10 acted like nails which were later on embedded into subsequent printed layer and as a result tensile strength between layers was improved which is clear from the tensile strength results obtained with mixes containing 10mm and 15mm long fibers. Among all fibrous mixes, as indicated above, maximum tensile strength was exhibited by fibrous mix containing 10mm long fibers at 30kg/m^3 (10FF30) which was 34% more than that of tensile strength of control printable mix.

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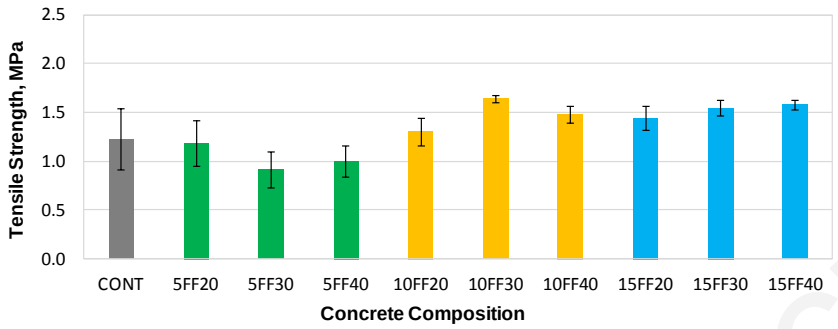


Fig.9. Tensile Strength [printed concrete]

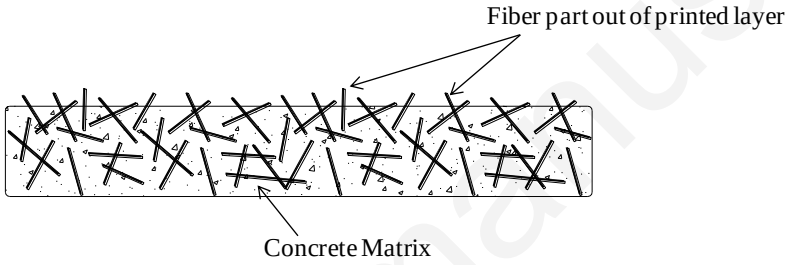


Fig.10. Positions of fibers near surface of printed layer

Comparison of tensile strength of printed and cast-in-mold concrete samples is presented in Fig.11 where it may be noted that results are presented for minimum (20kg/m^3) and maximum (40kg/m^3) dosages of fibers used in this study. Results indicated that printed concrete samples of all mixes were not able to achieve tensile strength as that of corresponding cast-in-mold concrete samples. It is pertinent to note in the results presented in Fig.11 that as the fiber length in the fibrous mixes was increased from 5mm to 15mm, the difference in the tensile strength exhibited by printed concrete and cast-in-mold concrete was decreased. This observation further strengthened the idea of nailing effect with long fibers.

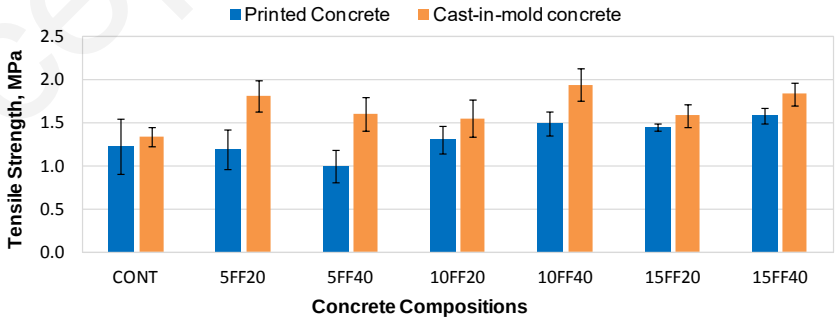


Fig.11. Comparison of tensile strength of printed and cast-in-mold concretes

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In each direct tension test on printed concrete samples, failure occurred at the interface of the layers; in no case failure occurred from within the layers. In Fig.12, failure surfaces of printed specimens tested in direct tension are shown, where difference in the surface of mixes containing 5mm, 10mm and 15mm long fibers is obvious.

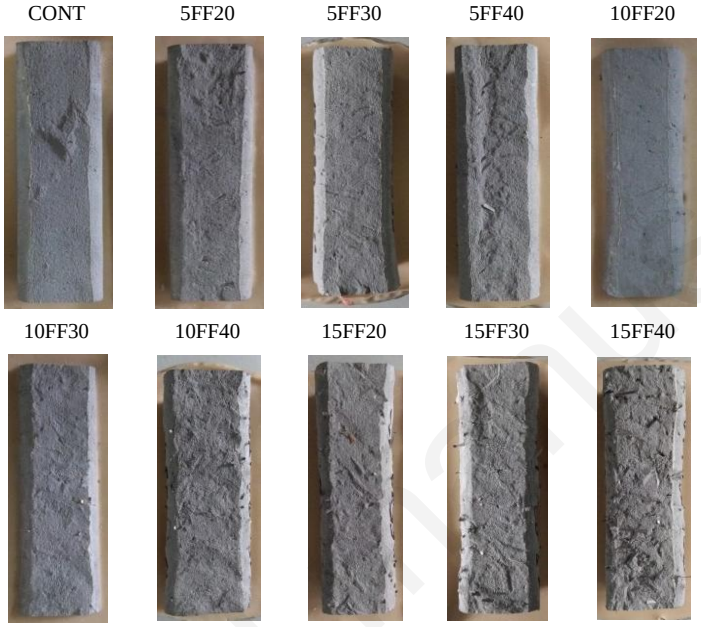


Figure 12: Failure surfaces of printed concrete samples [direct tension tests]

3.3 Flexural Strength

In-plane and out-of-plane flexural strength values [average of two samples] of printed concrete samples and cast-in-mold concrete (named as reference) samples are presented in Fig.13. It is obvious from these results that out-of-plane strength of each mix is greater than in-plane bending strength. The results indicated that addition of flexible metallic fibers of 5mm length up to dosage of 40 kg/m^3 negatively affected the flexural strength of printed concrete which was found to be even lesser than that of control mix. Similarly, no effect on the flexural strength was observed with the addition of fibers of length 10mm and 15mm at dosage of 20 kg/m^3 and 30 kg/m^3 since flexural strength of 10FF20, 15FF20, 10FF30 and 15FF30 mixes was almost similar to that of control mix. However, mix containing these fibers at dosage of 40kg/m^3 exhibited flexural strength value slightly greater than the control mix and among all fibrous concrete mixes, maximum in-plane and out-of-plane flexural strengths were achieved by mix containing fibers of 15mm length at dosage of 40 kg/m^3 (15FF40) which were 9.5% and 10.3% more than the control mix, respectively. The results indicated that flexible metallic fibers of length 15mm did not impart any distinguished positive impact on the flexural strength and addition of fibers of 5mm in length showed detrimental effect on the flexural strength of printable concrete mixes.

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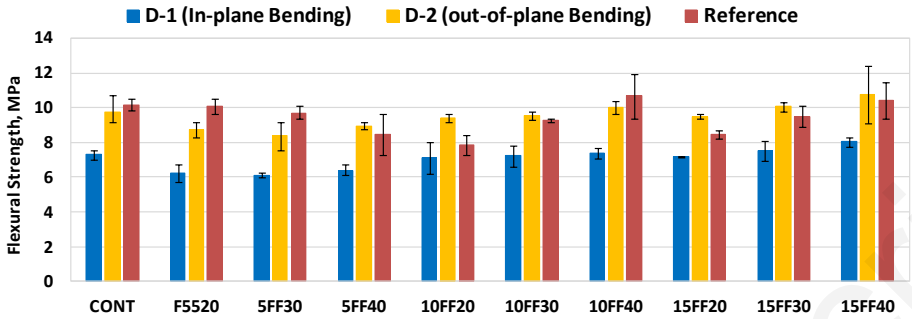


Fig.13. Flexural strength values of printed and cast-in-mold concrete samples

Comparison of out-of-plane average flexural strength exhibited by printed concrete and reference concrete samples indicated that all fibrous printed concrete mixes exhibited flexural strength values closer to their corresponding cast-in-mold concrete mixes. Mixes containing fibers of 15mm in length at all dosages studied here exhibited out-of-plane flexure strength values greater than attained by their corresponding reference concrete mixes. It is pertinent to mention here that similar to reference concrete mixes, all fibrous printed mixes follow almost same pattern of increase or decrease in flexural strength due to change in length and dosage of metallic fibers.

Failure pattern of printed samples of control and fibrous concrete samples tested in in-plane bending are shown in Fig.14, where it is clear that in all cases, flexural crack travelled vertically through the layers without de-bonding of layers. In no case, crack travelled horizontality between layers. This indicates good bonding between each layer of printed elements.



Fig.14. Failure mode in in-plane bending of printed concrete samples

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4 Conclusions

This study focused on the effect of metallic fibers on the print quality and mechanical strengths (tensile and flexure) of 3D printed concrete. Based on the findings, following conclusions are drawn:

- Use of 5mm long fibers up to dosage of 40kg/m^3 in concrete did not cause any notable negative effect on the print quality, however, it was significantly affected when 10mm and 15mm long fibers were used in concrete.
- Compared to control printed concrete, tensile strength (TS) of fibrous printed concrete was decreased due to adding 5mm long fibers while it was increased by using 10mm and 15mm long fibers. In general this was true for all fiber dosages used in this study. Maximum decrease in TS of 25% was exhibited by mix containing 5mm long fibers at 30kg/m^3 while maximum increase in TS of 34% was exhibited by mix containing 10mm long fibers at dosage of 30kg/m^3. All printed fibrous concrete mixes exhibited TS less than that of their corresponding cast-in-mold concretes. Decrease in the difference of TS between printed and cast-in-mold concretes was observed with increase in length of fibers used.
- For all fibrous printed concrete mixes, out-of-plane flexural strength (FS) was greater than in-plane FS. Compared to control printable mix, both in-plane and out-of-plane FS of fibrous printed concretes were decreased when 5mm long fibers were added up to 40kg/m^3 while FS values were remained same or increased for fibrous mixes containing 10mm and 15mm long metallic fibers. In-plane FS of all fibrous concrete mixes was lesser than FS of their corresponding cast-in-mold concrete mixes, however, no clear pattern regarding the comparison of out-of-plane FS of fibrous concrete mixes and their corresponding cast-in-mold concrete mixes was observed.

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References

1. Daniel, G. S., Victor, C. L.: A self-reinforced cementitious composite for building-scale 3D. Cement and Concrete Composites 90, 1-13 (2018).
2. Christ, S., Schnabel, M., Vorndran, E., Groll, J., Gbureck, U.: Fiber reinforcement during 3D printing. Materials Letters 139, 165-168 (2015).
3. Bos, F., Wolfs, R., Ahmed, Z., Salet, T.: Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. Virtual and Physical Prototyping 11(3), 209–225 (2016).
4. Hambach, M., Volkmer, D.: Properties of 3D-printed fiber-reinforced Portland cement paste. Cement and Concrete Composites 79, 62-70 (2017).
5. Bos, F.P., Bosco, E., Salet, T. A. M.: Ductility of 3D printed concrete reinforced with short straight steel fibers. Virtual and Physical Prototyping 14(2), 160–174 (2019).

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