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Structural Performance of One-Way Slabs Reinforced with Steel and Polypropylene Fibers

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ABSTRACT

The present study aims to investigate the effects of the steel fibers (SF) and polypropylene fibers (PPF) on the structural response of one-way simply supported reinforced concrete (RC) slabs at the ultimate limit state (ULS). Next, an optimized combination of the hybrid fibers is proposed. The experimental program includes 21 experiments on the one-way slabs with different SF and PPF ratios. The load-deflection curves were obtained for slabs using a four-point bending method. The ultimate capacity and mid-span deflection of the slabs were measured. The experimental results did not produce a consistent trend of ultimate loading. The different blends produced different failure modes, cracking load, and ultimate failure load. Based on the obtained test results, the slab specimen, SM6, with 0.7% SF and 0.9% PPF ratios has the maximum and the slab specimen, SM16, with 0.9% SF and 0.9% PPF ratios has the minimum load-carrying capacity, respectively. The first shows a 31% increase and the second indicates a 31% reduction when compared to the reference slab specimen, SM1, which has no fibers used in its concrete mixture. It is worth to mention that the slab specimen, SM6, which has the largest load-carrying capacity, also shows the highest ductility (172% enlargement in deflection when compared to the reference slab, SM1).

Keywords: Hybrid Fiber-reinforced concrete slabs; Flexural testing; One-way slabs; Polypropylene fibers; Load-carrying capacity; Ductility

INTRODUCTION

The reinforced concrete (RC) material is the most widely used material in the construction industry due to its readily and low-cost preparation procedure, its ability to be adapted in the required shapes and its already established properties such as high strength, high durability, fire-resistance, and so on. It has replaced stone and brick masonry as a building material. At present, reinforced concrete is used in all the types of construction starting from a simple house to a multi-story building. One-way reinforced concrete slabs are one of the frequently used RC members usually utilized in the buildings as the floor system or bridges as the decks. The enhancement of the strength and durability of the RC slabs is always an active area in the research works. Concrete is categorized as a brittle material and has low tensile strength, especially after the appearance of cracks, the load-carrying mechanism is highly compromised. The shrinkage cracks have always been a noticeable problem in the concrete structures. These cracks can be easily observed in concrete pavement slabs and the slabs under high-speed railways. For such structural elements, there is always a problem for the control of cracks that appear due to the expansion and contraction of concrete due to temperature changes. The fibers escalate toughness and ability to resist crack in hardened concrete by transferring the load at internal micro-cracks (Abbas et al. 2012; Shende et al. 2012). However, Therefore, with the advancement in composite material, especially fibers, the strength and durability of concrete can be enhanced by using different types of fibers (Mohammadi et al. 2008; Abdul-Zaher et al. 2016; Raza and Khan 2020).

Fiber-reinforced concrete (FRC) matrix primarily consists of hydraulic cement with fine and coarse aggregates and string-like discrete fibers. The toughness and the resistance to impact loadings are increased by using the synthetic and organic fibers having low elastic modulus and high elongation properties while the strength and the stiffness characteristics of concrete are improved using steel and carbon fibers having high elastic modulus (Singh 2010). An experimental and numerical study of HFRC (hybrid fiber-reinforced concrete) shows that a combination of PVA, PPF, and carbon fibers with a volumetric ratio of 0.4% decreased the cracking and shrinkage of concrete up to 34% (Denneman et al. 2011). Moreover, due to the addition of fibers, there is no influence on the loss of water from concrete by evaporation (Wongtanakitcharoen et al. 2007). PPF-reinforced concrete has a higher tendency of cracking due to higher elastic modulus and higher shrinkage (Aly et al. 2008). The fibers that are extensively used in concrete, are steel fiber, SF, and PPF (Bažant and Kazemi 1990; Shah et al. 1995). The mechanical properties of PPF reinforced concrete at elevated temperatures and high loads were influenced by the cross-sectional area of PPF (Di Prisco et al. 2009; Kim et al. 2013). Moreover, the spalling and brittle failure of concrete was increased due to the elevated temperatures and external loadings. To control the plastic and dry shrinkage cracking, a volumetric proportion of 0.1% of the polypropylene and glass fibers is enough (Banthia and Gupta 2006; Barluenga and Hernández-Olivares 2007).

The overall efficiency of fibers depends upon the fiber-matrix interactions (Abbas and Khan 2016). The PPF reinforced concrete helps in reducing the thickness of members and hence, reducing the weight of the structure, which makes handling, and shipping of the concrete, even easier (Singh 2010). Wu et al. (Wu et al. 2019) investigated the effect of SF on the flexural behavior of glass fiber reinforced polymer (GFRP) reinforced beams and concluded that by the addition of 0.6% SF by volume, the load-carrying capacity increased by 22%. The use of ordinary concrete where the compaction is done using a mechanical vibrator, the most reliable and widely used method is the use of fibers to reduce cracks, which are caused by paste contracts particularly thin artificial fibers with a volume less than 0.5% (Brandt and Gupta 2006). The tests on the fiber-reinforced concrete have shown that the compressive, tensile, and bending strengths increase, and the workability decreases with the higher volume of fibers (Brandt et al. 2003; ZHANG and LI 2008, Wang and Chouw 2018, Ahmad, Tahir et al. 2019). The surface cracks formed due to the internal vapor pressure of concrete may cause the spalling of concrete or the corrosion of reinforcement by reducing the performance of structure (Han et al. 2005; Naaman et al. 2005; Song et al. 2005; Sivakumar and Santhanam 2007; Pelisser et al. 2010). The compressive strength of the concrete is slightly affected by the increase in the quantity of PPF and glass fibers (Sivakumar and Santhanam 2007; Hsie et al. 2008; Sun and Xu 2009). The addition of PPF reduces the expansion of concrete and increases the strength significantly which helps the structure to stay in the more serviceable state (Qian and Stroeven 2000; Kakooei et al. 2012). With the increase of fibers quantity, the tensile strength of concrete can also be increased (Selina et al. 2014). The use of PPF by 0.1% is very less efficient for the on-grade slab whereas the use of 0.5% of PPF produced much more resistance to impact loading (Manolis et al. 1997). Fibers play an important role in resisting the flexural cracks in slabs (Pujadas et al. 2012; di Prisco et al. 2019; Facconi et al. 2019; AbdelmajeedLabib 2020; Kueres et al. 2020).

The present work aims to investigate the effect of different combinations of the SF and PPF (hybrid fibers) on the overall structural response of the one-way RC slabs. To achieve this purpose, 21 one-way RC slab specimens were cast and tested under a four-point flexural test to assess their load-carrying capacity, deflection, and cracking patterns at the ultimate limit state (ULS). This study could be helpful for the structural engineers in the analysis and design of such members under ULS.

EXPERIMENTAL SCHEME AND SETUP

EXPERIMENTAL PROGRAM

21 tests were carried out to study experimentally the behavior of the HFRC slab at ULS. Each of the slab specimens is named with numeric digit prefixed with alphabet SM where S denotes the specimen of one-way slab and M denotes the mix design. There are 21 different mix designs in the present experimental program. The ratio of SF and PPF varies between 0 to 1.0% and 0 to 0.9%, respectively. A summary of the tests which are conducted is provided in Table 1.

MATERIALS

In this research program, Type II Grade 43 Ordinary Portland Cement (OPC) was used fulfilling the requirements of ASTM C150/150M-18 (2018). The physical properties and chemical composition of the cement are given in Table 2. The coarse aggregates used in this research program are Margallah crush having a fineness modulus of 2.3 and the source of fine aggregates was Lawrencepur sand following ASTM C33/C33M-18 (2018). The maximum size of coarse aggregates was 12 mm. The mechanical properties of steel and PPF (see Figure 1) are shown in Table 3. The superplasticizer Chemrite NN was used by the weight of the cement, having a pH value of 8.0 to enhance the workability of concrete. The specifications of the superplasticizer are given in Table 4.

PREPARATION OF SPECIMENS

Twenty-one samples of one-way RC slabs with dimensions of 1016 mm x 457 mm x 100 mm were cast. The SF and PPF fibers ratio for each mixture varies from 0% to 1.0% and 0% to 0.9%, respectively. The mix ratio of 1:1.4:2.8 was developed. Water to cement ratio of 0.47 was used for the mixture. Table 5 shows the mixed proportion of concrete. There were used three longitudinal and seven transverse steel bars of 10 mm diameter having a yield strength of 410 MPa at equal spacing on the top and bottom of the slabs. The concrete cover on the sides of slabs was 20 mm and that was 15 mm at the top and bottom of the slabs. Before the casting of specimens, the slump value for each mix design was determined. It was observed that the slump value of HFRC decreases with the increase of fibers being used in concrete. It is well known that the addition of fibers to the concrete matrix generally tends to increase the porosity and, at the same time, to reduce the workability of fresh paste. A decrease of 188% occurred in the slump value of concrete when the SF increased from 0% to 1.0% and PPF increased from 0% to 0.9%. The larger contents of SF and PPF will lead to the balling and a thicker mix by reducing

FIGURE 1. Polypropylene and steel Fibers

TABLE 1. Test Matrix of the present research work

Sr. No.	Slab label	SF (%)	PPF (%)	Total percentage of fibers (%)
1	SM1	0.0	0.0	0.0
2	SM2	0.7	0.1	0.8
3	SM3	0.7	0.3	1.0
4	SM4	0.7	0.5	1.2
5	SM5	0.7	0.7	1.4
6	SM6	0.7	0.9	1.6
7	SM7	0.8	0.1	0.9
8	SM8	0.8	0.3	1.1
9	SM9	0.8	0.5	1.3
10	SM10	0.8	0.7	1.5
11	SM11	0.8	0.9	1.7
12	SM12	0.9	0.1	1.0
13	SM13	0.9	0.3	1.2
14	SM14	0.9	0.5	1.4
15	SM15	0.9	0.7	1.6
16	SM16	0.9	0.9	1.8
17	SM17	1.0	0.1	1.1
18	SM18	1.0	0.3	1.3
19	SM19	1.0	0.5	1.5
20	SM20	1.0	0.7	1.7
21	SM21	1.0	0.9	1.9

TABLE 2. Properties of cement

Property	Consistency	Initial Setting Time	Final Setting Time	Soundness	Fineness	Specific Gravity	Compressive Strength (28 Days)
Value	28.75%	91 min	3 Hours & 45 min	No Expansion	3190 cm^2/g	3.03	41.13 MPa

TABLE 3. Mechanical properties of steel and PPF

Property	Steel Fiber	Polypropylene Fibers
Density	N/A	0.9 ± 0.01 Kg/L
Diameter	0.55 mm	22 **µm**
Type	Hooked end	N/A
Length	35 mm	Variable
Tensile Strength	1345 MPa	300-450 MPa
Aspect Ratio	64	N/A
Melting Point	2300^{o}C	1600^{o}C

TABLE 4. Specification of superplasticizer

S. No.	Description	Details
1.	The density of at 25°C	Approximately 1.18 Kg/ltr
2.	PH value	Approximately 8
3.	The chloride content of NN	Nil (EN 934-2)
4.	Toxicity	Non-toxic
5.	Transportation	Non-hazardous

the workability. Three cylinders were also cast for each of the mixtures. The compressive and tensile strengths of the latter specimens were assessed on the same day as the slabs were tested. The compressive strength of all the specimens were obtained using a universal testing machine (UTM) with a maximum capacity of 2000 kN following ASTM C39 / C39M-18 . The complete stress-strain curves for all mix designs were presented in Figure 2.

EXPERIMENTAL TESTING AND PROCEDURE

The specimens were subjected to the four-point flexural test. The testing procedure was adopted from (Adom-Asamoah and Kankam 2009). The testing setup contained slab specimens fixed in a steel frame with simply supported end conditions. The four-point loading mechanism was adopted as demonstrated in Figure 3. A length of 50 mm of the slabs from both ends was placed on the supports. The distance between the supports was 305 mm. The load was applied using two steel bars placed at one-thirds points of the slab with the help of a load cell having a loading capacity of 2000 kN. Three LVDTs were placed at the bottom of the slab to measure the vertical deflections on 1/3rd, 2/3^{rd,} and mid-point of the slab. All the strain gauges were attached to the same tension side of the slab to measure the maximum strain on that tension side. The load was applied to the slabs with an interval of 5 kN using the load cell. The load-deflection curves for all the specimens were measured using a data logger connected to the load cell. Moreover, the initial crack loads, vertical deflections at the initial crack, ultimate loading capacity, and corresponding vertical deflections were measured for all HFRC slab specimens by hand when cracks appeared on the surface of the specimens.

RESULTS AND DISCUSSIONS

FIRST CRACK LOAD AND DEFLECTION BEHAVIOR

For specimens SM21 with the maximum amount of SF and PPF, the first crack appeared at a nominal loading of just 56.65 kN which is much lesser than the load attained by control specimen. This is due to the reason that the increased amount of fibers causes the capacity of slabs to be decreased. The concrete material becomes brittle at larger amounts of fibers. On the other hand, in the case of SM3 where only 0.7% of SF and only 0.3% of polypropylene was used, yielded a much better result of carrying a load of 91.13 kN. All the experimental results are presented in Table 6. When using polypropylene, there was a significant increase in the maximum deflection obtained by specimens as compared to the control specimen (SM2). The maximum amount of deflection was reaching the limit of 18.9 mm for 0.7% SF and 0.9% PPF. This was achieved in the specimen named SM6. According to experimental results, it was observed that with the use of more polypropylene, the more elastic behavior of concrete was obtained. It can be observed that while using 0.7% SF, the first crack deflection and the deflection at ultimate crack loading are increased with the increase of PPF. Similarly, when the PPF along with 0.8% SF, were increased from 0.1% to 0.9% with an increment of 0.2%, the effect of increasing the SF on the first crack deflection was irregular but on the deflection at ultimate loading was in the form of an increasing trend i.e., there was an increase of load-carrying capacity from 83.69 kN to 99.37 kN. It was noted that the effect of PPF along with the combination of 0.9% SF, on the first crack deflection and deflection at ultimate crack loading was first decreasing and then increasing with the use of 0.9% PPF. By increasing the PPF up to 0.7%, the first crack load and deflection at first crack loads were decreased from 81.45 kN to 36.65 kN and 5.35 mm to 3.14 mm, respectively. Moreover, when the combinations of 1.0% SF with different increasing quantities of PPF were used, the loading at first crack and the deflection at first crack loads were first increased from 56.81 kN to 90.25 kN and 3.75 mm to 7.1 mm, respectively, using PPF up to 0.5% PPF quantity and then started to decrease up to 64.8 kN and 4.4 mm, respectively, while using 0.9% PPF.

RESULTS AT ULTIMATE LOADING

After the formation of the first cracks, the load-bearing capacity of specimens decreased for plain concrete (SM1). The experimental load carrying capacities and the corresponding deflections at first cracks and the ultimate crushing of the slab specimens were shown in Figure 4 and Figure 5. We can observe that while using 0.7% SF, the ultimate crack loading and deflection are increased with the increase of PPF by 28.25% and 101.89%, respectively. Similarly, when the PPF along with 0.8% SF, were increased from 0.1% to 0.9% with an increment of 0.2%, the effect of increasing the PPF on the first crack loading was irregular but on the ultimate loading capacity was in the form of an increasing trend from 83.69 kN to 99.37 kN. The effect of

PPF along with the combination of 0.9% SF, their effect on the first and ultimate crack loading was inverse; by increasing the PPF, the ultimate crack loads and deflection were decreased by 46.86% and 38%, respectively. Moreover, when the combinations of 1.0% SF with different increasing quantities of PPF were used, the ultimate crack loads and deflection were first increased up to 28.17% and 37.66%, respectively using 0.5% PPF quantity and then started to decrease by 26.36% and 7.79%, respectively. It can be concluded that that the effect of PPF on the loading capacity of slabs was similar to that of on vertical deflections.

The experimental results did not produce a consistent trend of ultimate loading. The different blend produced different failure modes, cracking load, and ultimate failure load. The sample SM1 which has lesser initial crack loading than the control element took almost the same amount of loading to fail as compared to the control specimen. SM5 had the first crack at lesser loading than SM4 and SM6 and, also took less load for the specimen to completely fail. The maximum loading was attained by SM6 (see Figure 6) which had 0.7 % of SF and 0.3% of PPF and the maximum ductility was observed for the specimen SM6 having the SF of 0.7% and PPF of 0.9%. Figure 6 presents the load-deflection behavior of slabs with 0.7% SF and 0.9% PPF with the maximum capacity and deflection of 117.29 kN and 18.90 mm, respectively, for the specimen SM6. Figures 6, 7, 8, and 9 presents the experimentally obtained loads and corresponding deflections curves for the slab specimens. The high percentage of fibers presented low load carrying capacity of slabs. This may be ascribed to the addition of large quantity of steel fibres that may lead to congestion of fibres resulting in an improper bonding with concrete and the balling effect.

CRACK PATTERNS

The crack patterns of all slab specimens were examined as presented in Figure 10. The samples SM1, SM3, SM4, SM8, SM12, SM18, SM19, and SM20 failed in flexure representing that the specimens were included the quantities of fibers that resist the specimen against shear failures. While the specimens SM2, SM5, SM6, SM7, SM9, SM13, SM14, SM15, SM16, and SM21 failed in shear. These specimens consist of increased quantities of fibers causing the failure of specimens at the supports. The specimens SM10, SM11, and SM17 failed in shear failure with various flexure cracks. These were mostly the shear cracks showing that the PPF of higher percentage quantities (0.7-0.9%) cause the one-way slabs specimens to fail under combined shear and flexural cracks. Due to the bridging effect of the fiber matrix, the cracked concrete cover remained in contact with the specimens instead of spalling.

TABLE 5. Quantities of concrete constituents

Material	Density (Kg/m^3)
Cement	468.26
Coarse aggregates	1310.86
Fine aggregates	655.43
Superplasticizer	0.5% by volume
Water	220.08
Steel fiber	0-1.0% by volume
Polypropylene fiber	0-0.9% by volume
Water to cement ratio	0.47

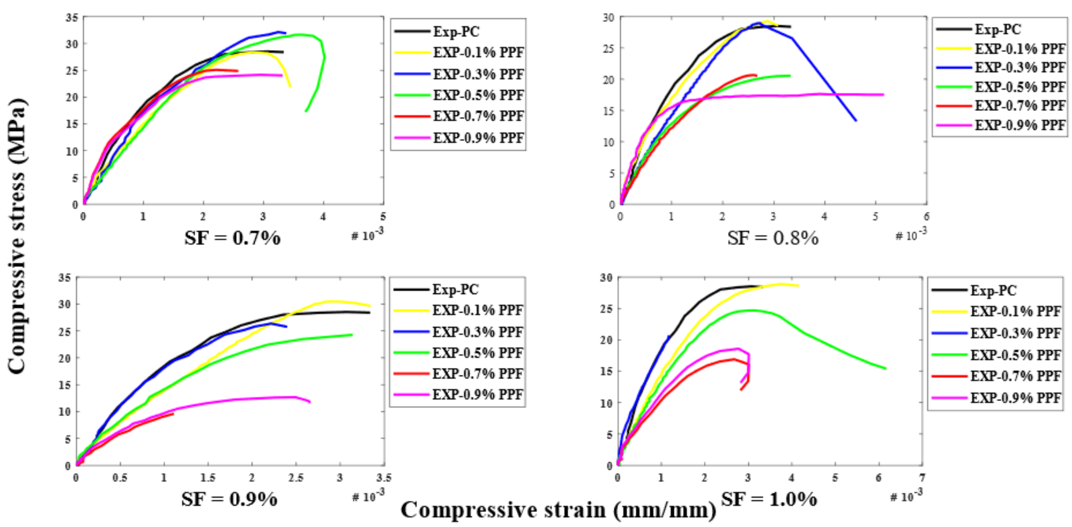

FIGURE 2. The compressive stress-strain curves of HFRC mix ratios

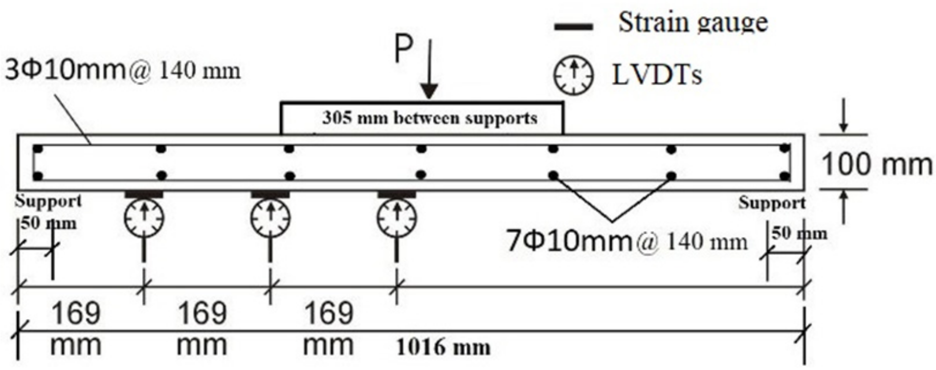

FIGURE 3. Testing setup for HFRC slabs

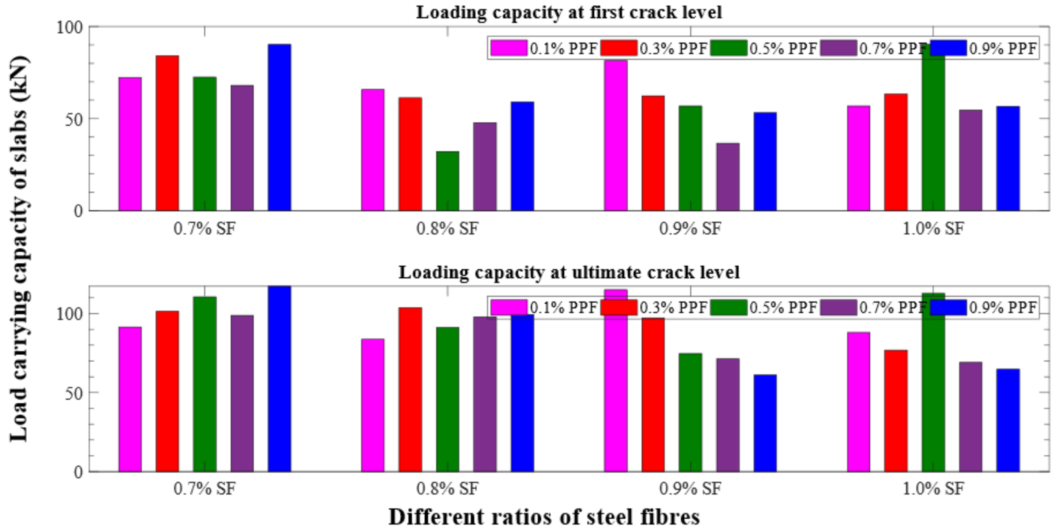

FIGURE 4. Comparison of load values at first and ultimate cracks

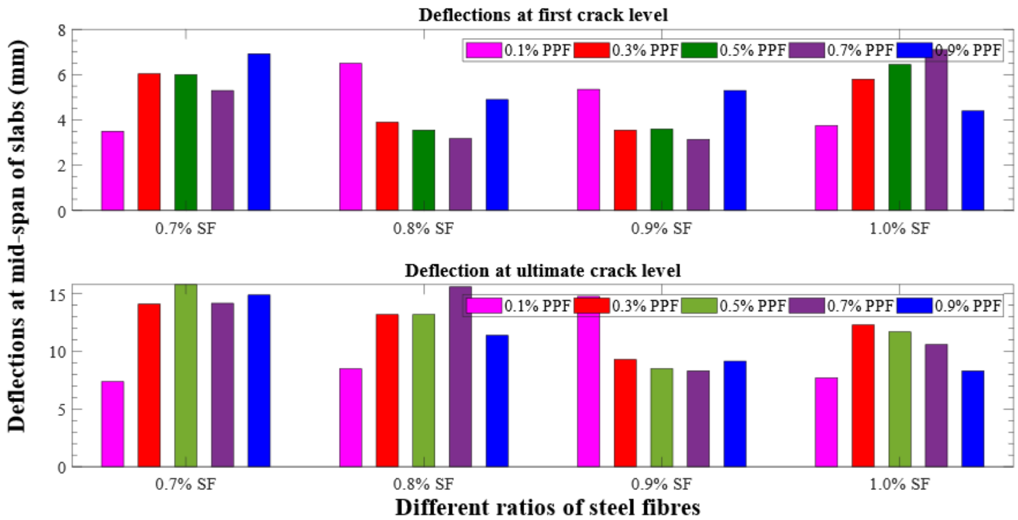

FIGURE 5. Comparison of deflection values at first and ultimate cracks

TABLE 7. Experimental results of load-carrying capacities (P_{cr}) and deflections of slab specimens

Slab Label	First Crack Load P_{cr} (KN)	Crushing Load P_{ult} (KN)	Deflection at First Crack (mm)	Deflection at the final crack (mm)
SM1	79.05	89.21	3.9	6.93
SM2	72.33	91.45	3.5	7.38
SM3	91.13	101.49	6.04	15.1
SM4	72.49	110.57	6	17.8
SM5	68.01	98.81	5.3	14.18
SM6	90.25	117.29	6.92	18.9
SM7	65.77	83.69	6.5	8.5
SM8	61.29	103.77	3.9	13.2
SM9	32.17	91.13	3.55	13.2
SM10	47.85	97.85	3.18	15.6
SM11	59.05	99.37	4.9	11.4
SM12	81.45	115.05	5.35	14.78
SM13	62.33	97.25	3.55	9.3
SM14	56.81	74.73	3.6	8.5
SM15	36.65	71.29	3.14	8.3
SM16	53.21	61.13	5.3	9.15
SM17	56.81	88.01	3.75	7.7
SM18	63.37	76.81	5.8	12.3
SM19	90.25	112.81	6.45	11.7
SM20	54.57	69.05	7.1	10.6
SM21	56.65	64.81	4.4	8.3

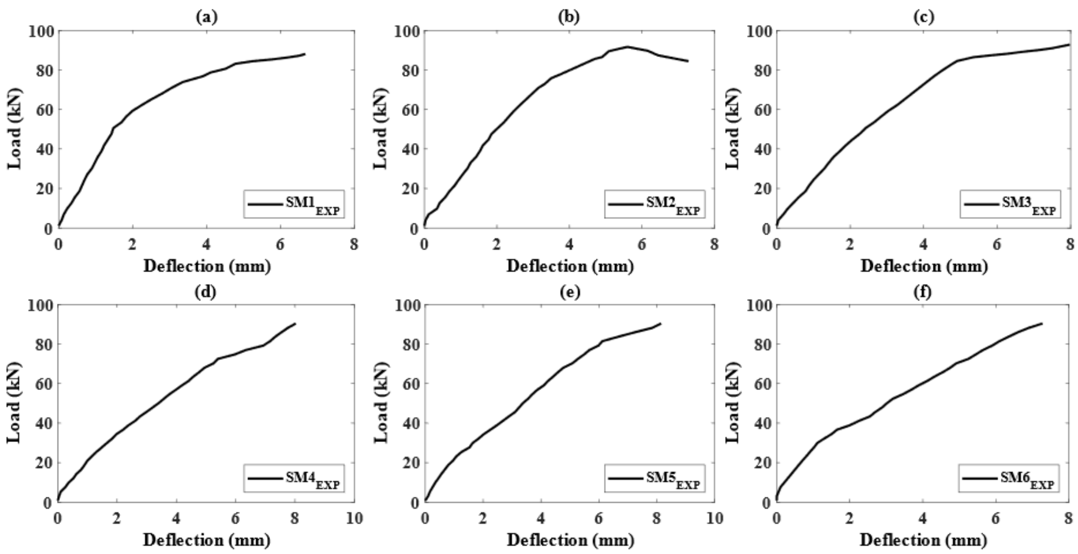

FIGURE 6. Load-deflection curves for 0.7 % Steel Fiber Samples with (a) Without Fibers Sample (b) 0.1% PPF (c) 0.3% PPF (d) 0.5% PPF (e) 0.7% PPF and (f) 0.9% PPF

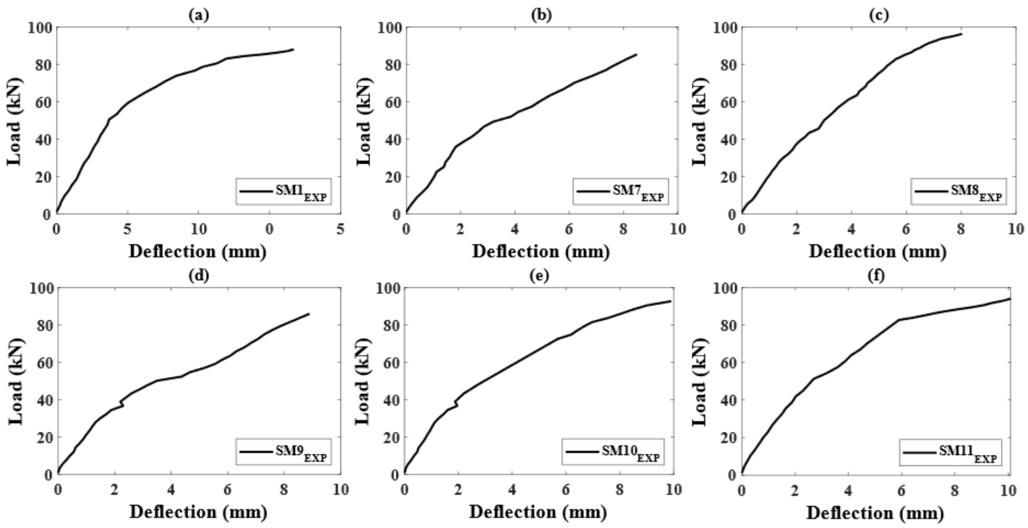

FIGURE 7. Load-deflection curves for 0.8 % Steel Fiber Samples with (a) Without Fibers Sample (b) 0.1% PPF (c) 0.3% PPF (d) 0.5% PPF (e) 0.7% PPF and (f) 0.9% PPF

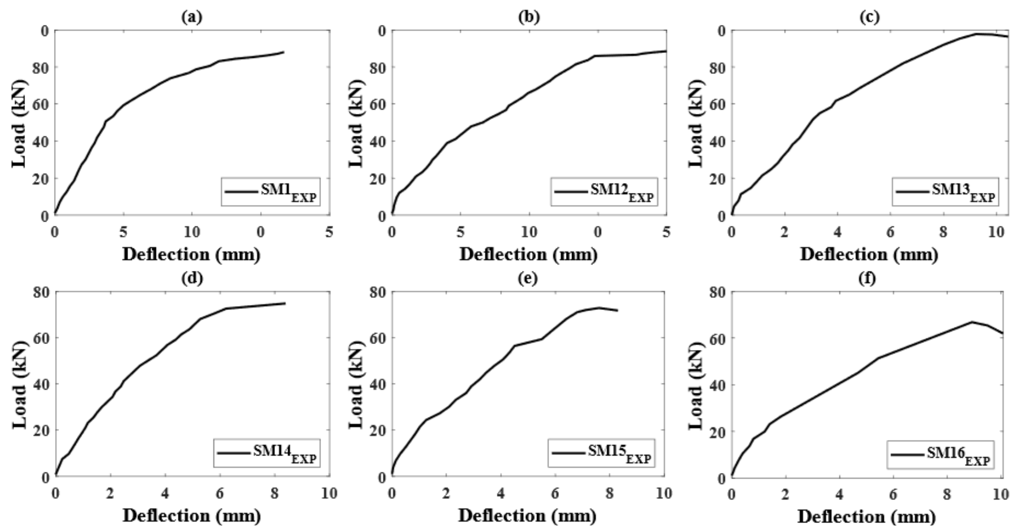

FIGURE 8. Load-deflection curves for 0.9 % Steel Fiber Samples with (a) Without Fibers Sample (b) 0.1% PPF (c) 0.3% PPF (d) 0.5% PPF (e) 0.7% PPF and (f) 0.9% PPF

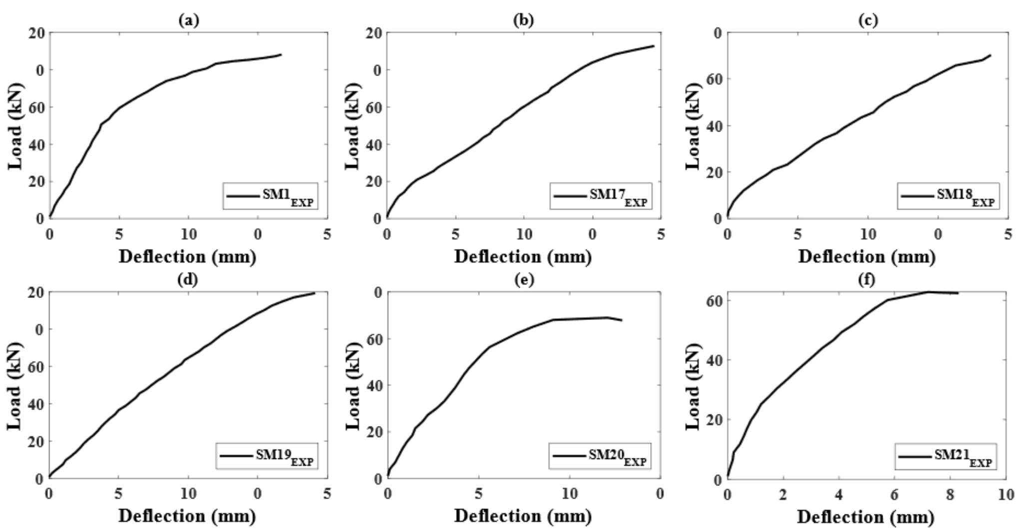

FIGURE 9. Load-deflection curves for 1.0 % Steel Fiber Samples with (a) Without Fibers Sample (b) 0.1% PPF (c) 0.3% PPF (d) 0.5% PPF (e) 0.7% PPF and (f) 0.9% PPF

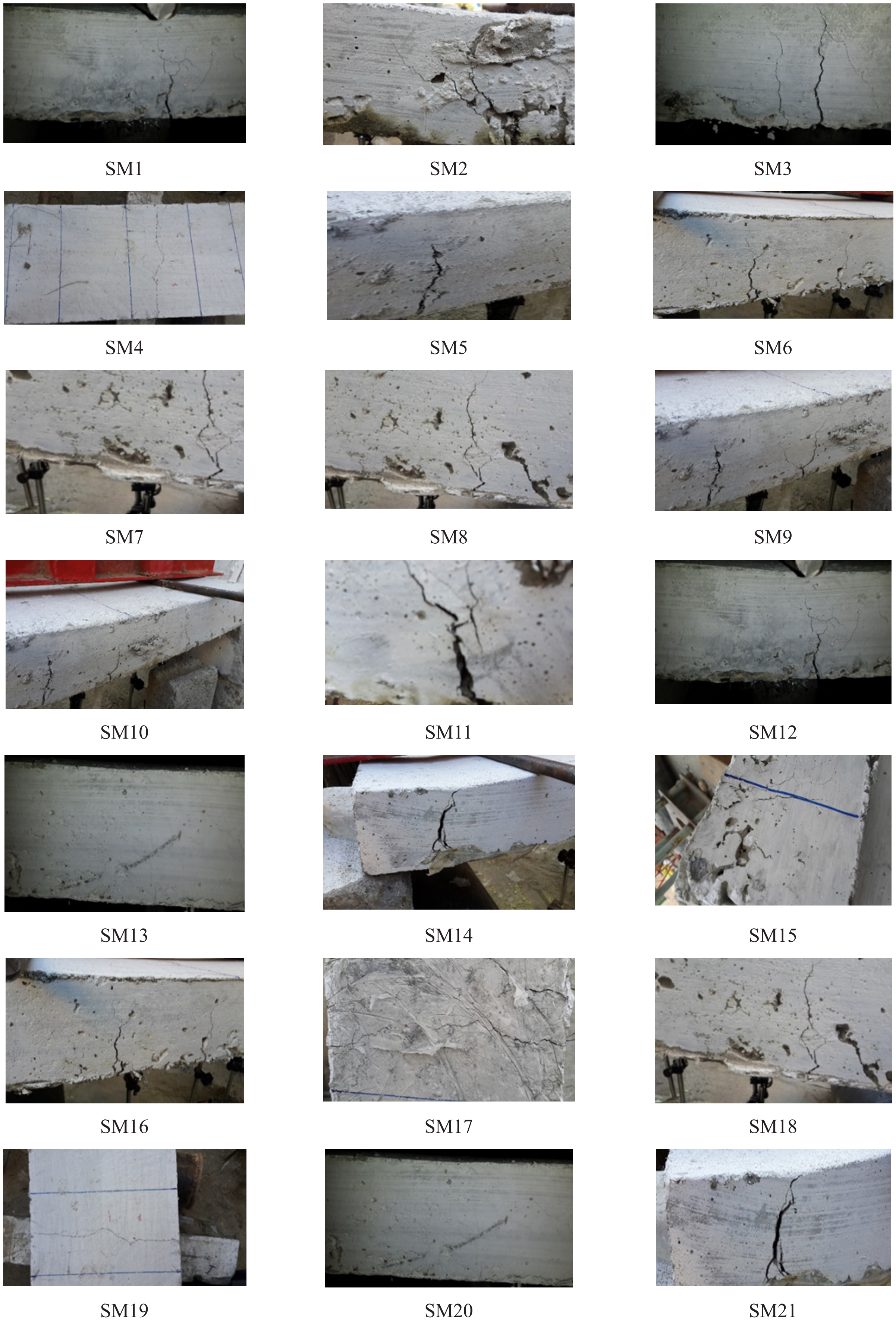

FIGURE 10. Failure modes and cracks patterns of slabs

CONCLUSIONS

Twenty-one RC one-way slab specimens with different ratios of steel and PPF were cast to determine the optimum contents of fibers for the maximum load-carrying capacity and ductility of RC slabs. The specimens were tested under four-point flexural loading and the load-deflection response and failure behavior were studied. The following conclusions can be deduced from the presented work:

1. The increase in the percentage of fibers does not necessarily lead to an increase in the flexural strength of the specimen. With the use of 0.7% of SF, the optimum results of the load-carrying capacity of 117.29 kN were produced by using 0.9% PPF. With the use of 0.8% SF, the optimum results of the loading capacity of 103.77 kN were produced using 0.3%. With the use of 0.9% SF, the optimum results of the loading capacity of 115 kN were produced using 0.1% PPF. With the use of 1% steel fiber, 0.5% of PPF produced the optimum result of 112.81 kN. The maximum load-carrying capacity of slabs was obtained at the fiber's combination of 0.7% SF and 0.9% PPF that was 131% of that of RC slab without fibers.
2. The optimum fiber content depends upon the mix ratio and the procedure used to carry out the mixing. The larger contents of fibers will lead to the balling and a thicker mix by reducing the workability. A percentage decrease of 188% occurred in the slump value of concrete when the SF increased from 0% to 1.0% and PPF increased from 0% to 0.9%.
3. The reduction in the cracking and deflection is greatly dependent upon the fiber distribution on the cross-section under consideration. We can observe that while using 0.7% SF, the deflection at ultimate loading is increased with the increase of PPF by 101.89%. Similarly, when the PPF along with 0.8% SF, were increased from 0.1% to 0.9%, the effect of increasing the PPF on the first crack deflection was decreasing from 6.5 mm to 3.8 mm but on the deflection at ultimate loading capacity was in the form of an increasing trend from 8.5 mm to 15.6 mm. The effect of PPF along with the combination of 0.9% SF, their effect on the deflection at ultimate crack loading was similar to that of effect at 0.8% SF; by increasing the PPF, the deflection at ultimate crack loads was decreased by 14.78 mm to 9.15 mm. Moreover, when the combinations of 1.0% SF with different increasing quantities of PPF were used, the deflection at ultimate crack loads was first increased up to 7.7 mm to 11.7 mm using 0.3% PPF quantity and then started to decrease by 48.19% at 0.9% PPF. The proper dispersion of fibers should be devised to get a uniform specimen. The results showed that by using hooked-steel fibers along with the PPF preserved the high-performance fresh properties of concrete and obtained a reliable behavior in the fracture results.
4. The outcomes of present work will help to introduce the HFRC in the construction industry, especially for one-way RC slabs, with reasonable confidence.

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DECLARATION OF COMPETING INTEREST

None.

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