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Effect of Macro and Micro Polypropylene Fibers on the Flexural Behavior of RC Slabs

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ABSTRACT

This research highlights the effect of the micro polypropylene fibers (mPPF), macro polypropylene fibers (MPPF), and hybrid fibers (combination of mPPF and macro steel fiber at the rate of half) on the flexural strength of the one-way reinforced concrete (RC) slabs. The optimum fiber content is considered based on the ultimate flexural load and mechanical properties. A total of 10 simply supported one-way RC slabs in dimensions 1100 × 400 × 80 mm (length × width × thickness) were prepared and tested under a four-point bending test to investigate their response to first crack load, ultimate load, deflection, and strain. The dosage of the fibers was 0.5%, 1%, and 1.5% by total volume of concrete. Also, the aspect ratios were 375 for mPPFs, 50 for MPPFs, 35 for macro steel fibers. The test results revealed that the flexural stiffness and crack resistance of the one-way RC slabs were improved compared to the control slab. Though the ultimate flexural load increased by 29.73% for the slab with mPPF at 0.5% dosage, 32.46% for the slab with MPPF at 0.5% dosage. The slab with steel fiber + mPPF at 1.5% dosage demonstrated an increased ultimate flexural load of 28.2% compared to the control slab, while the cracks widened. The load-deflection curve of the slab with mPPF at 0.5% dosage displayed the most elastic one-way RC slab among all the slabs, as it enhanced the first crack load by 112%. The load-deflection curve of MPPFRC slabs and the slabs with hybrid fibers displayed the gradual decline in post-cracking behavior.

1.Introduction

Concrete is generally firm in compression but weak in tension, where the tensile strength of the concrete is one-tenth of the compression strength (Omer and Jaf, 2020; Qader and Kakshar, 2023). Thus, the concrete's tensile strength can be enhanced by adding short discontinuous fibers (Fall, 2014). The function of the discontinuous fibers is to improve structural stability and durability when the concrete cracks (Zainal et al., 2023). With the addition of the discontinuous fibers to slabs, it provides a better resistance to static, impact, and fatigue loads (Banthia and Dubey, 2000). Polypropylene and steel fibers are two discontinuous fibers that are available in different shapes and aspect ratios. Polypropylene fiber reinforced concrete (PPFRC) and hybrid fiber reinforced concrete (HyFRC) are common choices in several site constructions to speed up the construction process. Therefore, the slabs are more practical with the additional short fibers (Facconi et al., 2019). In general, the larger fibers are more than 30 mm in length, referred to as macrofibers, and the shorter fibers are between 3 and 30 mm, defined as microfibers. Meanwhile, the hybrid fibers are the combination of the macro and micro fibers (Ndububa, 2022). The crack propagation is multiscale (Yaseen, 2020), so the additional discontinuous fibers are the most suitable choice to bridge micro and macro cracks due to their various lengths (Newman and Choo, 2003). The PPFRC and HyFRC are commonly used in bridges, shotcrete, slabs, parking, and precast elements (ACI 544.4R-18, 2018; Zheng and Feldman, 1995).

In recent years, numerous experimental researches have been performed to evaluate the behaviour of the conventional concrete slabs reinforced by different types of fibers. Ramadevi and Babu (2012) observed that the additional HyFRC (steel and polyolefin fibers) improved the slab's flexural strength by 136.16% and deflection by 125% when added in a dosage of 2% by weight of cement. Shatanawi et al. (2016) investigated that the deflection of the flat slabs improved by the presence of the micro polypropylene fibers for the concrete compressive strength less than 30 MPa. Khan et al. (2021) concluded that the maximum flexural load was noticed in the combination of 0.7% steel fiber and 0.9% polypropylene fiber by volume of concrete, which increased by 31% under the four-point bending test. Al-Rousan (2022) figures out the ultimate load of the one-way RC slabs reinforced with hybrid macro polypropylene fibers in a dosage of 0.55% by volume of concrete, where the ultimate load is enhanced by 14% compared to the reference slab. Moreover, Abbas et al. (2022) reported that the deflection and ultimate load of the RC two-way slabs reinforced with polyolefin fibers are degraded for the fiber dose of more than 1.5% by volume of concrete. The numerical model by Al-Rousan and Alnemrawi (2024) showed that the structural performance of the PP fiber one-way RC slabs enhanced proportionally by increasing fiber content.

2.Research Significance

Most research studies focused on the impact of micro and macro polypropylene fibers individually. Few research studies provide a comprehensive influence of the polypropylene fiber length and its combination with steel fibers (hybrid fibers) on the flexural behavior of the one-way RC slabs. The current study provides the influence of polypropylene and hybrid fibers on the serviceability and ultimate state of the RC slabs. The primary objectives of this study are to investigate the following: a) the effect of the micro PPFs, macro PPFs, and hybrid fibers on the flexural behavior of the one-way RC slabs, and b) the optimal fiber content.

3.Experimental Program

3.1Slab Specimen's Detail

A total of ten one-way slabs were prepared for conducting four-point bending tests. The simply supported slab specimens were in dimensions 1100 × 400 × 80 mm (length × width × thickness). The variables of the study are as follows: fiber type (polypropylene and steel), fiber length (micro and macro), aspect ratio (375, 50, and 35), fiber volume fraction (0.5%, 1%, and 1.5%) by total volume of concrete, and hybrid fiber (combination of 50% mPPF and 50% macro steel fiber per dosage) that are illustrated in Table 1 and Figure 1. As well, the physical fiber properties of both types are mentioned in Table 2 and Figure 2. In order to test the influence of the fiber length parameter separately, the tested slab specimens included three slab groups. The reinforcement of the slab specimens consisted of two steel pairs of 8 mm steel bars that were positioned longitudinally and transversely as the main and shrinkage-temperature reinforcements, respectively. The yield and ultimate strength of these steel rebars were 570 and 616.7 MPa, respectively.

Table 1. Coding of the slab specimens

Group	Group 1			Group 2			Group 3		
Fiber size	Micro			Macro			Hybrid (Macro + Micro)		
Fiber type	Polypropylene			Polypropylene			Steel + Polypropylene		
Volume fraction	0.5 %	1%	1.5%	0.5%	1%	1.5%	0.5%	1%	1.5%
Slab ID	mP-375-0.5	mP-375-1	mP-375-1.5	MP-50-0.5	MP-50-1	MP-50-1.5	MS-mP-0.5	MS-mP-1	MS-mP-1.5

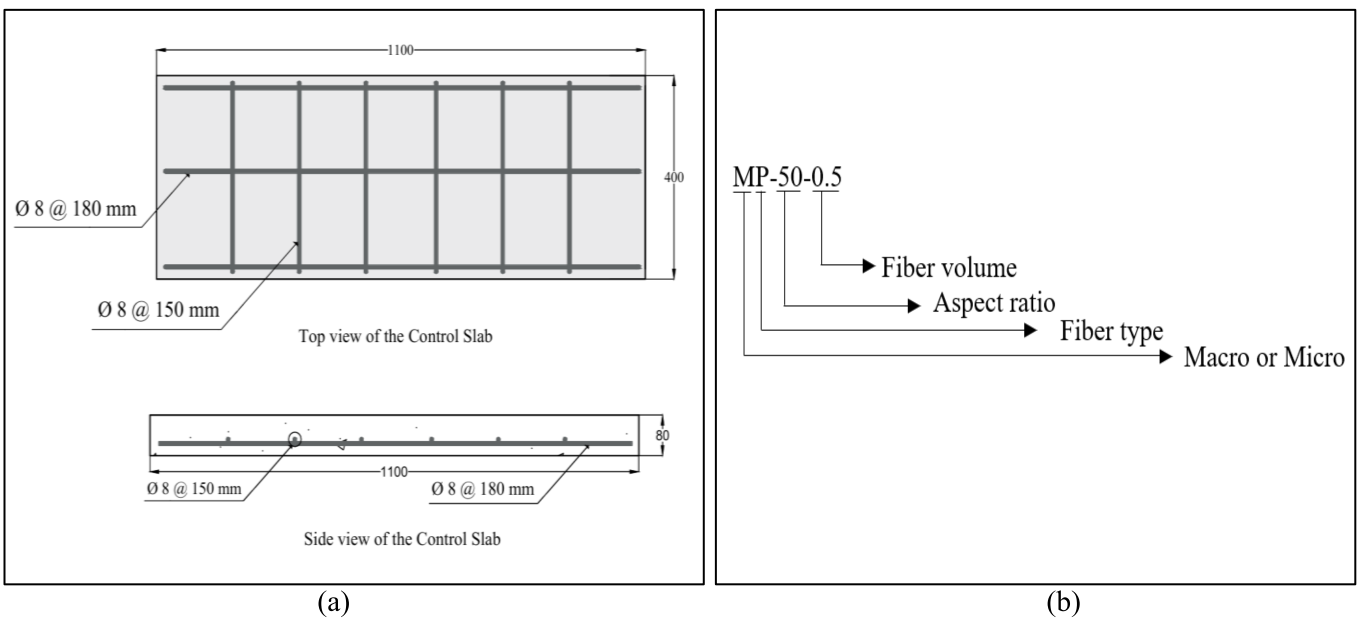


Figure 1. (a) Reinforcement detail, (b) Slab identities

Table 2. The physical properties of the fibers

Fiber ID	mPPF	MPPF	MSF
Fiber type	Micro polypropylene [1]	Macro polypropylene [2]	Macro steel [3]
Fiber form	Monofilament	Wavy, Monofilament	Wavy
Length (mm)	12	40	38
Diameter (mm)	0.032	0.8	1.1
Aspect ratio (L/D)	375	50	35
Density (kg/m^3)	910	910	7850
Appearance	Translucent	Translucent	Crescent
Melting point (˚C)	160 - 170	160 - 170	-
Tensile strength (MPa)	500	500	700

[1] LanmixPPM12 datasheet
[2] LanmixPPM40 datasheet
[3] LanmixW38 datasheet


a)


b)


c)

Figure 2. a) Micro polypropylene fiber, b) Macro polypropylene fiber, c) Macro steel fibers

3.2. Concrete Mixture

The used cement in the concrete mixture was ordinary Portland cement (OPC) Type I with 3- and 7-day compressive strengths of 15 and 21 MPa, respectively. Furthermore, the water absorption and specific gravity of the utilized coarse aggregate was 0.4% and 2.71, respectively. Also, the concrete contained fine aggregate with water absorption of 1.2% and specific gravity of 2.67. Although the concrete mixture proportioning is displayed in Table 3. The 10 slab specimen molds and twenty 150 × 300 mm cylinders were prepared, then the fibers were mixed with the concrete in a container using an 1800W drill mixer. The casting began by mixing the concrete with the fibers for 2 minutes while mixing continued, and after all the fibers were added the mixture mixed for 2 to 4 minutes. Then, the concrete was poured into the molds and vibrated for 1 to 2 minutes. Thereafter, the specimens were removed from the wood mold after 24 hours. Eventually, the slab specimens were prepared for testing after 28 days of curing, as displayed in Figure 3.

Table 3. The mix proportion of the concrete

Contents	Quantity (kg/m^3)
Cement	400
Water	160
w/c	0.4
Coers aggregate	785
Fine aggregate	1165
Super-plasticizer	3

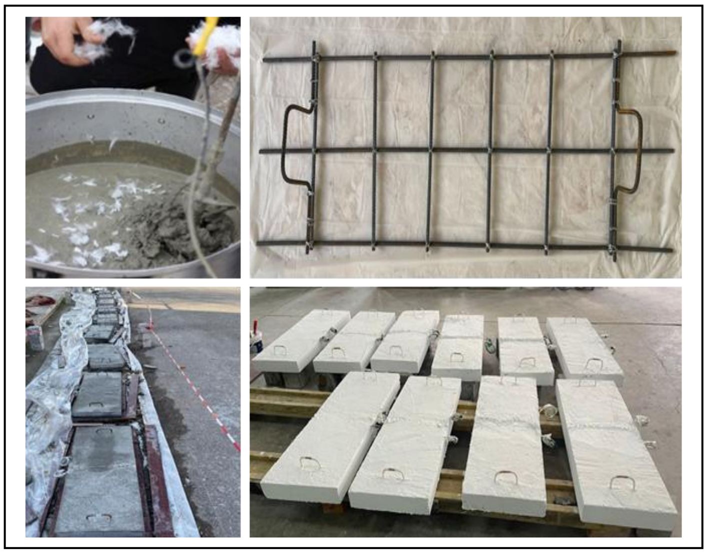


Figure 4. Concrete mixing and casting of the slab specimens

3.3Test Setup and Instruments

Throughout the experiments, the slab specimens were set up as one-way simply supported, and spanned 1000 mm in length. For the flexural strength test, a special frame was put together in the laboratory, which is apparent in Figure 4. In order to produce two points of loading (a region of constant moment-pure bending), the 520 mm apart spread beam was utilized and loaded by a hydraulic cylinder jacket using an intensive load (P). The objective was to obtain a shear span/effective depth (a/d) of more than 4. While experimenting, the used tools were a strain gauge, a linear variable differential transformer (LVDT), and a load cell (capacity of 1500 kN). It is readily apparent that the strain gauge is used to measure the tension concrete strain and the LVDT to vertical mid-span deflection, and the interval load was 3 kN, which was applied to the load cell. During testing these instruments were connected to the datalogger also a visual observation and resolution cameras were used to notice the first crack and propagations. Thereafter the crack width was measured by high-resolution digital images, that the images captured once the slabs have tested and then quantified by pixel-based measurement tools.

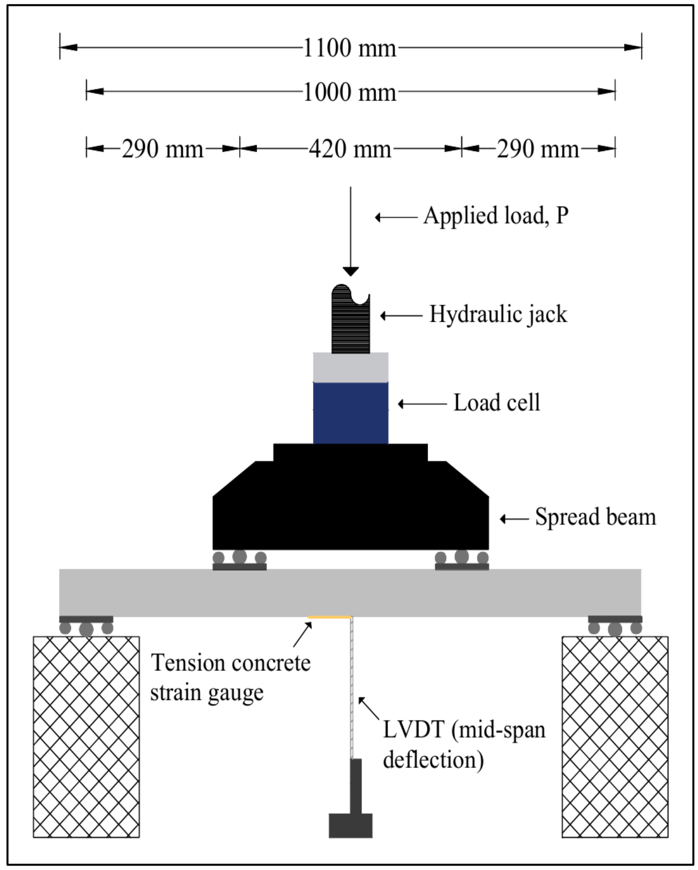


Figure 3. Flexural test set up

4.Results and Discussion

4.1Mechanical Properties of the Concrete

The concrete cylinders with no additional fibers had a compressive strength of 34.39, splitting tensile strength of 3.96 MPa, and a density of 24.57 kN/m^3. Adding micro, macro, and hybrid fibers to concrete has degraded the compressive strength and density of concrete, while improved the splitting tensile strength, as depicted in Table 4. The concrete cylinders tested in accordance to ASTM C39 (2023) and ASTM C496 (2017) to consider the compressive and splitting tensile strengths, respectively.

Table 4. Mechanical properties of the FRC

Concrete mix	Compressive strength (MPa)	Splitting Tensile Strength (MPa)	Density (kN/m³)
Control mix	34.3	3.96	24.57
mP-375-0.5	22.3	4.49	24.55
mP-375-1	21.05	4.64	23.41
mP-375-1.5	10.29	4.7	22.38
MP-50-0.5	29.01	3.6	24.68
MP-50-1	22.97	3.76	24.48
MP-50-1.5	14.81	3.59	22.82
MS-mP-0.5	31.29	5.01	24.20
MS-mP-1	30.78	3.9	24.52
MS-mP-1.5	28.9	4.36	24.39

The compressive strength values of the concretes decreased as follows: the micro polypropylene fiber reinforced concrete (mPPFRC) by 35.15-70.1%, the MPPFRC by 33.21-56.9%, and the HyFRC by 9.01-15.96%. Meanwhile, numerous studies have demonstrated that the incorporation of the PPFs reduces the compressive strength of concrete (Rahmdel et al., 2025; Richardson, 2006). Also Wang et al. (2019) stated that the use of PPFs at a dosage of 0.5% inversely impacted the compressive strength of concrete. This behavior is attributed to the fact that the additional PPFs deteriorate the bond between cement and aggregate, also disrupt the calcium silicate hydrate (C-S-H) (Mashrei et al., 2018). The splitting tensile strength of the micro and hybrid fiber reinforced concrete has slightly improved by 13.63-20.6% and 10.02-26.3%, respectively. Nevertheless, the MPPFs have dropped splitting tensile strength of concrete by 4.98-9.34%, due to fiber clumping and improper dispersion of the fibers, resulting in air voids, as in the case of this study that aligns with Sadiqul Islam and Gupta (2016) and Pangestuti et al. (2021). While Ramujee (2013) observed that the compressive and splitting tensile strengths of the concrete increased with higher fiber content. In addition, the PPFs and hybrid fibers reduced the density of the concrete as follow: the mPPFRC by 0.04-8.9%, the MPPFRC by 0.44-7.19%, and the HyFRC by 0.2-1.48%. Because the incorporation of fibers results in lower density due to increased air voids in concrete and fiber's low specific gravity, which were also noticed by Hasan et al. (2019).

4.2. Test Results

The main results are illustrated in Table 5, which includes cracking and ultimate phases. Based on the stated findings, the flexural strength and performance are improved by adding polypropylene and hybrid fibers because the stability within slabs increased. Also, the ductility index of the tested RC slabs was considered by a ratio of ultimate deflation to yield deflation. Thereby the Figure 5 showed all test results as normalized values relatives to the control slab.

Table 5. The test results of the RC slabs

Slab ID	P_{cr} (kN)	δ_{cr} (mm)	P_u (kN)	δ_u (mm)	ε_c ($\mu\varepsilon$)	W_{cr} (mm)	μ_Δ
Control Slab	7.51	1.1477	27.78	37.26	2231	4.27	14.56
mP-375-0.5	15.9	2.5	36.04	22.97	3084	1.9	14.20
mP-375-1	9.762	1.782	26.3	18.68	2135	0.718	11.26
mP-375-1.5	7.4	1.929	17.92	10.59	1548	0.904	5.43
MP-50-0.5	8.3	2.91	36.8	36.07	3201	2.19	9.25
MP-50-1	13.07	2.368	33.7	34.8	2605	3.219	17.55
MP-50-1.5	11.46	1.83	31.3	25.7	2013	1.61	12.44
MS-mP-0.5	9.845	1.68	33	39.7	2825	6.61	18.58
MS-mP-1	13.18	2.93	34.7	39.12	2863	7.05	13.50
MS-mP-1.5	10.776	1.465	35.6	38.43	2901	8.16	14.44

P_{cr} - First crack load, δ_{cr} - Deflection at first crack, P_u - Ultimate flexural load
δ_u - Ultimate deflection, ε_c - Concrete strain, W_{cr} - Crack width, μ_Δ - Ductility index

The incorporation of the micro and macro polypropylene fibers (PPFs) to RC slabs has enhanced the first crack load and deflection at first crack load. As (Blazy and Blazy, 2021) reported that the presence of the fibers bridges the microcracks and distribute the stresses more evenly, as a result the crack initiation has delayed. For the group of micro polypropylene fibers (mPPFs), the first crack load of the slabs mP-375-1.5 initiated at a loading of 7.4 kN, which is slightly less than the control slab by 1.46%, simultaneously the ductility reduced by 62.7%, that these degradations attributed to balling and improper dispersion of fibers. Despite this, the slabs mP-375-0.5 and mP-375-1 increased the first crack load by 112% and 29.98%, respectively. The group of macrofibers and hybrid fibers also delayed and improved the first crack load of the RC slabs. The macro polypropylene fibers (MPPFs) increased the first crack load of the RC slabs by a range of 10.51-74.03%. However, the hybrid fibers raised the first crack load of the RC slabs by 31.1-75.49%.

The slab mP-375-0.5 has enhanced the ultimate load by 27.73% compared to the control slab, while the slabs mP-375-1 and mP-375-1.5 decreased the ultimate load by 5.32% and 35.49%, respectively. Although the MPPFs increased the ultimate load of RC slabs by a range of 12.67-32.46%. On the other hand, the deflection of the RC slabs dropped when the PPFs were added, therefore the deflection of the mPPFRC and MPPFRC slabs degraded by a range of 38.35-71.57% and 3.19-33.17%, respectively. This is mainly due to balling and improper dispersion of the fibers, which cause stress concentration rather than stress distribution. The results consistent with Dhanapal and Jeyaprakash (2020) and Zainal et al. (2023), which they notes that the inclusion of the PPFs has degrade the deflection of the RC slabs. Meanwhile the ultimate flexural load of the RC slabs diminished when the higher amount of the PPFs was added. While, the ultimate flexural load of the HyFRC slabs enhanced by a range of 18.79-28.14%, also elevated the deflection by a range of 3.14-6.54%, this is due to the macro steel fibers have a higher modulus of elasticity and slip during loading.

The tensile strain of the slab mP-375-0.5 increased by 38.23% compared to the control slab, as it produced a high elastic limit region for the RC slab. While the tensile strain of the slabs mP-375-1 and mP-375-1.5 reduced by 4.3% and 30.61%, respectively, since they have a higher stiffness value. Also, the presence of the MPPFs in RC slabs improved tensile strain by a range of 15.59-43.47%, that the slab MP-50-1.5 excluded and the MPPF lowered its tensile strain by 9.77%. Conversely, the hybrid fibers increased the tensile strain of the RC slabs by a range of 26.62-30.01%, for the reason that the steel fibers have a higher modulus of elasticity and bridged the wider cracks, so the slabs deformed more under flexural load.

The FRC slabs exhibited various crack widths due to the bridging mechanism and limiting the crack propagation. The mPPFRC slabs demonstrated the narrower crack by a range of 45.75-83.77%, which they possessed a higher stiffness compared to the control slab. While the MPPFs narrowed down the crack width of RC slabs by a range of 22.85-65.1%, and the results are agree with Al-Rousan (2022), who reported the crack width increased by 17.92% when the MPPFs were added. Although the hybrid fibers widened the cracks of the RC slabs by a linear range of 54.8-91.1%. This inconsistency in the widening of the cracks is due to balling and uneven dispersion of the fibers throughout the RC slabs, which cause a weak point that created a wider crack under a higher ultimate flexural load compared to the control slab.

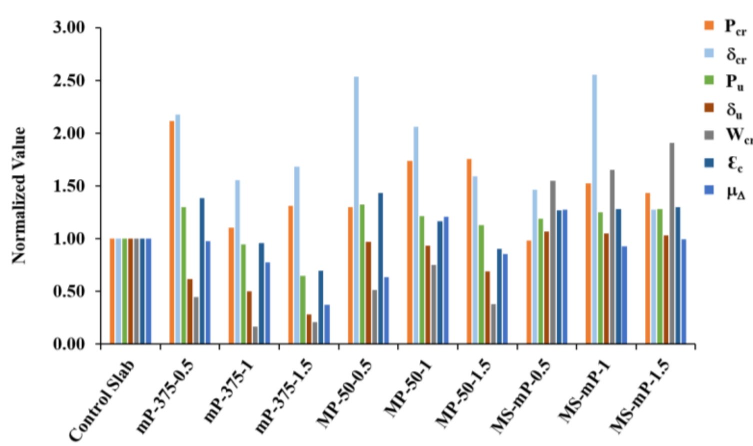
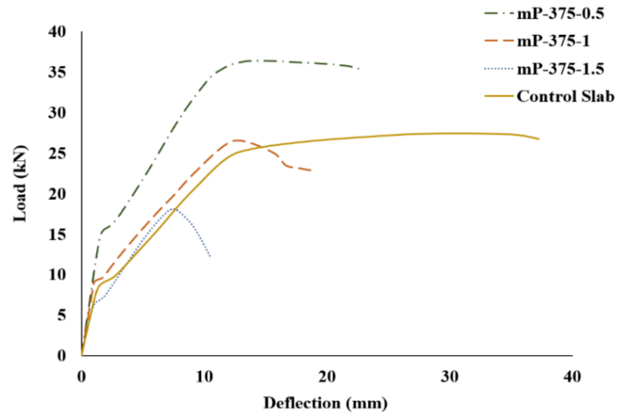


Figure 5.Normalized test results of the RC

4.3. Load-Deflection Curve

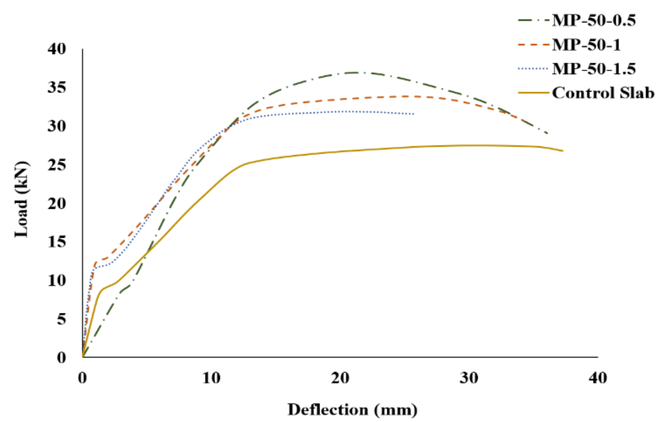
According to the experimental results in Table 5, the load-deflection curves for the slab specimens were obtained. The three stages of the load-deflection curves are the linear elastic region up to the first flexural crack, then the elastic region ended, the steel yielding started, and the last stage is failure. The load-deflection curves of the tested slabs are displayed in Figure 6, that presented the first crack load, ultimate load, post-cracking behavior.

Depending on the load-deflection curves of Figure 5, the mPPF are enhancing the first crack load of the RC slabs by a range of 1.5-112% compared to the control slab since the mPPFs are arresting the microcracks and postponing the crack initiation. However, flexural load decreased significantly after the ultimate load was reached means the mPPFs do not incorporate the post-cracking behavior due to the low modulus of elasticity and degradation in mechanical properties of concrete (Başsürücü et al., 2022). Meanwhile, the MPPFs influence the first crack load and peak load of the RC slabs. Because of the availability of the MPPFs improves the concrete matrix and minimizes the crack widening. Therefore, the post-cracking behavior is enhanced and has a gradual decline. The hybrid fibers have the most effective improvement in flexural performance, the first crack load, ultimate load, and ductility. Also, the hybrid one-way FRC slabs posed the ultimate deflection before failure among the RC slabs and have a significant gradual decrease in the post-cracking behavior. Thereby, the slabs MP-50-1 and MS-mP-0.5 improved ductility of the RC slabs by 20.53% and 27.61%, respectively. The load-deflection curves of RC slabs are contrary to the load-deflection curves of Khan et al. (2021) and Ramadevi and Babu (2012), that their load-deflection curves has a rapid drop after ultimate flexural load.

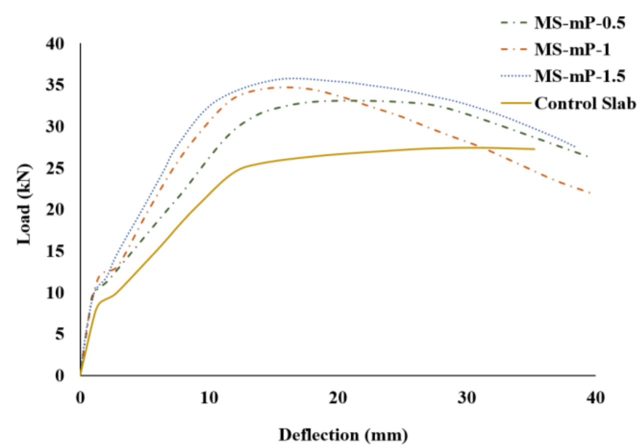


a) mPPF

Figure 6 Load-deflection curves of the



b) MPPF addition



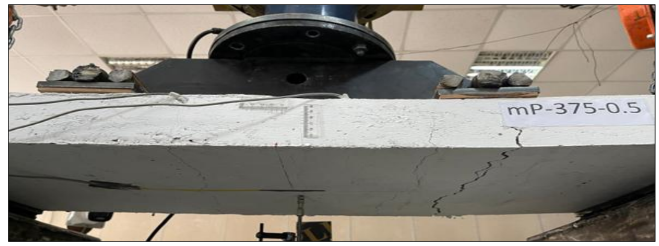
c) Addition of steel fiber and

Figure 6. Cont'd

4.4. Crack Pattern and Propagation

All the ten one-way RC slabs exhibited different crack patterns. The cracks were formed at the bottom tensile side, which was the highest moment region of the slabs, then propagated orthogonally along with the load increasing. Thereafter, the cracks grew into a particular pattern and then failed in flexural, as displayed in Figure 7. However, the flexural cracks were expanded after the steel yielded and continued until the crushing on the compression side. The crushed concrete cover remained in contact with slab specimens rather than spalling since the fibers bridged the cracks and produced stiff slabs.

a) Control Slab



b) mP-375-0.5

Figure 7. Cont’d

c) mP-375-1

d) mP-375-1.5

e) MP-50-0.5

f) MP-50-1

g) MP-50-1.5

h) MS-mP-0.5

i) MS-mP-1

j) MS-mP-1.5

Figure 7. Crack patterns of the tested one-way RC slabs

4.5. Optimal Content

Figure 8 presents the first crack and ultimate loads of the tested one-way RC slabs for the various volume fractions. According to test results, the volume fraction of the fibers impacts the load-carrying capacity of the RC slabs. The slab mP-375-0.5 sustained the 15.9 kN just before the first crack occurrence and provide the most elastic slab due to delayed crack initiation. Following slabs MP-50-1 and MS-mP-1 have crack loads at 13.07 kN and 13.18 kN, respectively. Whereas the control slab has a first crack load at 7.51 kN. The ultimate load within the groups is as follows: the slab MP-50-0.5 has an ultimate load of 36.8 kN that increased by 32.46% compared to the control slab. Then the slab mP-375-0.5 by 29.73%, and the slab MS-mP-1.5 by 28.2%.

The deflection of the tested one-way RC slabs for the various volume fractions is displayed in Figure 9, regarding to the first and ultimate loading stages. the deflection at the first crack load increases with a higher percentage fiber volume fraction because of delayed crack initiation. Despite this, the deflection at ultimate load reduces with higher percentage of mPPF and MPPF volume due to fiber balling and clamping. On the other hand, the deflection increased with a higher fiber volume fraction for the slabs with hybrid fibers.

The optimal fiber content can be estimated by the first crack load, ultimate load, ductility, stiffness, and cost of the fibers. The optimal fiber content of the tested one-way RC slabs was determined based on the ultimate flexural load and the mechanical properties of the FRCs. Therefore, the fiber dosage of 0.5% by volume of the concrete, is the optimum content for the slabs reinforced with mPPF and MPPF. Although, the optimal hybrid fiber content for the third group is 1.5% by volume of the concrete.

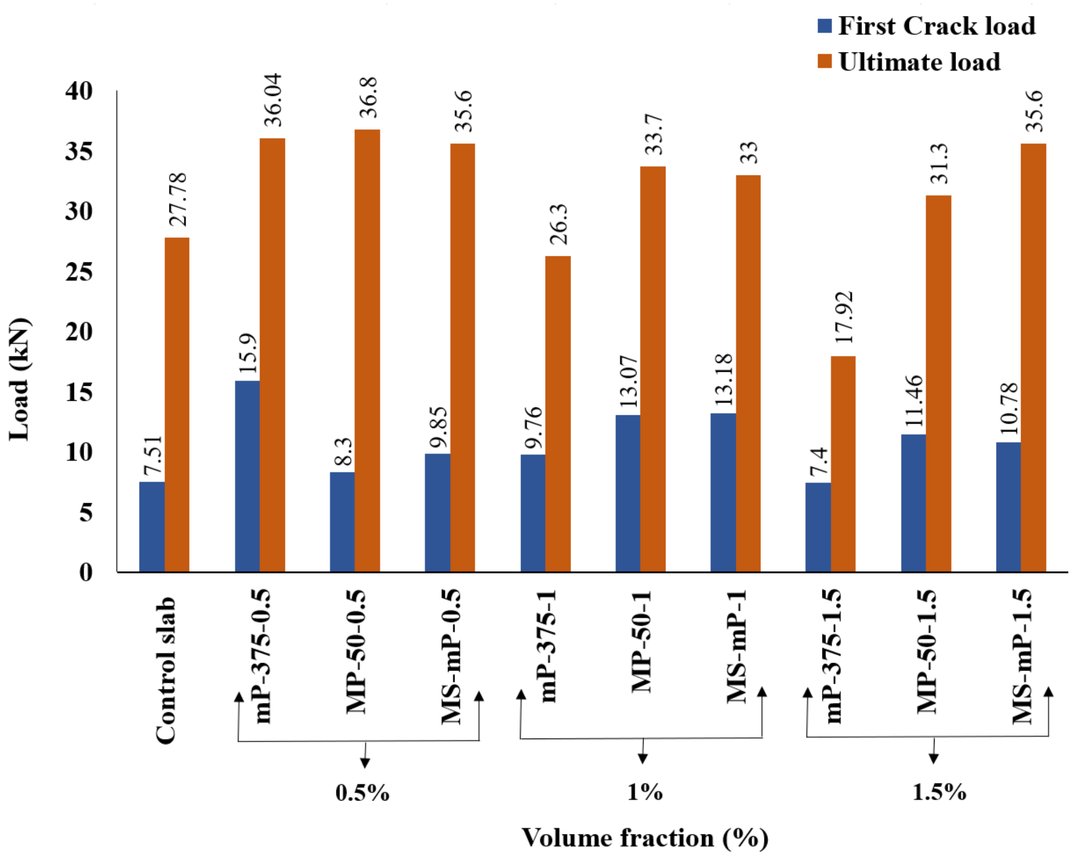


Figure 8. First crack and ultimate loads of the tested one-way RC slabs

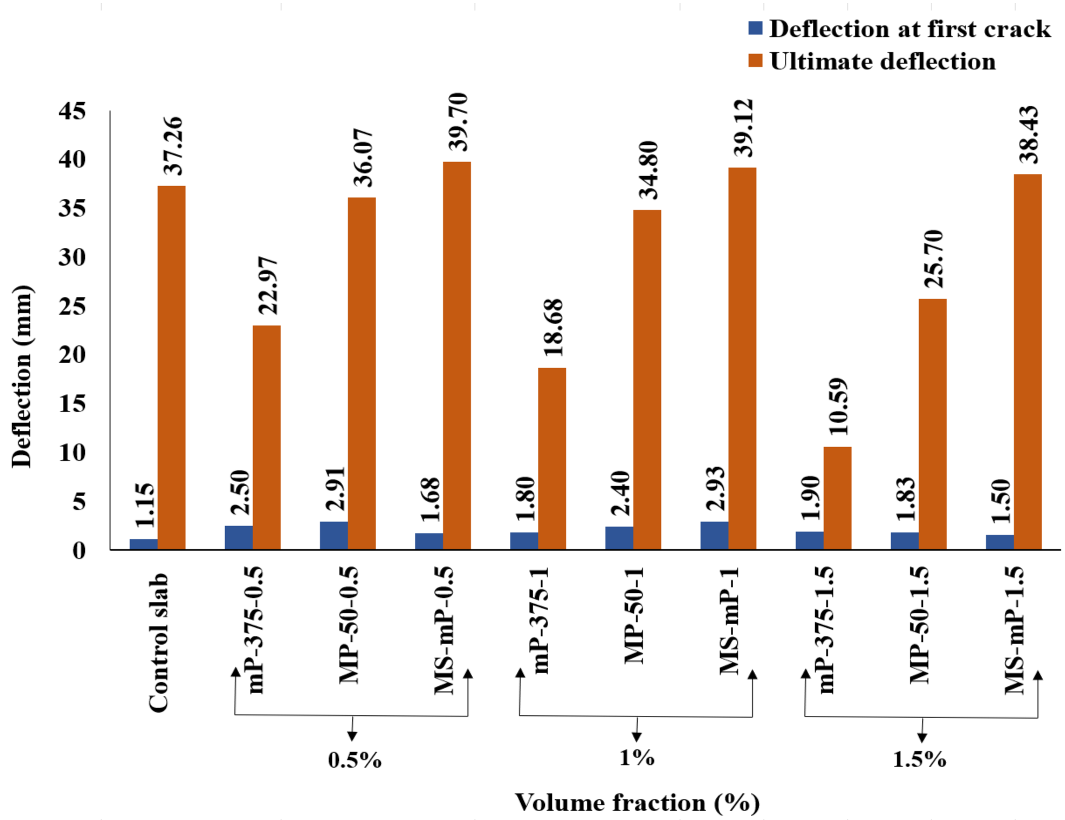


Figure 9. First crack and ultimate deflections of the tested one-way RC slabs

5.Conclusion

The study provided the following conclusions:

- The first crack and ultimate flexural loads are highly influenced by the type and aspect ratio of fibers. The mPPFs for fiber volume more than 0.5% displayed no measurable increase in ultimate flexural loads because of balling and improper distribution of the fibers. While, the MPPFs and hybrid fibers provided noticeable enhancement in load carrying capacity due to bridging capacity of the fibers in post-cracking behavior.
- Hybrid fibers improved deflection of the RC slabs by 3.1-6.59%, linearly with hybrid fiber content. While the increase in polypropylene fiber dosage beyond 0.5% diminished the deflection of RC slabs, due to reasons that the higher amount of these fibers causes stiffness and brittleness of the RC slabs.
- The aspect ratio of the mPPFs and MPPFs at a dosage of 0.5% enhanced the first crack and ultimate flexural loads of the RC slabs by ranges of 112%-10.51% and 29.73%-32.46%, respectively. Conversely, both aspect ratios of the PPFs provided no enhancement in structural behavior of RC slabs beyond a volume fraction of 0.5%.
- The mechanical properties of the macro and micro fibers were non-proportional with volume of the fibers. because of the higher amount of the fibers showed clumping and dispersion issues.
- The further enhancements in load-carrying capacity, crack control, and stiffness by the inclusion of the fibers offer potential for diminishing the long-term maintenance cost for RC slabs. Also suggests for sustainable cost-efficient RC slabs, due to improvements in the durability.
- It is recommended that future studies examine the long-term durability of the macro and micro fiber reinforced concrete under cyclic loading.

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