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Shahzinan J. ZAEZUE[1] ✉ https://orcid.org/0000-0001-6376-724X

Waleed K. HADI[2]

[1]University of Thi-Qar, College of Engineering, 64001, Iraq
[2]Mazaya University College, Civil Engineering Department, Iraq

Effect of hybrid steel-polypropylene fiber on punching shear behavior of flat slab with an opening

Keywords: hybrid fiber, steel fiber, polypropylene fiber, punching shear, slab with opening

Introduction

Plain concrete is prone to punching failures because of its low tensile strength, poor toughness, low flexural strength, low shear strength and brittle nature (Barrera, Bonet, Romero & Miguel, 2011; Gu, Wu, Wu & Wu, 2012). Slab collapse, and particularly flat slab collapse when supported by columns, is typically attributed to a punching failure. Such failures occur in the slabs with little to no notice before they collapse, and they are frequently accompanied by bending, cracking and pronounced fluctuations in the post-peak behavior as a result of a decrease in the load following the peak stress point (Di Prisco & Felicetti, 1997). Standard practice calls for placing transverse stirrups at close intervals to strengthen concrete confinement, slowing the spread of cracks and improving the punching shear performance of reinforced concrete slabs (Paulay & Priestley, 1993; American Concrete Institution [ACI], 2005).

✉shazanan.j.z@utq.edu.iq

Fiber-reinforced concrete has become an innovative reinforcement option since the 1960s, when it started to replace the more traditional reinforcement approach of using stirrups. In order to prevent bond failure in extremely stressed areas of a structure (such as beam-column joints, column bases and beam midspans), fiber-reinforced concrete (FRC) has been widely adopted as a preventative measure (Mansour, Bakar, Ibrahim, Marsono & Marabi, 2015).

Due to its low cost, exceptional toughness and higher shrinkage cracking strength in concrete reinforced with this type of fiber (Alhozaimy, Soroushian & Mirza, 1996; Qian & Stroeven, 2000; Banthia & Gupta, 2006), polypropylene, the most common synthetic fiber, has received the most interest among the researchers. Though steel fiber has had numerous applications in the past few decades thanks to its ability to improve the performance of structural parts, new research is looking into the usage of fiber combinations in the cementitious composite. The primary objective of this multi-fiber approach is to minimize cracking in cementitious materials throughout a wide range of loading conditions and strain amplitudes (Brandt, 2008; Issa, Metwally & Elzeiny, 2011; Banthia, Majdzadeh, Wu & Bindiganavile, 2014; Chi, Xu & Yu, 2014). Steel-polypropylene hybrid fibers were conceptualized to combine the benefits of both fiber forms. In a hybrid fiber system, stronger steel fibers increase the ultimate strength and first crack stress, while flexible and ductile polypropylene fibers increase the ductility and toughness after cracking (Yao, Li & Wu, 2003). Numerous studies (Dry, 1994; Sivakumar, 2011; Xu, Xu, Chi & Zhang, 2011; Chi, Xu, Mei, Hu & Su, 2014; Afroughsabet & Ozbakkaloglu, 2015) have pointed out the benefits of combining steel with polypropylene fibers. Xu et al. (2011) observed the steel-polypropylene FRC's tensile strength. Their research revealed that the use of hybrid steel-polypropylene fibers can significantly increase the tensile strength of conventional concrete.

Sivakumar (2011) examined the toughness, ductility and flexural strength of a concrete specimen made up of combinations of hybrid polypropylene fibers and steel fibers, and found comparable findings.

Chi et al. (2014) studied the effects of the tri axial compression with steel-polypropylene hybrid fiber reinforced concrete (HFRC). The results revealed that the steel fibers, the triaxial strength of which significantly increased with the increase of the steel fiber volume fractions, were the primary contributors to the composite's improved strength.

Labib (2020) presented an experimental study to estimate the influence of the steel-polypropylene hybrid fiber on the punching shear capacity. The test results revealed that the hybrid fiber concrete mixtures have outdone normal and single fiber concrete mixtures in terms of punching shear capacity. Other concrete proprieties, such as compressive strength, flexural strength, cracking behavior, ductility and toughness, have also shown this improvement.

So far, no research has been conducted into the potential benefits of hybrid steel-polypropylene mixes in increasing the punching shear capacity of slab with opening.

This research aimed to quantify the influence of steel-polypropylene HFRC on improving the punching shear capacity of concrete slabs and to discuss the influence of fiber volume fraction on punching shear.

Material and methods

All slabs were reinforced with deformed bars in conformity with the ASTM A615/A615M-15a standard (ASTM International [ASTM], 2015) with a 10 mm diameter for flexural reinforcement. Hooked-end steel and polypropylene fibers were used in this study as shown in Figure 1. The properties of the steel reinforcement and the fiber are listed in Table 1. The usage of sulfate-resistant portland cement type (V) in conformity with to the ASTMC150/C150M-21 standard (ASTM, 2021) was required. In order to make the material more workable, high-range water-reducing Sika® ViscoCrete®-5930 super plasticizer (SP) consistent with the requirements of the ASTM C494/C494M-19 standard (ASTM, 2019) was used. In this study, the coarse aggregate that complied with the ASTM C33/C33M-13 standard (ASTM, 2013) and sand with a maximum size of 4.75 mm each were used. The materials were tested at the Labs of the College of Engineering – University of Thi-Qar. A steel reinforcement bar was placed horizontally inside the molds before pouring the concrete mixture into them. All samples were covered with a wet blanket for 28 days for curing after 48 h of casting.

a b

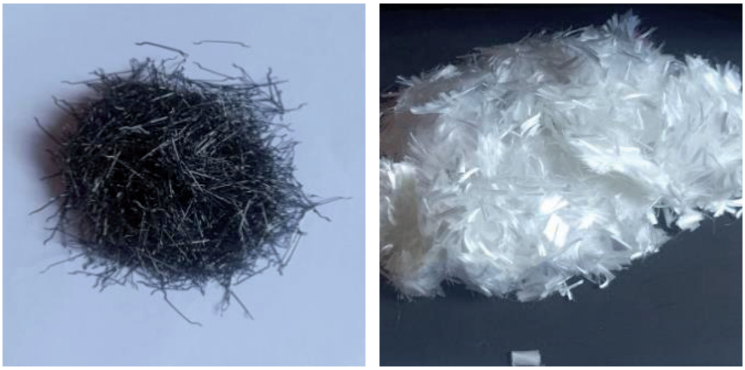

FIGURE 1. Types of fibers: a – steel fiber; b – polypropylene fiber

Source: own work.

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TABLE 1. Steel reinforcement bar and fibers properties

Material	Property	Value/Description
Steel bar	Bar diameter [mm]	10
	Yield stress [MPa]	550
	Ultimate stress [MPa]	643
	Elongation [%]	11.87
Steel fiber	Length [mm]	30
	Diameter [mm]	0.5
	Aspect ratio length to diameter (L/D)	60
	Geometry	hooked-ends
	Tensile strength [MPa]	1 300
Polypropylene (PPF)	Length [mm]	12
	Diameter [mm]	0.032
	Aspect ratio length to diameter (L/D)	375
	Geometry	straight
	Tensile strength [MPa]	600–700

Source: manufacturers' specifications.

Mix designs

The reference mixture was intended to have a cube compressive strength of 35 MPa, in accordance with the BS 1881-116 standard (British Standards Institution [BSI], 1991). Each sample mix design is differentiated from the others using a different volumetric ratio of hybrid fibers. The workability of fiber reinforcement concrete mixtures was improved by using super plasticizers, a water-reducing addition. Table 2 lists the mix proportions that were employed in this study. All components were combined in a concrete mixer for around 10 min.

TABLE 2. Details of mix proportions

Mix	Cement content [kg·m^{-3}]	Sand content [kg·m^{-3}]	Coarse aggregate content [kg·m^{-3}]	Water content [kg·m^{-3}]	Super plasticizers content (by weight of cement) [%]	Steel fiber content [%]	Polypropylene fiber content [%]
S1	410	750	1 100	184.5	0.5	0	0
S2	410	750	1 100	184.5	0.5	0.75	0.15
S3	410	750	1 100	184.5	0.5	0.75	0.3
S4	410	750	1 100	184.5	0.5	1.5	0.15
S5	410	750	1 100	184.5	0.5	1.5	0.3

Source: own work.

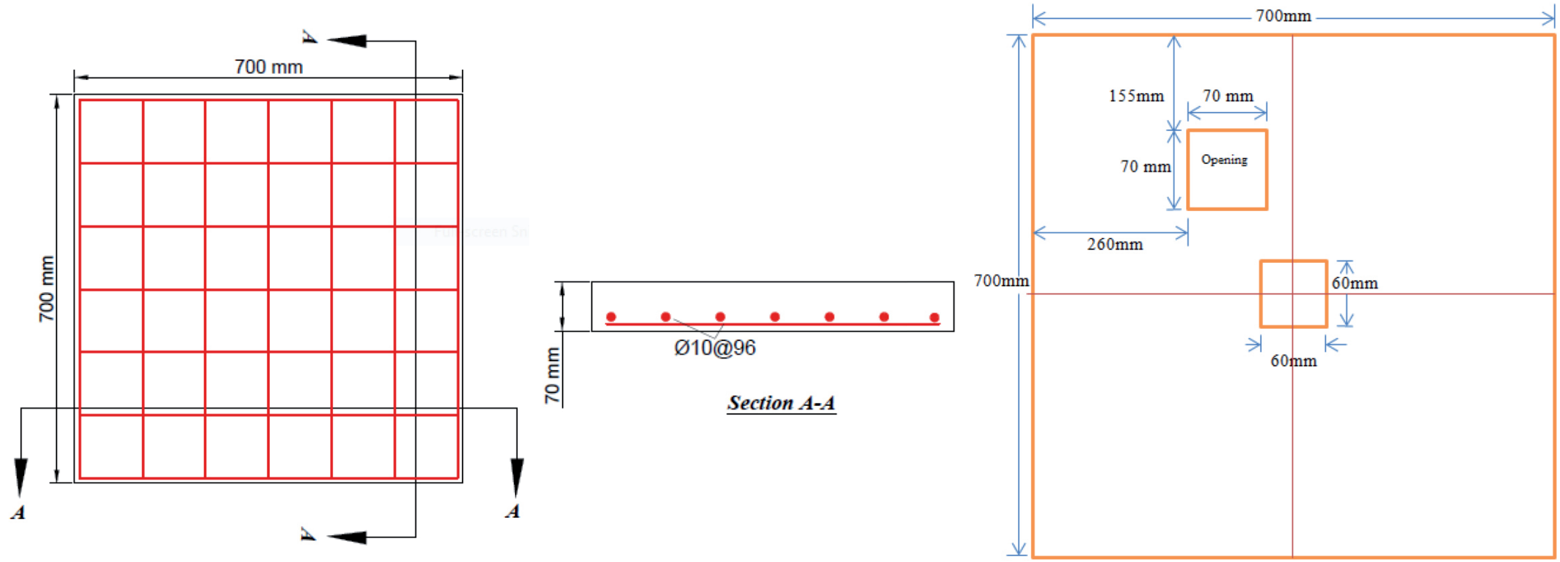

FIGURE 2. Details of reinforcement and specimen opening layouts

Source: own work.

Sample preparation

The dimensions of slab specimens were 700 × 700 × 70 mm. They were reinforced with Ø10 in both directions (seven bars in each direction) with the 15 mm concrete cover. The slab supported by a steel frame (600 × 600 mm) provided a 700 mm clear span in two directions. Figure 2 depicts the geometry and reinforcement of the slab sample. The slab had an opening (70 × 70 mm) at the panel corner as shown in Figure 2. The loads were applied on a solid square steel shaft (60 × 60 mm) at the center. A single dial gauge was used to measure the deflection at the center point of the slabs. Figure 3 displays the molds before casting concrete, the machine of applied load, the frame support of the slab and dial gage.

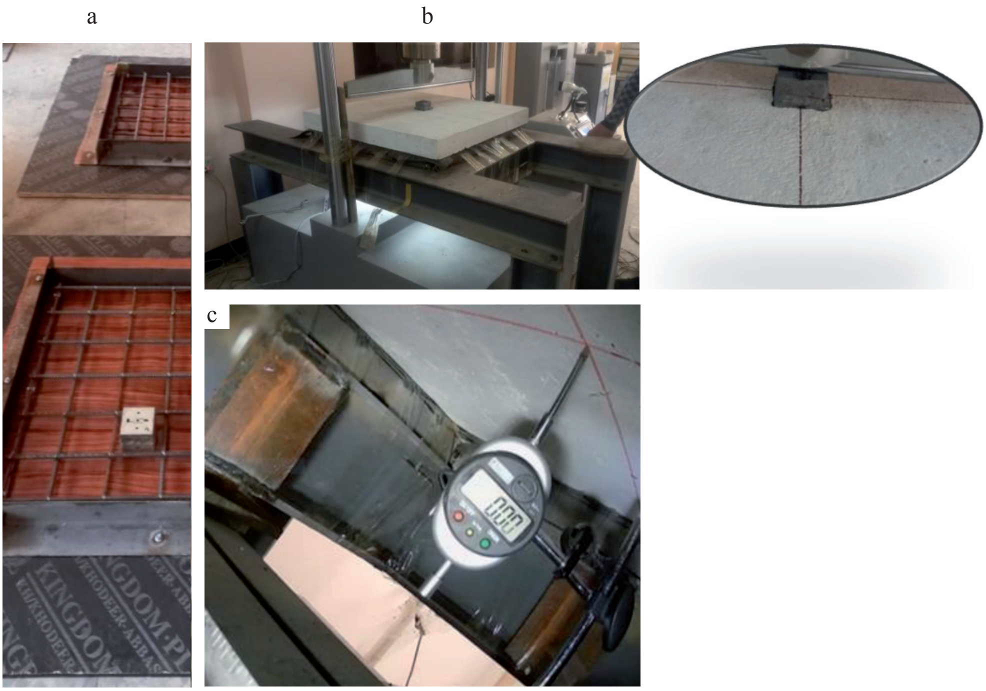

FIGURE 3. Slab testing: a – molds of slab; b – test device and loading plate; c – dial gages
Source: own work.

Results and discussion

Ultimate load and first crack load

The ultimate load capacity and first crack load values of slab samples are recorded in Table 3. It can be noted from the results that the addition of fibers led to an increase in the load capacity of about 52% for slabs without an opening

TABLE 3. Ultimate load and first crack load of slab specimens

Slab	First crack load [kN]	Ultimate load [kN]	Slab	First crack load [kN]	Ultimate load [kN]
S1-S	23.84	83.3	S1-O	20.63	81.2
S2-S	40.5	111.59	S2-O	35.95	107.47
S3-S	42.82	115.25	S3-O	38.48	108
S4-S	43.67	122.48	S4-O	40.7	109.4
S5-S	44.67	126.78	S5-O	41.9	115.92

and up to 42% for slabs with an opening. In slabs without openings, the increase in load capacity was more noticeable. For S2-S, S4-S, S2-O and S4-O slabs, the polypropylene fiber was constant at 0.15%, and the use of steel fiber with volume fractions of 0.75% and 1.5% enhances the ultimate load of the beam by approximately 33.96%, 52.19%, 32.35% and 42.75%, respectively. For S3-S, S5-S, S3-O and S5-O slabs, the polypropylene fiber was constant at 0.3%, and the steel fiber with volume fractions of 0.75% and 1.5% enhances the ultimate load of the beam by approximately 38.36%, 52.19%, 16.07% and 42.75%, respectively. Figure 5 clearly shows the influence of the hybrid fiber volume on the punching shear resistant of tested slabs. The ultimate loads of slabs with openings were decreased by 2.5–10.67% compared to similar slabs without openings.

The first crack load is significantly improved with fibers by 69–87%, for slabs without an opening and 74 to 103% for slabs with an opening. What is more, the presence of an opening decreases the first crack load between 6.2 and 13.46%, however, the influence of an opening was decreased as the hybrid fiber ratio increased. Figure 4 shows the ultimate load for different volume fraction of a hybrid fiber for the slab both with and without an opening.

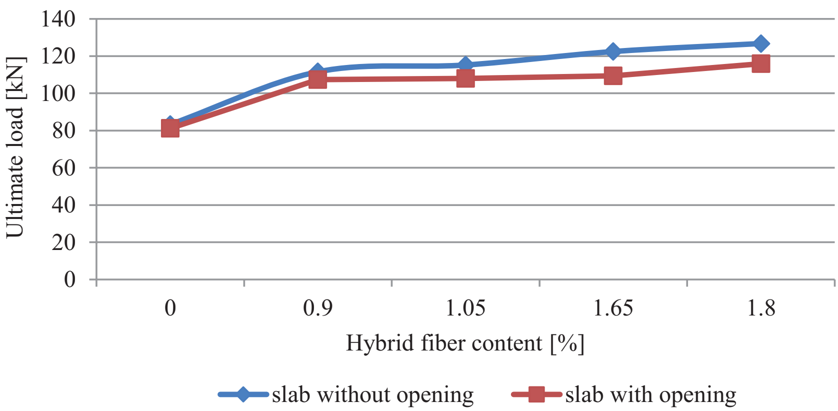

FIGURE 4. Ultimate load versus hybrid fiber content
Source: own work.

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Load–deflection response

Figures 5–9 display the load–deflection curves for each two-way slab specimen. Typically, the elastic stage without cracks in the load–deflection curves begins with a linear behavior, followed by a nonlinear portion of the curve with an elastic cracking behavior. It is clear that the deflection obtained for specimens mixed with fibers is lower than for the control slab specimens (S1-S and S2-O), proving that the deflection was absorbed by the slab structure. Concrete mixtures using the hybrid fiber have better ductility and stiffness. The central deflections of slabs decreased slightly with increasing the volume fraction of hybrid fibers equivalent loads as demonstrated by Figures 10 and 11, from Figures 6–10 it can also be concluded that the slabs with openings develop higher deflections than the solid slabs.

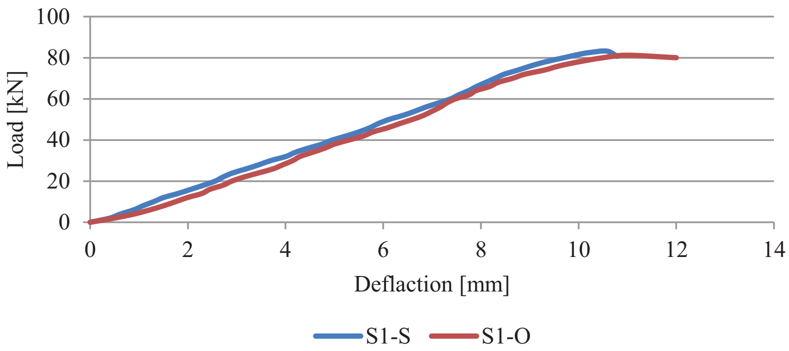


FIGURE 5. Load–deflection curves of control slab with and without opening

Source: own work.

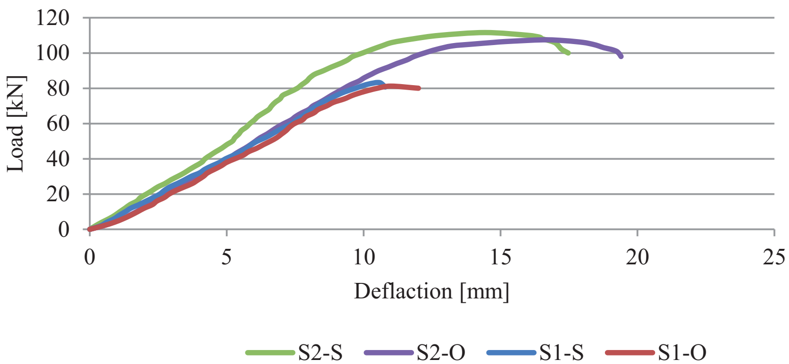


FIGURE 6. Load–deflection curves of slab with 0.9% of hybrid fibers

Source: own work.

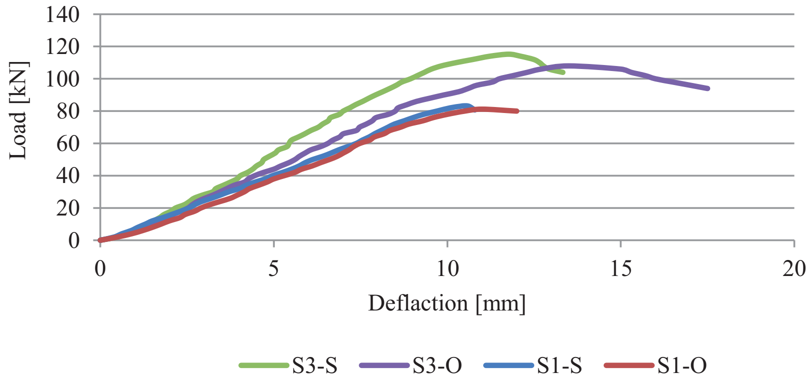


FIGURE 7. Load–deflection curves of slab with 1.05% of hybrid fibers
Source: own work.

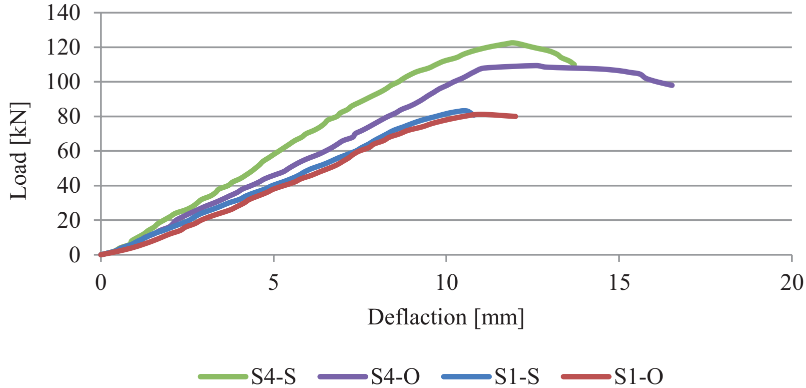


FIGURE 8. Load–deflection curves of slab with 1.65% of hybrid fibers
Source: own work.

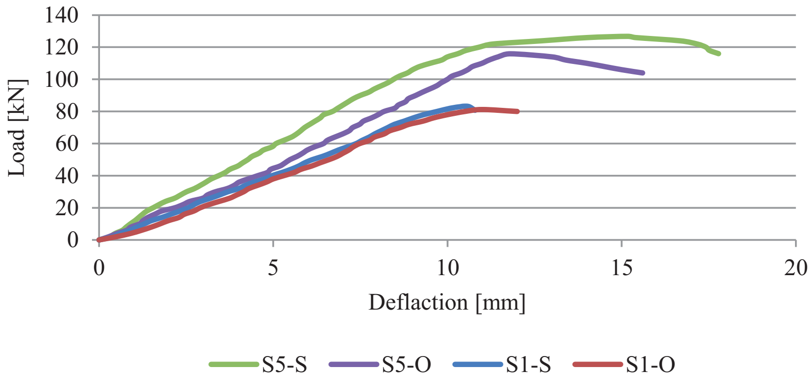


FIGURE 9. Load–deflection curves of slab with 1.8% of hybrid fibers
Source: own work.

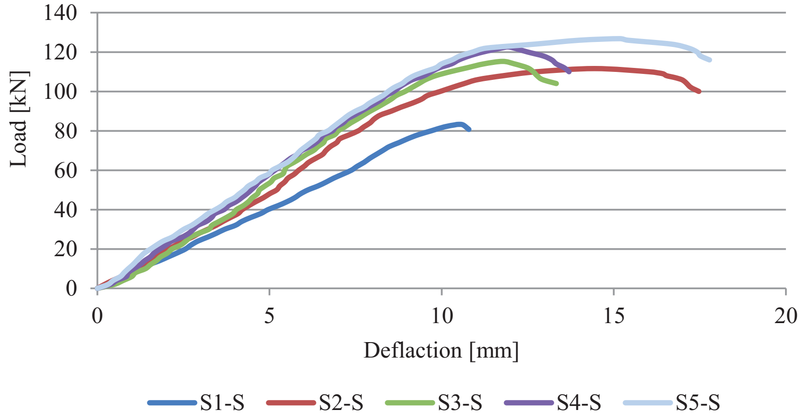


FIGURE 10. Load–deflection curves of solid slab with different ratio of hybrid fibers
Source: own work.

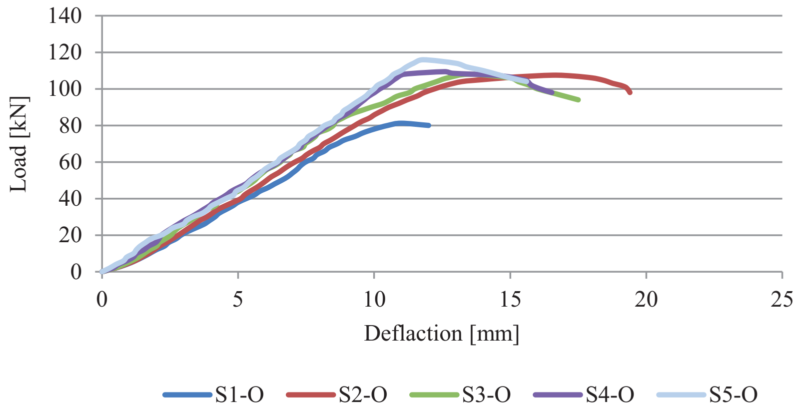


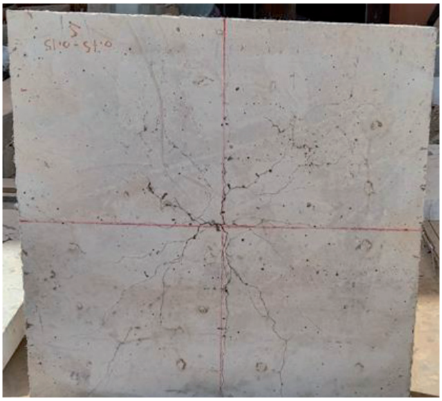
FIGURE 11. Load–deflection curves of slab with opening (different ratio of hybrid fibers)
Source: own work.

Modes of failure and crack patterns

Figure 12 shows all experimentally tested samples. In general, the slabs' tensile face is where the cracks first appeared, roughly under the laden area's boundaries, and then formed slowly across the whole slab. The cracks got steadily wider as the load got close to the slab's maximum shear strength. As the slabs began to fail, a loud noise was heard and the cut cone-shaped section of the slab was pushed under the load. This behavior was described by Kuang and Morley (1993).

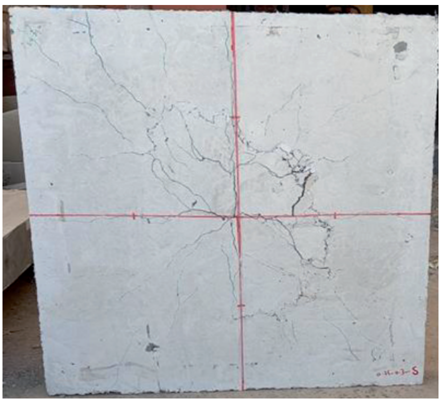
(a) S1-S

(b) S1-O

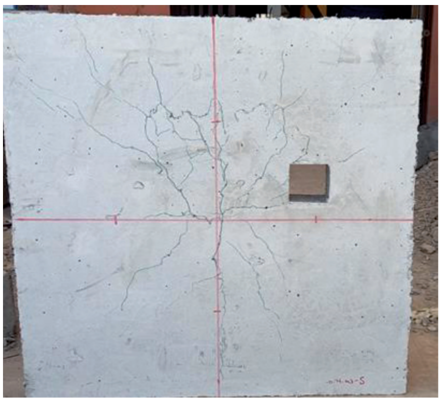


(c) S2-S

(d) S2-O



(e) S3-S



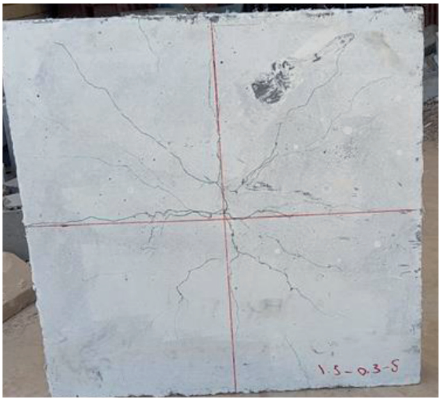
(f) S3-O

FIGURE 12. Crack and failure pattern of tested slabs (a–f)

Source: own work.

(g) S4-S

(h) S4-O



(i) S5-S

(j) S5-O

FIGURE 12 (cont.). Crack and failure pattern of tested slabs (g–j)

The control specimens without fibers failed in a more violent way and cracks spread widely. In other specimens with a hybrid fiber, there were more cracks in the slabs with greater fiber contents, and these were finer than the cracks in the slabs with minor values of volume fraction of steel fibers. Also, the cracks became closer to the punching zone by increasing fiber contents.

Conclusions

In general, the cracking and punching shear load increased together with the growth of the amount of hybrid fibers, just as the hybrid fiber ratio increased with the growth of the ultimate punching load. It was found that when adding hybrid fibers to the solid slabs by ratios from 0 to 1.8%, the ultimate load increases from 33.96 to 52.19%, as compared with slabs without hybrid fibers. It was found that the hybrid fiber ratio in slabs with an opening is significant. The capacity of slabs was increased by about 32%, 33%, 34.73% and 42.75%, with the hybrid fiber ratio of 0.9, 1.05, 1.65 and 1.8, respectively, as compared with slabs without hybrid fibers.

In comparison to the similar solid test specimens, the presence of opening in slab specimens leads to a decrease in the ultimate load capacity. The ultimate load for slabs with an opening decreased by 13.46%, 11.23%, 10.13%, 6.8% and 6.2%, respectively.

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Summary

Effect of hybrid steel-polypropylene fiber on punching shear behavior of flat slab with an opening. This research aimed to gain a better understanding of how the addition of fiber influences the punching shear capacity of two-way slabs by conducting an experi-

ment into the structural behavior of flat slabs with and without a square opening using different volume fractions of hybrid steel-polypropylene fiber (0%, 0.9%, 1.05% and 1.8%). Ten 700 × 700 × 70 mm slabs were divided into five pairs, with two samples used as control samples (with and without openings), and eight other samples with different volume fraction of fibers. Results showed that an increase in fiber content enhanced the shear strength of the slabs. For example, as the volume fraction of hybrid fiber increased from 0.0 to 1.8%, the ultimate load increased by 52% for slabs without an opening and up to 42% for slabs with an opening.