

Article

Fiber-Type Influence on the Flexural Behavior of RC Two-Way Slabs with an Opening

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Abstract: Combining fiber with concrete mixes has become essential and its widespread use improves the strength of structural concrete elements. This research conducted an experiment into the structural performance of flat slabs with and without a square opening using four types of fiber (hooked-end, straight, corrugated steel fiber and polyolefin fiber) to gain a better understanding of how the variance of fiber type and shape effects the flexural behaviors of two-way slabs. The test program involved (a) testing the properties of hardened concrete, such as compressive properties, modulus of rupture and splitting tensile strength, and (b) testing the flexural behavior of two-way slabs. Ten slabs were divided into five pairs, including two specimens used as reference specimens (with and without openings), and eight other specimens with different types of fibers. Results revealed that the existing fiber in concrete improved the mechanical properties of hardened concrete mix, and the compressive strength test showed higher improvement in specimens with hooked and straight steel fiber. The flexural behavior of reinforced concrete slab was significantly enhanced, and the flexural strength capacity was especially improved for the slabs strengthened with hooked-end and corrugated steel fiber. Polyolefin fiber showed a slight enhancement of mechanical properties and good improvement in flexural capacity. Generally, the highest increments in compressive strength and modulus of rupture were 24.8%, 20% and 11%, and the ultimate load-carrying capacity of slabs was 39%, 13% and 19% for specimens with steel hooked, steel corrugated and polyolefin fibers, respectively, compared with control specimens.

Keywords: steel fiber; polyolefin fiber; flexural behavior; two-way slab; slab with opening



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1. Introduction

The recent advances made in polymer material development have had a positive effect in engineering technology. The constructions and materials fields make the most use of these technologies. Polyolefin, poly-propylene and polyethylene have undergone extensive and fast development in the last decades [1].

David Fall et al. [2] investigated the effect of fibers on the structural behavior of four edges simply supported by a two-way reinforced concrete slab, such as in crack patterns and load-carrying capacity. Double hook-end steel fibers were used, and three slab samples were loaded with a central point load. The results showed significant effects on structural behavior through providing post-cracking ductility, with an improvement in loading capacity around 20%. Furthermore, the tested sample showed load redistribution in a manner that allowed more load to be transferred to the support in the weak direction.

Szymon Grzesiak et al. [3] and recent research on concrete reinforced with fiber in general show that the ratio of added fiber to concrete improves the energy absorption capacity of concrete which leads to improving the strength of the concrete structure. The study was conducted into the mechanical properties of high-performance fiber-reinforced concrete (HPFRC) for different types and different percentages of polymer fiber. The flexural tensile strength was investigated using a square panel and a beam. For both

types of fiber, an increase was shown in the splitting tensile strength of concrete mixes. Meanwhile, compressive strength decreased with increasing fiber ratio compared with control samples, and flexural tests proved that using polyvinyl alcohol fiber (PVA) gives higher ductility behaviors.

Altun et al. [4] presented the flexural behavior of a reinforced concrete box using steel fiber beams of normal concrete strength (22 mPa compressive strength) and 6 cm lengths of steel fiber, with a volume ratio of 0.77. The results show a decrease of around 44% of the weight. In addition, the load capacity was reduced by 29%.

Dapeng Yang et al. [5] submitted a considerable experimental study on concrete slab reinforced with steel fiber against spall. Furthermore, they investigated the mechanical properties of different concrete mixes with different fiber ratios. In general, the mechanical properties showed a similarity with the results of other research, while in a field explosion conducted to study the dynamic response and damage modes, the results presented a good resistance to spall, especially the concrete reinforced with hooked steel fiber, where with an increase in the length of fiber and in the volume of the fiber ratio, the spall resistance was significantly improved.

Most concrete composite structural elements can have substantial ductility. In general, the ductility is dependent on fiber type, fiber ratio, anchorage mechanism and tensile strength. The enhancement of ductility is taken into account when determining the thickness of floors. The calculation for floor thickness design takes into account the first post crack due to flexural strength in positive (sagging) moment capacities, while the effect of fibers is neglected regarding negative moment strength [6].

Kosa and Naaman (1990) [7] concluded that long-term environmental exposure to salt solutions significantly reduced the crack performance of steel-fiber-reinforced concrete (FRC) due to the decrease in fibers as they are corroded at the cross section. In short-term exposure conditions in salt solution, post-peak residual strengths at low levels of tensile and flexural strains were found to be higher compared with control specimens.

Polyolefin fiber is made of either high-density polyethylene or from polypropylene. In general, the fiber length is 3 to 6 cm and the sectional area around 0.6–1.5 mm². The mechanical properties generally include a tensile strength of 300 to 600 N/mm² and a modulus of elasticity of about 4 to 10 GPa [8]. Two techniques have been frequently used to fabricate macro polyolefin fiber. The first technique involves melt-spinning polyolefin granules into strings and then hot-working the monofilaments into fibers [9]. The polyolefin fiber density is around 0.9 g/cm³, which is less than the density of steel fiber (7.8 g/cm³). The small volume ratio of either steel fiber or polyolefin fiber in concrete have no significant effect on the total weight of the concrete [10].

Recently, much essential research has addressed the sustainability of material production, especially regarding large-scale production such as that of cement and concrete mixes. This also includes the use of fibers in concrete structural elements, as well as in several other fields. However, most studies did not consider the indirect costs such as social and environmental effects, and took into account only the direct cost of the materials used. Dong et al. [11] studied the flexural behavior of deck plates using micro-synthetic-fiber-reinforced concrete, and initially studies into the mechanical properties were conducted. The flexural strength showed enhancement compared with normal concrete specimens, and in maximum strength tests, the specimens showed a residual strength fracture. The strength capacity of deck slabs and the cracking load were increased with increasing fiber ratio.

Alireza et al. [12] undertook a specific test program into the water permeability of plain and fiber-reinforced concrete through exploring crack behavior (width, length, tortuosity and surface roughness). The results show that concrete permeability is a function of crack permeability, as well as that of the roughness and tortuosity of crack. The presence of fiber reduced the permeability due to reducing crack tortuosity and the friction caused by crack surface roughness.

Lijuan Zhang et al. [13] investigated the effect of the shape of steel fiber (straight, corrugate and hooked) and volume ratio with different volume fractions (0, 0.5%, 1%, 1.5%, and 2%) on

mechanical properties including the flexural strength of a prism. The results proved that the shape of the steel fiber had a significant effect on flexural strength. Corrugated and hooked-end steel showed higher improvement in flexural strength due to generating a good bridging action in the concrete matrix. Deformed steel fibers had a greater impact than those with a straight shape.

Arkadiusz Denisiewicz and Tomasz Socha [14] studied the mechanical and physical properties of fine-grained fiber concrete. Two types of fiber were used: steel fiber and polypropylene fibers. The concrete mixture samples were tested for slump class, bending, shrinkage, compressive strength and water tightness. The results revealed that the steel fiber had a small effect on workability compared with polypropylene, and that steel fiber decreased the shrinkage whereas polypropylene fibers significantly increased the concrete shrinkage. The positive effect of polypropylene was increasing the bending and compressive strength of concrete samples.

Petr L. and Marie H. [15] presented a numerical study of concrete samples exposed to chlorides, in relation to the service life of lightweight waste structural members. The study used different types of waste material to produce lightweight concrete, such as red clay and red ceramics, with steel fiber at different percentages. The main factors studied were the constant diffusion coefficient and time-dependent diffusion coefficient, to analyse the effects on the service life of the structure. Based on their results, it was found that more fibers reduce the service life and preloading of the structure.

Many field applications are now widespread and used frequently, such as using fiber-reinforced polymers in concrete structure elements due to improvements in flexural behavior. These fiber polymers are used as bars or as sheets (such as FRP, GFRP and BFRP bars) to enhance the flexural behavior of slabs, panels, columns and beams. The research was verified by theoretical analysis and is considered to align with international standards. BFRP with polymer cement composite is also widely used in strengthening concrete structural elements such as slabs and bridge decks due to damage and degradation in the material with time. Outcomes reveal good bonding and a reduction in crack width, and enhanced flexural capacity [16,17].

The design standards and codes specify mechanical requirements for structural use. Therefore, those fibers capable of complying with the standards for residual strengths are called structural fibers, and are normally macro-steel fibers.

2. Materials and Experimental Work

2.1. Materials

2.1.1. Cement

Ordinary Portland cement (type I) was available in the local market (Mabroka) and was manufactured by an Iraqi company. The physical and chemical properties were established in the engineering college laboratory at the University of Basrah and are shown in Tables 1 and 2.

Table 1. Chemical composition and main components of cement.

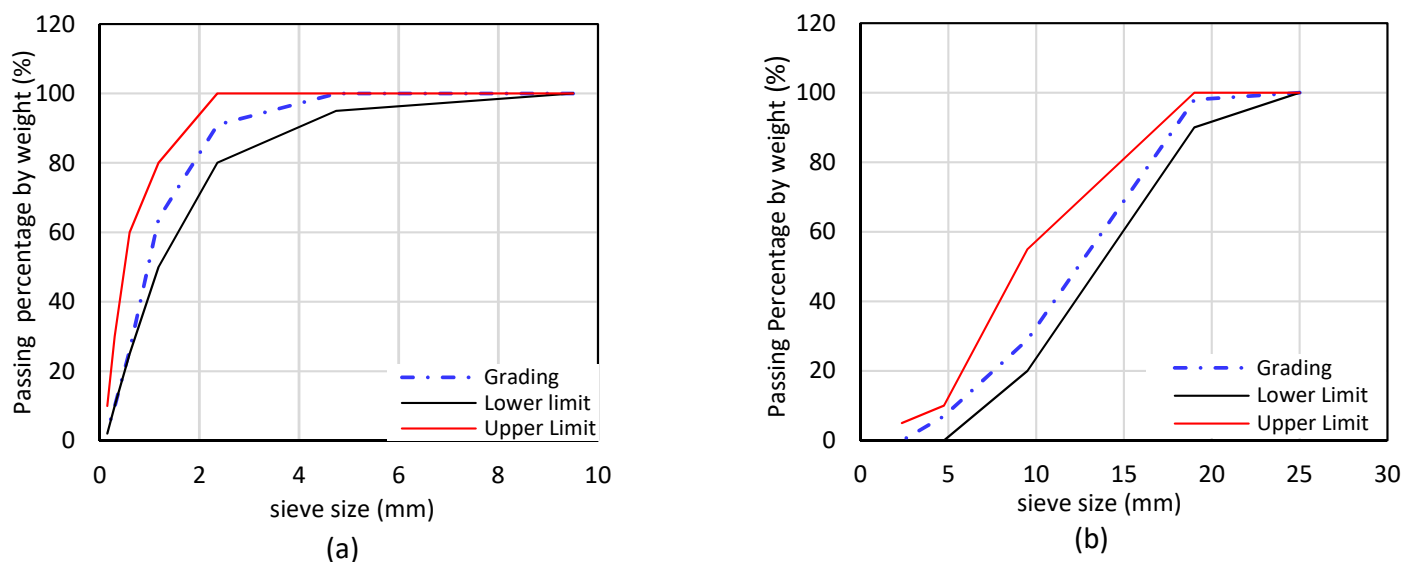
Chemical Components of Cement									Main Components of Cement				
SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	Insoluble Residue	LOI	C ₃ S	C ₂ S	C ₃ A	C ₄ AF
20.7	5.3	3.9	62.8	1.94	0.35	0.66	1.96	0.47	1.4	50.2	24.3	6.81	10.5

Table 2. Physical properties of cement.

Property	Standard	Test Method	Unit	Result
Fineness	ASTM C204 [18]	Mesh 170	%	6.4%
		Blaine air permeability	(m ² /kg)	309
Setting time	ASTM C191 [19]	Initial	minute	135
		Final	minute	260
Compressive strength	ASTM-C349 [20]	3 days	mPa	19.2 mPa
		7 days	mPa	26.3 mPa

2.1.2. Aggregate

Local crushed coarse aggregates and fine aggregate (sand) were provided from the Al Zubair area, which lies in south of Iraq. The gradations for fine and coarse aggregates are shown in Figure 1. The grading was tested according to ASTM C33/86 [21].

**Figure 1.** Aggregate grading as: (a) Fine aggregate grading; (b) Coarse aggregate grading.

The physical properties of course aggregate and fine aggregate are listed in Table 3 and were tested according to the ASTM C 128 [22].

Table 3. Physical properties of aggregate.

Aggregate Type	Bulk Specific Gravity (SSD)	Apparent Specific Gravity	Dense Dry Density (Kg/m ³)	Loose Dry Density (Kg/m ³)	Sulphate Content (%)	Absorption (%)
Coarse Aggregate (gravel)	2.46	2.50	1620	1468	-	0.89
Fine Aggregate (sand)	2.68	2.74	1871	1722	0.24	1.62

2.1.3. Fibers

The polyolefin and steel fiber properties are listed in Table 4. Figure 2 shows the type and shape of steel and polyolefin fibers.

Table 4. Properties of fibers used.

Fiber Type	Shape	Length (mm)	Diameter (mm)	Aspect Ratio ** (mm)	Tensile Strength (MPa)
Straight steel fiber	Straight	12	0.25	50	2850
Hooked steel fiber	Hooked	30	0.5	60	>1000
Corrugated steel fiber	Corrugated	30	0.55 *	55	>700
Polyolefin fiber	-	60	0.84 *	71	465

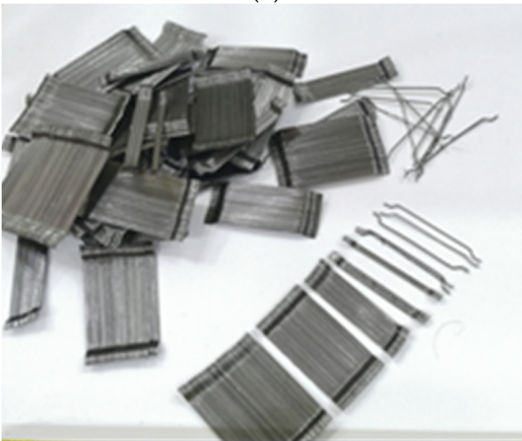
*: equivalent diameter, **: (Length/Diameter).



(a)



(b)



(c)



(d)

Figure 2. Types of fibers: (a) Straight steel fiber; (b) Corrugated steel fiber; (c) Hooked steel fiber; (d) Polyolefin fiber.

2.1.4. Mix Proportion

ViscoCrete (F-180 G) superplasticizer was used as an additive to mix the formula in accordance with ASTM C494 [23], at a percentage of 0.6% of the total cement weight. Tap water from Basrah city was used. The mix proportion used in this experiment is listed in Table 5.

Table 5. Mix proportion quantities.

Cement (Kg)	Fine Aggregate (Kg/m ³)	Fine Aggregate (Kg/m ³)	Water (Kg/m ³)	Fiber (Kg/m ³)	Super Plasticizer (Kg)
370	740	1110	181	3.7	2.22

2.2. Sample Preparation

2.2.1. Mechanical Properties

The same percentages of the four fibers were used in all samples with a constant ratio (1% Vf). These percentages were chosen based on previous research, and varied between 0.5% and 2%, which is the correct ratio to provide a suitable consistency and workability for fresh concrete mixes. The mechanical properties were tested for each type of fiber (compressive strength, modulus of rupture and tensile strength). The samples were prepared according to the ASTM C192 [24].

Three cylindrical samples (150 × 300 mm) were prepared as compressive strength test cylinders for each mix according to the ASTM C39 [25]. A splitting tensile strength test was conducted using a cylinder with dimensions 150 mm diameter and 300 mm height to comply with standard specification ASTM C496 [26]. Furthermore, three prism samples were prepared for each mix to conduct flexural strength tests. The prism dimensions were 500 × 150 × 150 mm according to ASTM C78/C78M [27].

After 24 h, all prepared specimens were demolded and kept in water at a temperature of 20 °C continuously for 28 days until the time of the test.

2.2.2. Two-Way Slab Details

The dimensions of the two-way slabs were 800 × 800 × 100 mm. They were reinforced with ϕ 12 mm in both directions (5 bars in each direction) with concrete covering 25 mm. The yield stress of the steel bar used was 428 mPa with ultimate stress F_u equal to 543 mPa, and the strain yield was (0.00226). The slab was supported by a steel frame (700 × 700 mm) providing a 700 mm clear span in two directions. Figure 3 gives detail of the geometry and reinforcement of the slab sample. The slab had an opening (150 × 150 mm) at the center of panel and loads were applied on a steel plate with the dimensions 200 × 200 mm at the center.

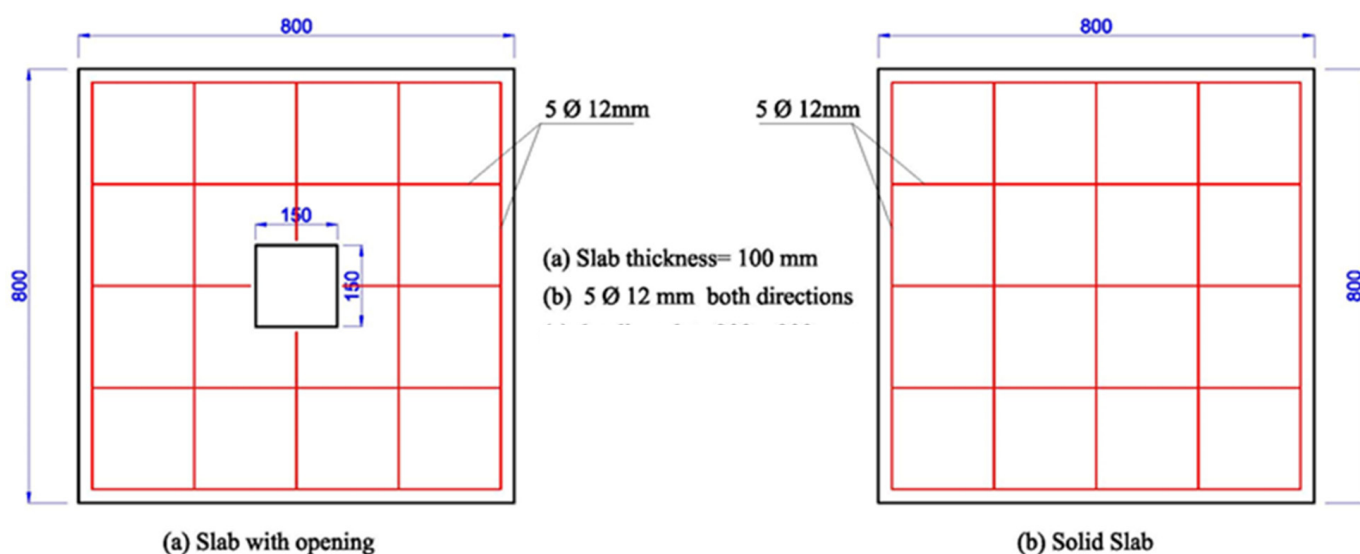


Figure 3. Two-way reinforced slab details (mm) as: (a) slab with opening; (b) solid slab.

Figure 4 shows the wooden mold before casting concrete and also shows the test devices setup, the universal machine of applied load and the frame support of the slab.

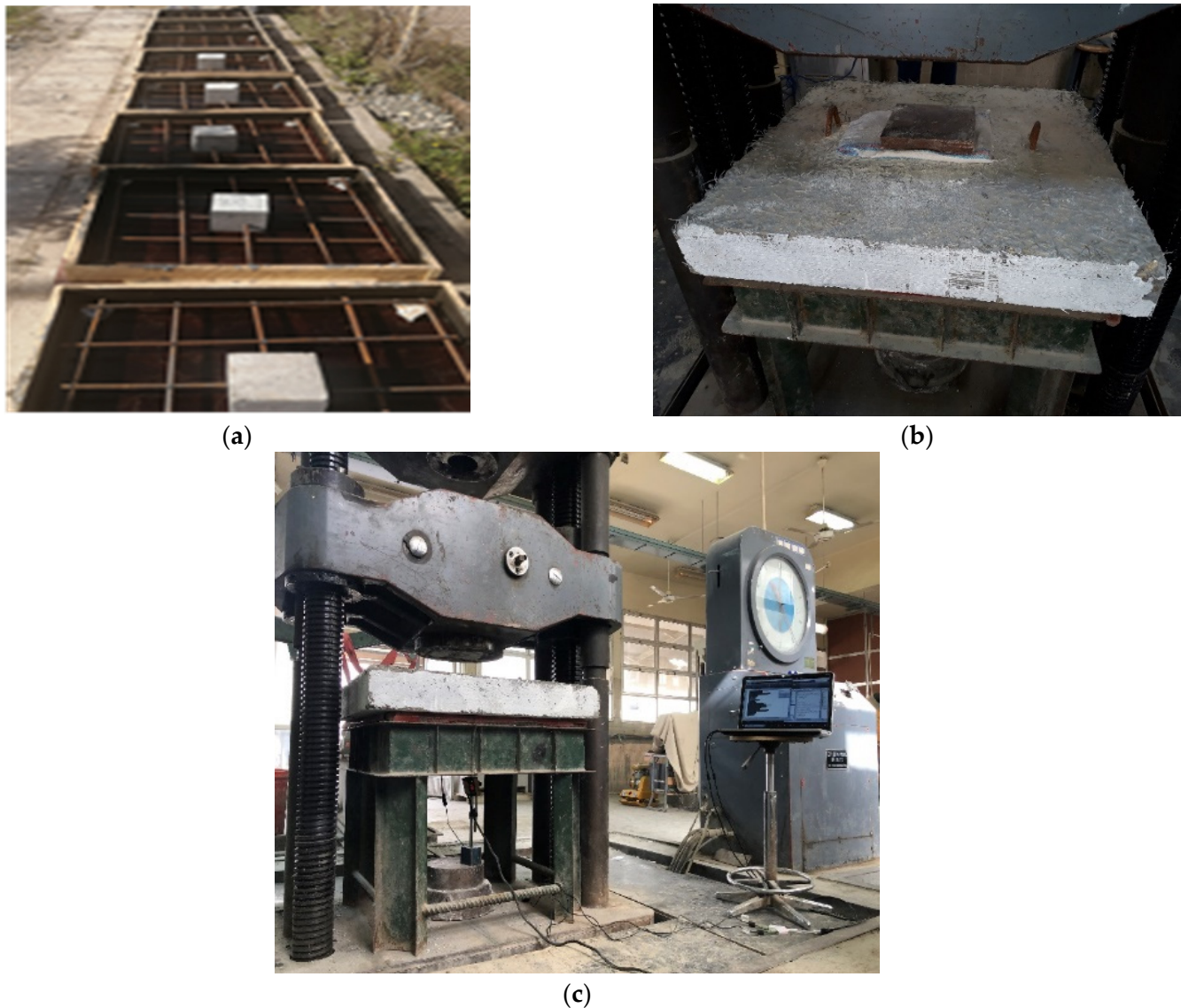


Figure 4. Work process as: (a) Wooden form of slab; (b) Loading plate; (c) Loading setup schematic and measurement devices.

3. Mechanical Properties Results

In general, steel fibers in concrete produce a moderate enhancement of compressive strength. The fibers used in the concrete mixes increased the compressive strength by around 24.8%, 20%, 22%, and 11.3% for straight, hooked, corrugated, and polyolefin fibers, respectively, compared with control specimens. Fibers increased the absorption of energy or improved ductility and the steel fiber produced higher compressive strength. Because steel fiber is stiff and well-bonded, it could better prevent micro-cracks from developing in samples compared with polyolefin fiber. Results are listed in Table 6 and Figure 5a.

Table 6 and Figure 5b present the modulus of rupture and it can be seen that there is a remarkable improvement in the bending capacity of the prism reinforced with fiber, and that this improvement is greater than that of other properties. Increases of about 109%, 78% and 62% for steel hooked, steel corrugated and polyolefin fiber, respectively, can be seen. Initially, the fiber improves the toughness or energy absorption capacity. As previously indicated, the higher bond and friction between fiber and concrete matrix lead to improvements in the flexural strength.

The splitting tensile strength of concrete modified with fiber shows significant enhancement due to the generation of a strong interlock between the fiber and concrete

matrix, especially with the hooked-end and corrugated steel fiber. The higher increment ratio in splitting tensile strength was 94% and 77% for hooked and corrugated steel fiber, respectively, compared with plain concrete, as shown in Figure 5c.

Table 6. Mechanical properties tested results of mixes.

Sample Type	Symbols	Compression Cylinder Test (MPa)	Modulus of Rupture (MPa)	Splitting Tensile Strength (MPa)
Without fiber (control)	control	36.2	4.20	2.32
Straight steel fiber 12 mm	S-1	45.2	6.38	3.81
Hooked steel fiber 30 mm	H-1	43.5	8.76	4.51
Corrugated steel fiber 30 mm	C-1	44.2	7.49	4.12
Polyolefin fiber 60 mm	P-1	40.3	6.80	3.12

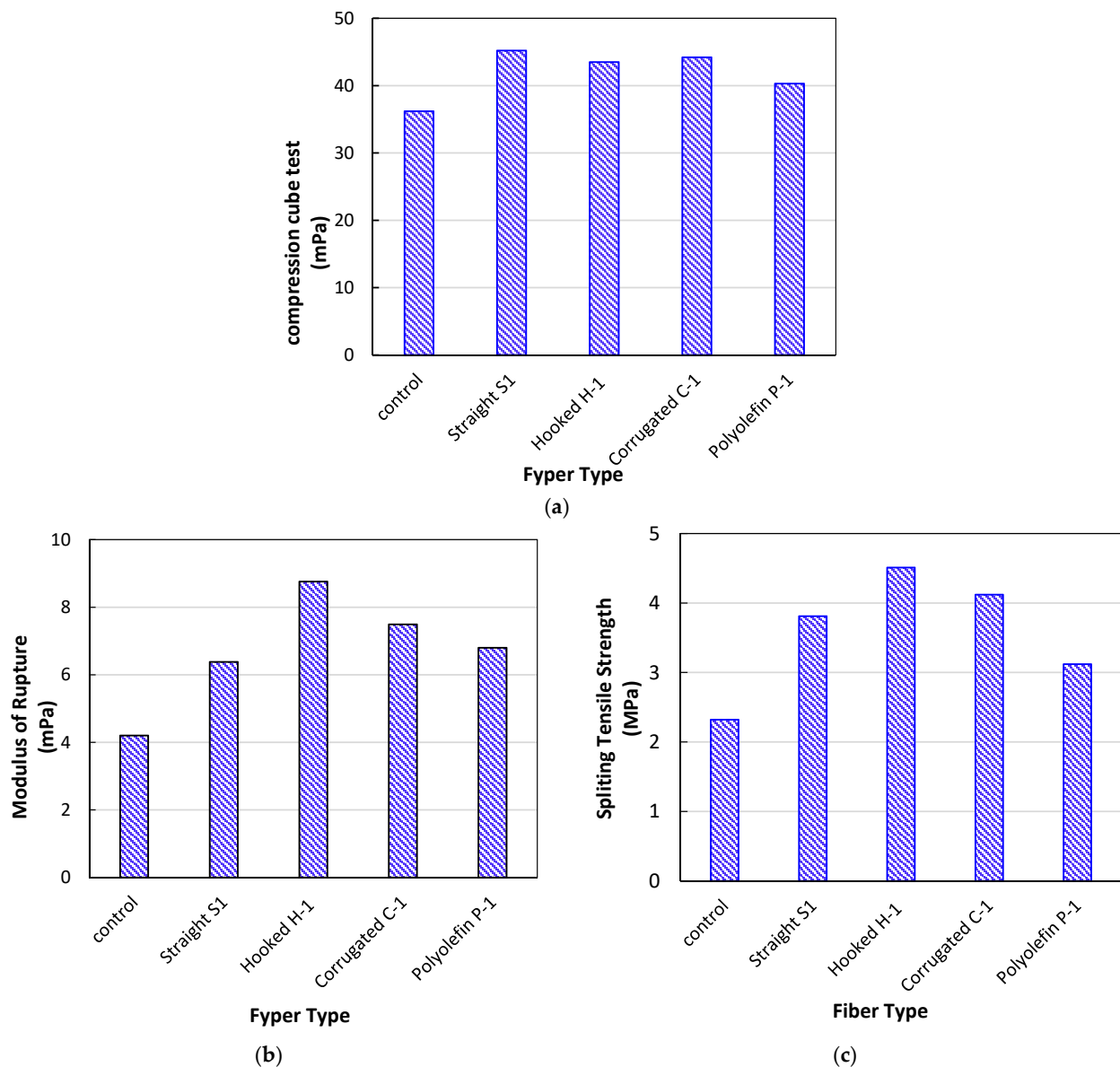


Figure 5. Mechanical properties of concrete mix with fiber as: (a) Compression cube test; (b); Modulus of Rupture; (c) Splitting Tensile Strength.

4. Failure Modes and Crack Patterns

All experimentally tested specimens are shown in Figure 6. Diagonal cracks at the bottom surface started from the corners of the opening and propagate from the center toward the corners of the slabs, and all specimens failed in flexural patterns. On the control specimen with an opening, cracks spread widely and were accompanied by a minor, narrow, short crack in addition to the main cracks across the whole slab. In the other specimens with steel fiber, fewer cracks were generated from the corners of openings towards the corner of slab which indicated a greater increase in the stiffness of the slab and led to a higher ultimate load compared with the control specimen. The slab with polyolefin showed more ductile behavior and the crack devolved much more than those in the specimens with steel fiber.

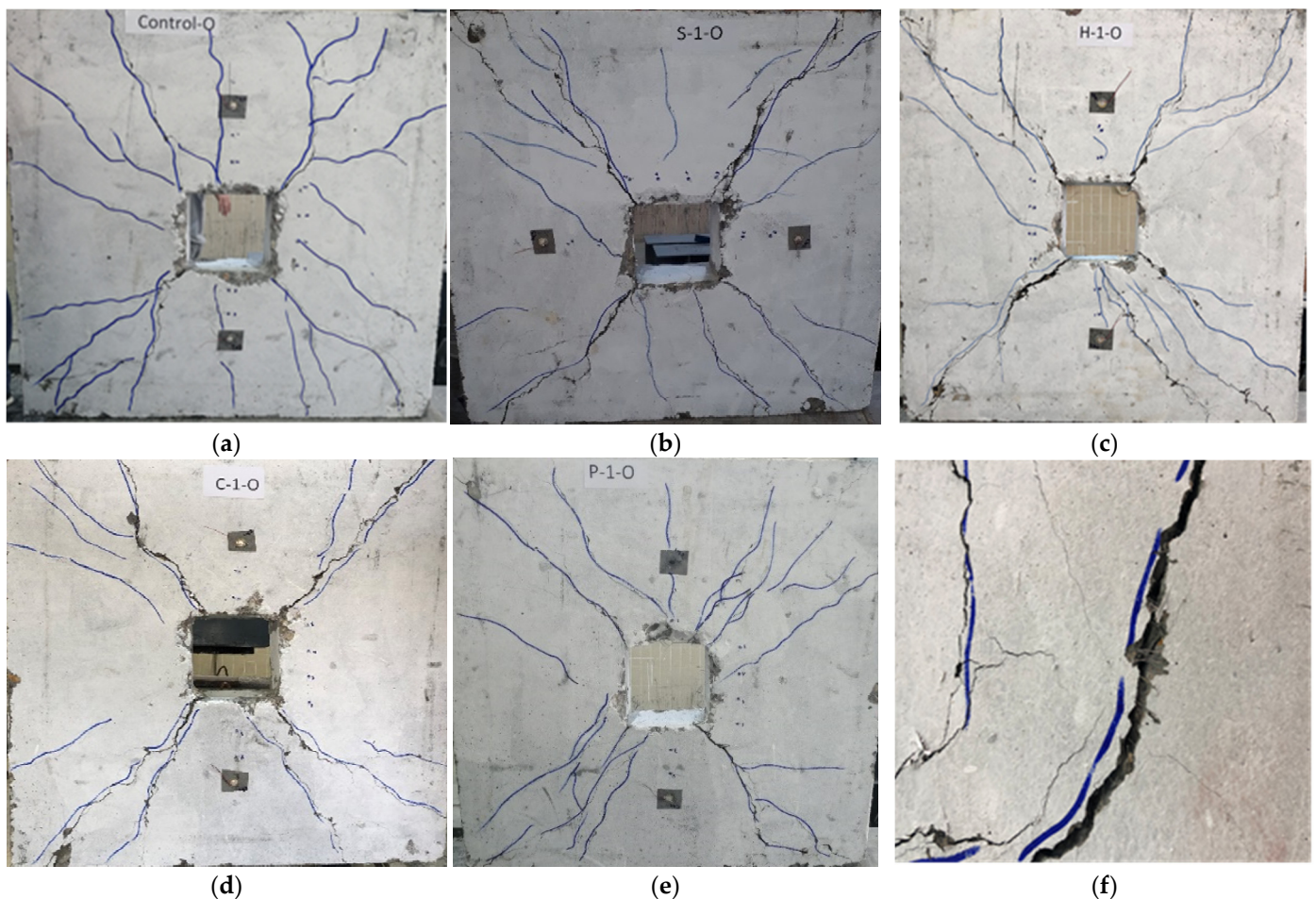


Figure 6. Crack and failure pattern of a slab with an opening. (a) Control sample without fiber; (b) Slab with straight steel fiber; (c) Slab with hooked steel fiber; (d) Slab with corrugated steel fiber; (e) Slab with Polyolefin fiber; (f) Fracture failure of slab with fiber.

Cracks increased gradually until a slight stiffness reduction was noticed and crack width increased. At this stage the energy was slightly absorbed and plastic deformation began to appear. At the ultimate load capacity of the slab, no more cracks formed, and the final failure modes were similar in all cases. The main failure mode was flexural mode because the main reinforcement of the slab was chosen to avoid punching shear.

The cracking loads for solid slabs with fiber increased by about 43%, 27% and 33% for steel hooked, steel corrugated and polyolefin fibers, respectively, while for the slabs with an opening, the increases in cracking loads were 10%, 42% and 25%, respectively.

Figure 7 shows the first crack load for slabs without an opening and it is clear that the specimen with polyolefin showed extra-fine cracks compared with samples that had steel

fibers with less ductile behavior. Table 7 and Figure 8 show the cracking loads for different type of fiber for slabs both with and without openings.

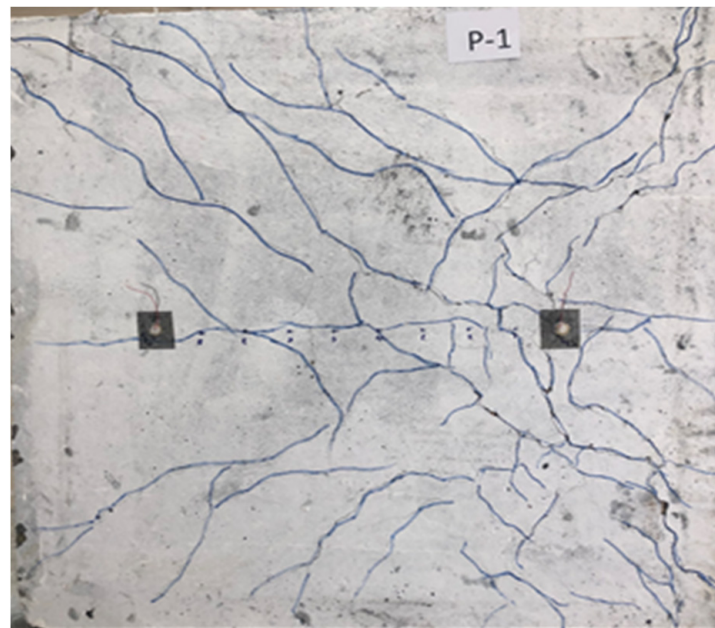


Figure 7. Cracks and failure pattern for solid slab with polyolefin.

Table 7. Cracking and ultimate load of specimens for solid slab.

Sample	Pcr (Solid) (KN)	Pcr (Opening) (KN)	Pcr (Solid)/Pcr (Control) (Ratio)	Pcr (Opening)/Pcr (Control) (Ratio)	Pcr (Solid)/Pcr (Opening) (Ratio)
Control	31.5	32.0	1.00	1.00	0.98
H1	45.0	35.0	1.43	1.10	1.29
C1	40.0	45.5	1.27	1.42	1.14
S1	35.0	41.5	1.11	1.17	1.19
P1	42.0	40.0	1.33	1.25	0.95

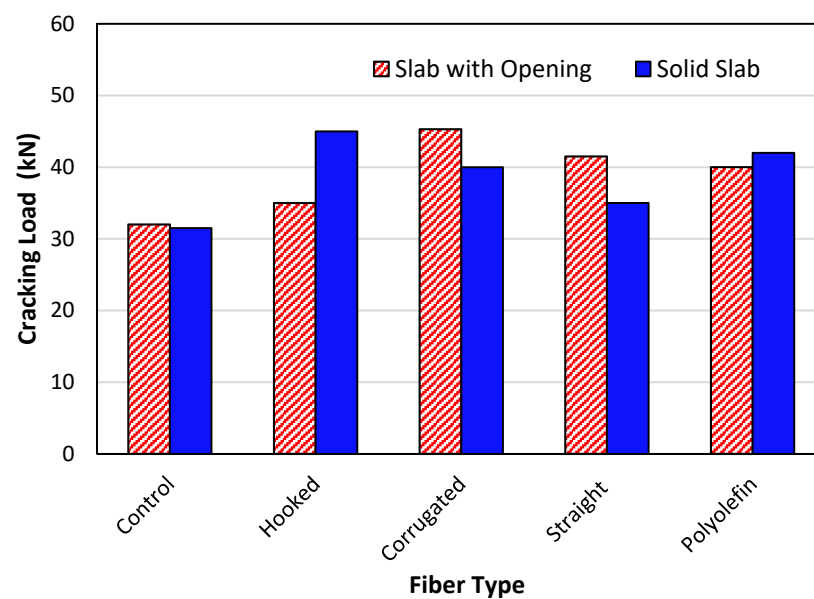


Figure 8. Effect of fiber type on cracking load.

5. Load-Deflection Results

The load-deflection curves for all tested two-way slab specimens are shown in Figure 9. All the deflection values of the slabs were measured at the center of the slab. In general, the load-deflection curves start with a linear behavior as an elastic stage without cracks, followed by a nonlinear part of the curve with an elastic cracking behavior. It can be seen that the recorded deflection for samples mixed with fibers is less than those of the control slab samples, indicating that the slab structure absorbed the deformation. Using fibers in concrete mixes improves the ductility and the stiffness, but this should be within a limited volume fiber ratio as the increases in ultimate load are lower beyond a certain fiber volume ratio due to the material becoming brittle.

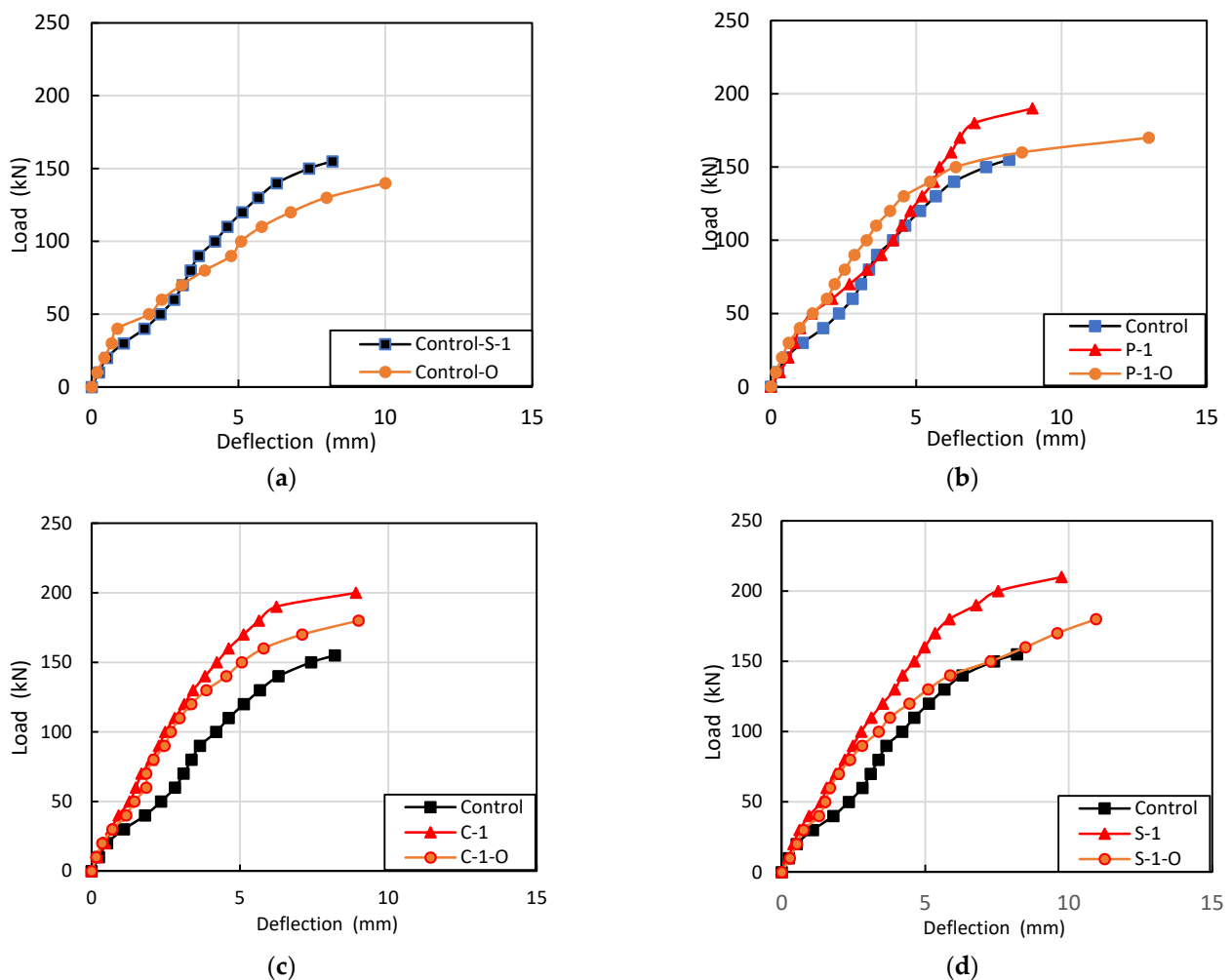


Figure 9. Load-deflection with different types of fiber. (a) Control slab with and without opening; (b) Slab with polyolefin fiber; (c) Slab with corrugated steel fiber; (d) Slab with straight steel fiber.

The control slab shows less flexural capacity strength compared with the other slabs with or without openings. Furthermore, the slabs with steel fiber seemed stiffer than slabs with polyolefin fiber which developed a large deflection compared with the control slabs and slabs with steel fibers at the final stage of failure. This is due to the increase in ductility of specimens with polyolefin.

The ultimate loads and the corresponding vertical deflections are shown in Figure 10, and the ultimate load capacity values of slab specimens are listed in Table 8. The results indicate that the reinforced concrete slabs with openings achieved extra improvement of between 13% and 25% of the capacity of the control slab without an opening. The improvement in the solid slabs with fibers varied between 16% and 44% compared with

the control solid slab which indicates the slab with an opening can retain a good flexural strength capacity by using fibers as additive. From Figures 9 and 10 it can also be concluded that the slabs with openings develop larger deflections than the solid slabs.

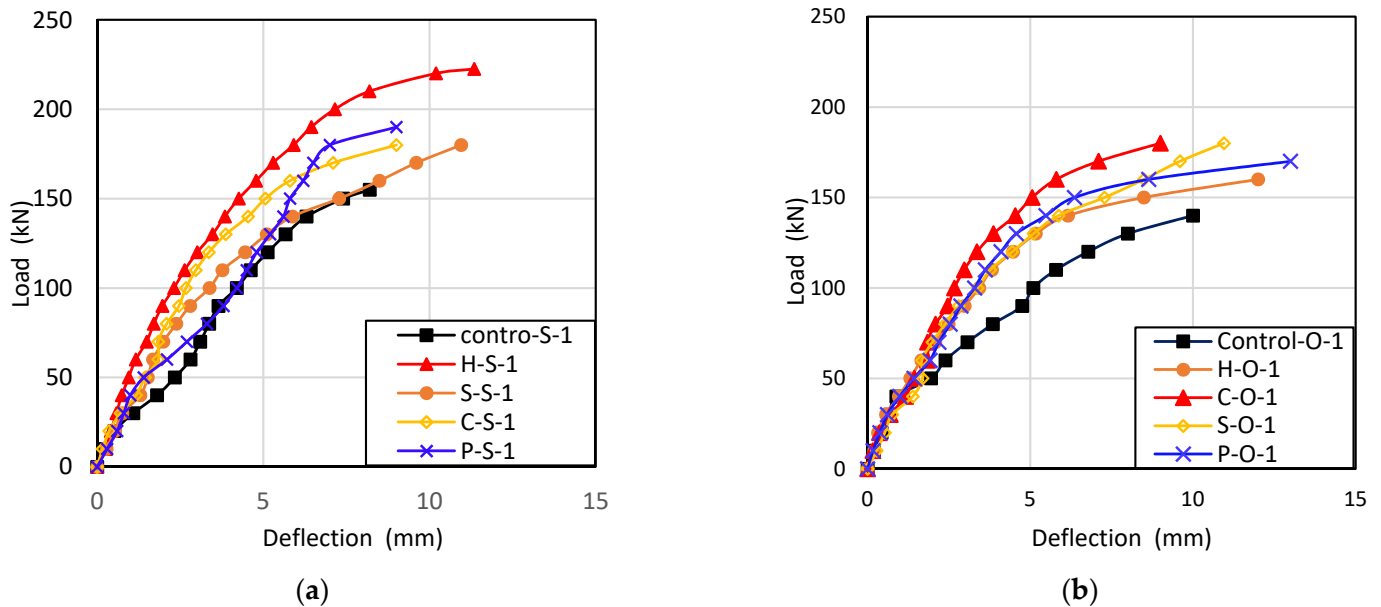


Figure 10. Load-Deflection with different types of fiber. (a) Solid slab; (b) Slab with opening.

Table 8. Ultimate load of specimens for slab with opening.

Sample	Ultimate Load (Solid) P_u (KN)	Ultimate Load (with Opening) P_u (KN)	P_u (Solid)/ P_u (Control) (Ratio)	P_u (Opening)/ P_u (Control) (Ratio)	P_u (Solid)/ P_u (Opening) (Ratio)
Control	160	140	1.00	1.00	1.14
H1	223	161	1.39	1.15	1.39
C1	180	179	1.125	1.28	1.00
S1	181	161	1.13	1.15	1.12
P1	191	170	1.19	1.21	1.12

It seems that the action of fiber in concrete slabs is the ability of fibers to transmit forces through cracks, restricting the widening of the crack and reducing debonding faster. In other words, the concrete mix with fibers provides extra strength post-cracking, leading to an enhancement of the ultimate loading capacity. Furthermore, the enhancement in ultimate loads is affected by the fiber type and its distribution in the concrete matrix of the samples.

The ultimate load increment for solid slabs and slabs with an opening varies between 13% to 39%, compared with control specimens. The improvement in specimens with steel fiber was higher than in specimens with polyolefin.

6. Conclusions

The effect of the type of fiber on the mechanical properties of concrete and the flexural behavior of reinforced concrete two-way slabs (with and without openings) has been investigated in this study and the result can be summarized:

1. The compressive strength of concrete modified with fibers showed that the specimen with steel fibers had improved compressive strength. The corrugated and hooked steel

fibers showed higher improvement compared with other type of fibers. Polyolefin fiber slightly increased the compressive strength compared with control specimens. The addition of fiber had a slight improving effect on the compressive strength, varying between 11.3% to 24.8%.

2. Splitting tensile strength test results suggest good enhancement for all specimens using different types of fiber in concrete mixes. Hooked and corrugated steel fiber showed the highest improvements (94% and 77%) compared with a control plain specimen. Polyolefin fiber showed less improvement than steel fiber.
3. The hooked steel fiber gave the best performance of the fiber types in improving modulus of rupture, where the increase ratio was 109% compared with the control specimen, whereas the polyolefin fiber enhancement was around 62%. Generally, the improvement was superior in modulus of rupture.
4. The effect of fiber shape with a constant dosage of steel fibers on the flexural behavior and tested mechanical properties shows that hook steel fiber produced the higher improvement.
5. It was concluded that the cracking load increased for all sample with fibers and the highest improvement occurred for combined reinforced concrete with hooked fiber (43%) for a solid slab compared with a reference slab. A moderate increment in cracking load was obtained by using polyolefin fiber (19%). It was noticed that the flexural behavior of two-way slabs with fibers appeared more ductile. Slabs with openings presented good improvements in cracking and ultimate load while developing larger deflections than the solid slabs.
6. All the specimens failed in flexural mode due to the interaction of fibers with concrete and this combination reduced the weakness of flexural behavior, especially in slabs with an opening. Moreover, the enhancement in flexural behavior was good compared with control specimens due to improved ductility and delays in the progress of cracks.
7. Generally, fibers increase the bond more efficiently between concrete matrix by friction and mechanical interaction, so it is preferable to use hooked or corrugated steel fibers for flexural improvement.

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