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Flexural Behavior of Reinforced Concrete One-way Slabs with Longitudinal Hollows

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Abstract

This paper presents an experimental investigation of the flexural behavior of reinforced concrete one-way slabs with longitudinal hollows. Hollow ratios (weight reductions) used in this work are 11.43% and 22.86%. Two longitudinal reinforcement ratios (ρ = 0.58 % and 1.03 %) and four steel fibers volumetric ratios (V_f = 0, 0.2, 0.4, and 0.8%), were used. Results show that slabs with longitudinal hollows having weight reduction up to 22.86%, show reductions in strength (ultimate load) up to 32% and toughness (energy absorption) up to 45% and higher deflections compared to corresponding solid slabs. However, these reductions lowered to 27.5% and 24.5%, respectively using 0.8% steel fibers or 6.3% and 25.5%, respectively by increasing longitudinal reinforcement from 0.58% to 1.03%. Furthermore, increasing longitudinal reinforcement from 0.58% to 1.03% along with using 0.4% steel fibers in a hollow slab gives a strength gain of 17.5% with a reduction in toughness of only 9.8% compared to reference solid slab with 0.58% longitudinal reinforcement and 0% steel fibers. Results also showed that hollow slabs offer stiffer load-deflection behavior (lower deflections) and less maximum crack width as longitudinal reinforcement and/or steel fibers.

Keywords: One-way slab; Hollow-core; Longitudinal hollow; Steel fiber; Flexural behavior

1. Introduction

The concrete slab is one of the main structural members in concrete structures and consumes the major quantity of concrete. The heavy weight of slabs in concrete structures results in larger sizes of other supporting members like beams, columns, and foundations [1] leading to environmental and economic effects by consuming more raw materials and requiring higher costs [2].

Reducing slab self-weight by introducing core hollows is an effective method to overcome these issues [3]-[7]. Nowadays, lightweight hollow core slabs are widely used in construction [8]-[11] which offer other advantages such as high thermal and acoustic insulation, good fire resistance, better seismic behavior, and the ability to resist loads on longer spans than solid slabs[12],[13].

Hollows are often located in the mid-height of slab cross-section where relatively low stresses are applied. This leads to a lightweight slab with high flexural strength [14]. Previous works show that hollow core slabs have similar flexural behavior to solid slabs [4],[6]. Typically, hollow core slabs are designed as simply supported one-way slabs that resist transverse loads [15],[16] and their behavior is dominated by flexure where no conventional shear reinforcement is used in such slabs which makes them susceptible to brittle web shear failure at lower loads than those predicted by design codes [17]-[20]. Using steel fibers in concrete is proven to be effective, enhancing flexural, shear, and ductility performance by bridging cracks and reducing their widths leading to internal stress redistribution [21],[22].

Many researchers have studied the structural behavior of hollow core slabs under the effects of different parameters. Rahman et al. [15] tested 15 slabs of different spans and depths. They noted that using a depth of more than 200 mm hollow-core slabs changed the failure mode from flexure to flexure-shear. Cuenca and Serna [23] conducted an experimental program to test 26 steel fiber-reinforced hollow-core slabs. They found that steel fibers enhance the tested slabs' load capacity and ductile behavior. They concluded that using fibers is a possible solution to overcome shear failure. Baran [23] investigated the effect of concrete topping on the flexural behavior of precast prestressed hollow-core concrete slabs. It was reported that topping concrete improved cracking moment and initial stiffness with limited ultimate moment capacity because of the lack of composite action between slab and topping. In this regard, Ibrahim et al. [24] stated that rough and wet surface conditions between the slab and topping concrete produce the highest shear strength. Wariyatno et al. [3] used PVC pipe or Styrofoam to form longitudinal hollows in concrete slabs and reduce their self-weights by 24 % and 25%, respectively. Results showed that hollow-core slabs have lower strength and stiffness than solid slabs. Slabs with Styrofoam show higher flexural strength than slabs with PVC pipe. Baarimah and Syed Mohsin [24] investigated the structural behavior of the slabs by considering two different parameters; (i) the thickness of the slab and (ii) the volume fraction of steel fiber. The experimental result suggested improvement of the load-carrying capacity and ductility as well as delay in crack propagation for the slabs. In addition, it is observed that the addition of fibers compensates for the reduction in the slab thickness as well as changes the failure mode of the slab from brittle to a more ductile manner. Conforti et al. [12] studied the shear behavior of polypropylene fiber-reinforced hollow-core slabs. They showed that polypropylene fibers improved the shear strength of hollow-core slabs by 25%. Naser et al. [13] investigated the flexural behavior of ferrocement thin hollow core slabs with different types of reinforcement namely: steel wire mesh, macro and micro steel fibers, or a combination of both, steel bars and CFRP bars. They found that the highest flexural strength was achieved in a slab reinforced with only macro steel fibers, while the most increased stiffness and lowest deflection was recorded in the slab reinforced with steel bars. Nguyen et al. [19] performed an experimental investigation to study the shear behavior of hollow-core concrete slabs reinforced by polypropylene, hooked steel, and straight steel fibers under fire. They noticed that polypropylene fibers increased concrete resistance to explosive spalling, while steel fibers substantially enhanced load capacity under elevated temperatures. Also, steel fibers improved ductility and toughness and shifted the mode of failure from shear to flexural-shear or even flexural. Hakeem et al. [27] presented an experimental study of steel fiber effects on bubble slabs and checked if steel fiber covers the messing efficiency and the effect on the type of failure. The experimental results showed that the steel fiber bubble slabs increased in yield load and ultimate load and changed of type of failure from brittle sudden shear failure for the bubble slabs to ductile flexural failure.

2. Research Significant

Introducing hollows in concrete slabs saves construction materials directly by reducing slab weight and indirectly by allowing for smaller supporting members like columns and foundations. Although hollows are often created in the mid-depth of slabs where concrete has the lowest contribution to their flexural capacity, the shear strength of hollow-core slabs is still questionable. This research is focused on examining the impact of longitudinal hollows on the capacity and behavior of reinforced concrete one-way slabs. The effects of longitudinal reinforcement and steel fibers are also investigated.

3. Experimental Program

The experimental program consists of testing ten simply supported reinforced concrete one-way slabs. Details of the experimental procedure are presented in the following sections.

3.1 Materials

The materials used in this investigation are:

1- Ordinary Portland cement satisfying Iraqi standard specification No.5/2019 [28].

2- Fine aggregate (sand) and coarse aggregate (natural gravel with a nominal maximum size of 10 mm) satisfying Iraqi standard specification No.45/1984 [29].

3- Tap water for aggregate washing, concrete mixing, and curing of specimens.

4- Steel reinforcement: Ø6 mm and Ø8 mm deformed steel bars with a yield strength of 435 MPa.

5- Straight steel fiber with a nominal length of 13mm and diameter of 0.2mm (aspect ratio = 65), Fig. 1.

Figure 1. Steel fibers used

One concrete mix was used for all slabs with proportions of 1 cement, 1.5 fine aggregates, and 3 coarse aggregates (by weight) with 0.5 w/c ratio. Different steel fiber ratios were used in slabs as will be explained later.

3.2 Details of Slabs

Ten reinforced concrete one-way simply supported slabs were tested in flexure as shown in Fig. 2. All slabs have the same dimensions. They have an overall length of 1000 mm (900 mm center to center of supports), a width of 450 mm, and a thickness of 70 mm.

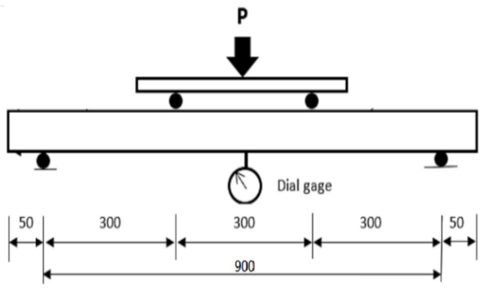
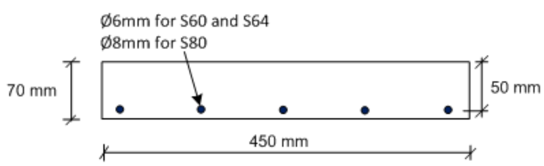
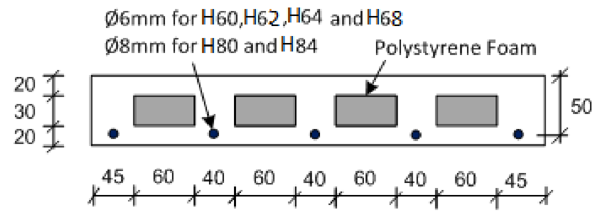


Figure 2. Test set-up of slabs (all dimensions in mm)

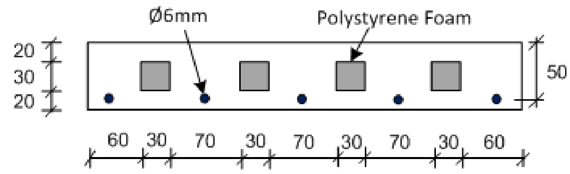
Three solid slabs and seven have four longitudinal hollows, either rectangular (30mm x 60mm) with a hollow ratio of 22.86% or square (30mm x 30mm) with a hollow ratio of 11.43%. Each slab is longitudinally reinforced by five steel bars either φ 6 mm (ρ = 0.58 %) or φ 8 mm (ρ = 1.03 %). Four steel fiber volumetric ratios are used (V_f = 0, 0.2, 0.4 and 0.8%). Based on the parameters mentioned above, slabs are designated using one letter and two numbers. The letters S and H refer to solid and hollow slabs, respectively. The first numbers 6 or 8 refer to the diameter of longitudinal reinforcements (6mm or 8mm, respectively), and the second numbers 0, 2, 4, and 8 to the steel fiber ratio of 0, 0.2, 0.4, and 0.8, respectively. In one slab (H64s), a small "s" followed the second number to indicate that the cross-section of hollows is square while all other slabs have rectangular hollows.
Details of the tested slabs are listed in Table 1 and illustrated in Fig. 3.



(a) Solid slab (S60, S64 and S80)



(b) Slab with rectangular hollows (H60, H62, H64, H68, H80 and H84)-dimensions in mm.



(c) Slab with square hollows (H64s)-dimensions in mm.

Figure 3. Cross sections of slabs**.**

3.3 Polystyrene Foam for Hollows

Polystyrene foam is used for the continuous longitudinal hollows within the slabs. The foam blocks are installed with reinforcing cages in the mold as shown in Fig. 4.

3.4 Testing of Slabs

As mentioned before, all ten slabs were tested over a simply supported span of 900 mm under one-way flexural loading as shown in Fig. 5. A hydraulically universal testing apparatus with a 3000 kN capacity is used to apply monotonic loads up to failure

Table 1. Details of slabs

Slab	Hollow section	Hollows Ratio, %	Reinf. details	Reinf. Ratio (ρ), %	Steel fibers Ratio (V_f), %
S60	-	0	5 φ 6 mm	0.58	0
S64	-	0	5 φ 6 mm	0.58	0.4
S80	-	0	5 φ 8 mm	1.03	0
H60	Rectangular (30mm x 60 mm)	22.86	5 φ 6 mm	0.58	0
H62	Rectangular (30mm x 60 mm)	22.86	5 φ 6 mm	0.58	0.2
H64	Rectangular (30mm x 60 mm)	22.86	5 φ 6 mm	0.58	0.4
H68	Rectangular (30mm x 60 mm)	22.86	5 φ 6 mm	0.58	0.8
H64s	Square (30mm x 30 mm)	11.43	5 φ 6 mm	0.58	0.4
H80	Rectangular (30mm x 60 mm)	22.86	5 φ 8 mm	1.03	0
H84	Rectangular (30mm x 60 mm)	22.86	5 φ 8 mm	1.03	0.4

through two steel rods (line loads) spaced 300 mm apart (the distance from the support to the load is 300 mm), Fig. 2. Vertical deflections are measured at the middle of the slab span using a dial gauge with a precision of 0.01 mm. Readings of the loading were taken in 2 - 3 kN steps. The deflection values were noted at each load reading using a dial gauge at the slab center. Maximum cracking width behavior was also monitored using a special device containing slices with specific thickness entering the crack measuring the crack width at all stages of loading.

Figure 4. Steel reinforcement and polystyrene foam

Figure 5. A slab was tested in the loading machine.

4. Results and Discussion

4.1 Compressive and Tensile Strengths

Cubes (100 × 100 × 100 mm) and cylinders (100 × 200 mm) were tested to determine compressive and splitting tensile strengths according to BS EN 12390-3:2019 [30]and ASTM C496-11 [31], respectively. The results shown in Table 2 reveal that incorporating steel fibers in concrete increases both compressive and splitting tensile strength by (9.4-18.5) % and (13.6-49.4) % respectively with a higher effect on the latter. These results are compatible with the results obtained by other researchers [32],[33].

Table 2. The compressive and splitting tensile strength of samples with different steel ratios

Steel fibers Ratio (V_f), %	Compressive strength (MPa)	Compressive strength increasing (%)	Tensile strength (MPa)	Tensile strength increasing (%)
0	29.7	-	3.16	-
0.2	32.5	9.4	3.59	13.6
0.4	33.8	13.8	4.13	30.7
0.8	35.2	18.5	4.72	49.4

4.2 General Response and Cracking Pattern

Similar overall behavior was observed for all slabs under loading as shown in Fig. 6. At first, slabs show elastic response until initiation of cracks at the tensile (bottom) face within the middle third of the span at about 41 – 45% of ultimate load. With increasing load, cracks continue to widen and propagate upward and load-deflection curves show less gradients. Further loading caused cracks to penetrate the compression side, longitudinal steel to yield and load-deflection curves to flatten where excessive deflection occurred under slight load increase, and then the slab failed.

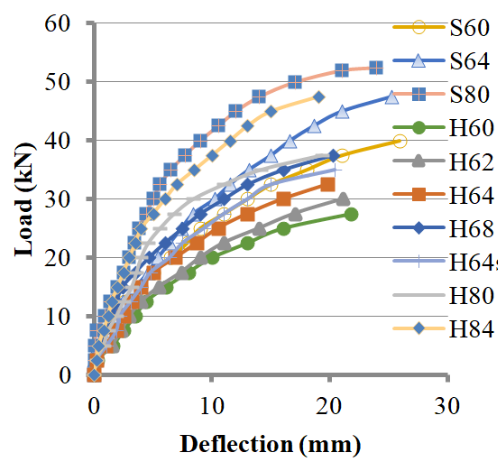


Figure 6. Load-deflection curves of all tested slabs

Fig. 7 shows the cracking pattern at the failure of the tested slabs. It can be seen that slabs with higher steel reinforcement had generally more cracks with less spacing. The hollow ratio and steel fiber ratio had no clear effect on the crack pattern of the slabs.

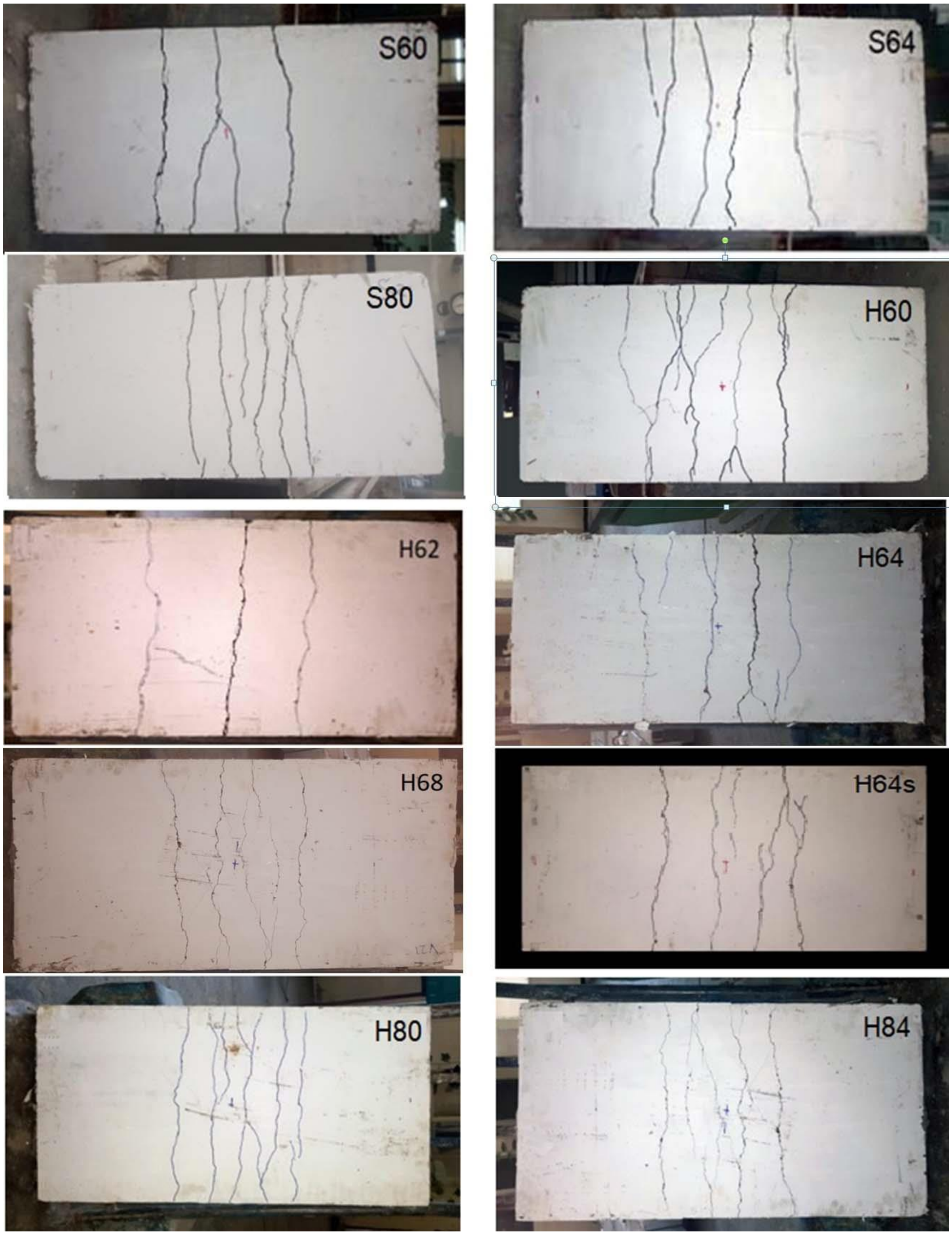


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Figure 7. Cracking pattern of the tested slabs.

Maximum deflections range from 19 to 26 mm, while maximum crack widths at failure range from 2.5 to 4.2 mm as shown in Table 3. Increasing steel reinforcement and steel fiber ratio generally decreases maximum deflections and crack width. This can be explained by the better efficiency of fibers to bridge smaller cracks delaying their coalescence in localized and large cracks. No clear trend is observed for the effect of hollows on the tested slabs' maximum deflections and crack widths. Detailed discussions of the effects of hollows, reinforcement, and steel fibers on slab results are presented in the following sections.

Table 3. Maximum deflections and crack widths of slabs.

Slab	Hollows Ratio, %	Reinf. Ratio (ρ), %	Steel fibers Ratio (V_f), %	Maximum deflection, mm	Maximum crack width, mm
S60	0	0.58	0	25.9	4.2
S64	0	0.58	0.4	25.2	2.75
S80	0	1.03	0	23.9	3.5
H60	22.86	0.58	0	21.8	3.7
H62	22.86	0.58	0.2	21.1	3.5
H64	22.86	0.58	0.4	19.8	3
H68	22.86	0.58	0.8	20.2	2.5
H64s	11.42	0.58	0.4	20.4	2.9

4.3 Effect of Longitudinal Hollows

Table 4 and Figs. 8 - 10 illustrate the effect of longitudinal hollows on cracking loads, ultimate loads, and load-deflection behavior of slabs. Results show that for slabs with longitudinal reinforcement of 0.58% and steel fiber ratio of 0.4%, using longitudinal hollows with hollow ratios of 11.42% (H64s) and 22.86% (H64) decreases cracking load by 22.5 and 30%, and ultimate loads by 26.3% and 31.5%, respectively. A similar trend was reported by Wariyatno et al. [4] (25-31% reduction in average load capacity for a 25% hollow ratio). These reductions are expected due to the decrease in hollow slab rigidity and capacity and can be considered acceptable taking into account the advantage for slab weight to be lower. Comparable results are noticed for nonfibrous slabs, where using the hollow ratio of 22.86% reduces cracking loads by 34.2% and 27.2% and ultimate loads by 32% and 29.2% for longitudinal reinforcement ratios of 0.58% (H60) and 1.03% (H80), respectively. It is also noticed that a hollow slab with higher longitudinal reinforcement (H80) shows slightly lower strength reduction than a hollow slab with lower longitudinal reinforcement (H60).

Table 4. Effect of longitudinal hollows on slab results.

Slab	**Hollows Ratio, %**	**Reinf. Ratio (ρ), %**	**Steel fibers Ratio (V_f), %**	**P_{cr}, kN**	**% Decrease**	**P_u, kN**	**% Decrease**	**Toughnes s, kN.mm**	**% Decreasing**
S60	0	0.58	0	17.5	-	40	-	711	-
H60	22.86	0.58	0	11.5	34.2	27.5	32.0	408	42.6
S80	0	1.03	0	22	-	53	-	954	-
H80	22.86	1.03	0	16	27.2	37.5	29.2	530	44.4
S64	0	0.58	0.4	20	-	47.5	-	798	-
H64s	11.42	0.58	0.4	15.5	22.5	35	26.3	490	38.6
H64	22.86	0.58	0.4	14	30.0	32.5	31.5	436	45.3

Load-deflection curves for nonfibrous hollow slabs (H60 and H80) show less stiffness (higher deformation) than corresponding solid slabs (S60 and S80) as shown in Fig. 9 and lower toughness by 42.6% and 44.4%, respectively.

Fig. 10 shows similar behavior for fibrous hollow slabs (H64s and H64) but relatively more concurrent to the corresponding solid slab (S64) with a toughness reduction of 38.6% and 45.3%, respectively. However, these high reductions in toughness are a concern issue.

4.4 Effect of Longitudinal Reinforcement

Table 5 and Figs. 9, 11, and 12 illustrate the effect of longitudinal steel reinforcement on cracking loads, ultimate loads, and load-deflection behavior of slabs. Results show that increasing longitudinal reinforcement from 0.58% to 1.03% raises cracking load by 25.7%, 39.1%, and 50%, and ultimate loads by 32.5%, 36.3%, and 44.6% for nonfibrous solid slab (S80), nonfibrous hollow slab (H80) and fibrous hollow slab (H84), respectively. A comparable trend was also noticed by Wariyatno et al. [4] (26.5-37.4% increase in average load capacity for nonfibrous hollow and solid slabs).

Table 5. Effect of longitudinal reinforcement on slab results.

Slab	Hollows Ratio, %	Reinf. Ratio (ρ), %	Steel fibers Ratio (V_f), %	P_{cr}, kN	% Increase	P_u, kN	% Increase	Toughness , kN.mm	% Increase
S60	0	0.58	0	17.5	-	40	-	711	-
S80	0	1.03	0	22	25.7	53	32.5	954	34.2
H60	22.86	0.58	0	11.5	-	27.5	-	408	-
H80	22.86	1.03	0	16	39.1	37.5	36.3	530	29.9
H64	22.86	0.58	0.4	14	-	32.5	-	436	-
H84	22.86	1.03	0.4	21	50.0	47	44.6	641	47.0

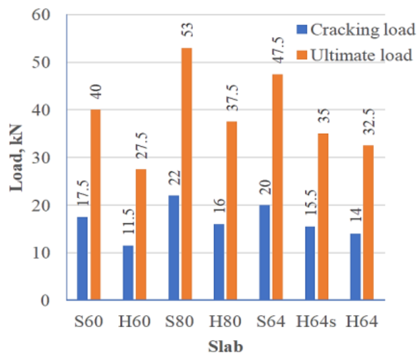

Figure 8. Effect of longitudinal hollows on cracking and ultimate loads.

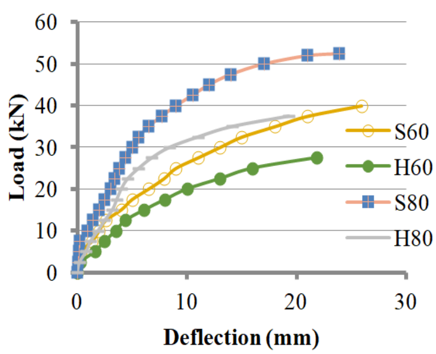

Figure 9. Load-deflection curves of non-fibrous slabs

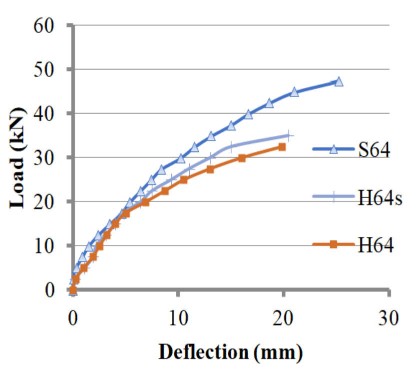

Figure 10. Load-deflection curves of slabs with ρ=0.58 % and V_f = 0.4%.

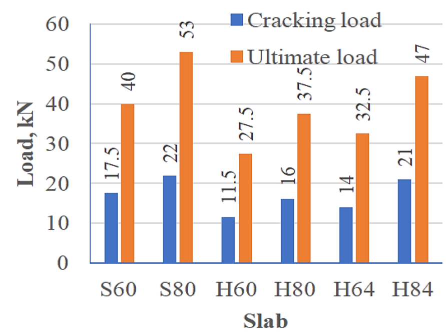

Figure 11. Effect of longitudinal reinforcement on cracking and ultimate loads.

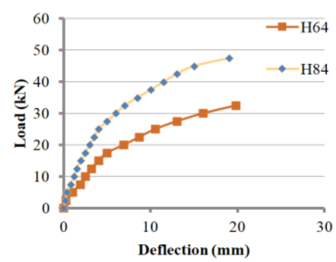

Figure 12. Load-deflection curves of hollow slabs with Vf = 0.4%.

A hollow slab (H80) performs better in terms of strength increase than a solid one (S80) when longitudinal reinforcement increases, reflecting the major role of reinforcement in overcoming the weakness of hollow slabs. Also, fibrous hollow slab (H84) shows the highest strength gain due to the role of fibers in arresting cracks, which are more in slabs of higher longitudinal reinforcement than those in slabs of lower longitudinal reinforcement, consequently increasing strength. Cracking loads of hollow slabs are shown to be more affected (higher increasing ratio) by increasing longitudinal reinforcement than ultimate loads.

Load-deflection curves for nonfibrous slabs with longitudinal reinforcement of 1.03% (S80 and H80) show higher stiffness (lower deformation) than corresponding slabs with longitudinal reinforcement of 0.58% (S60 and H60) as shown in Fig. 9 and higher toughness by 34.2 and 29.9%, respectively. Fig. 10 shows similar behavior for fibrous hollow slabs (H84 and H64) with a toughness increase of 47% for the former as compared to the latter. 4.5 Effect of Steel Fibers

Table 6 and Figs. 13 - 15 illustrate the effect of steel fibers on cracking loads, ultimate loads, and load-deflection behavior of slabs. Results show that incorporating steel fibers with volumetric ratios of 0.2%, 0.4%, and 0.8% in hollow slabs with longitudinal reinforcement of 0.58%, raises cracking load by 8.6%, 21.7%, and 43.4%, and ultimate loads by 9.1%, 18.1%, and 34.5%, respectively. Steel fiber enhancement for these slabs still humble up to a steel fiber ratio of 0.4% and becomes remarkable at a steel fiber ratio of 0.8%. This is not the case for hollow slabs with higher longitudinal reinforcement of 1.03% (H84) where using 0.4% steel fibers increases cracking and ultimate loads by 31.2% and 25.3%, respectively. This again shows the doubled positive effect of increasing longitudinal reinforcement and steel fibers. Results also show that steel fibers generally raise cracking loads of hollow slabs more than rising ultimate loads.

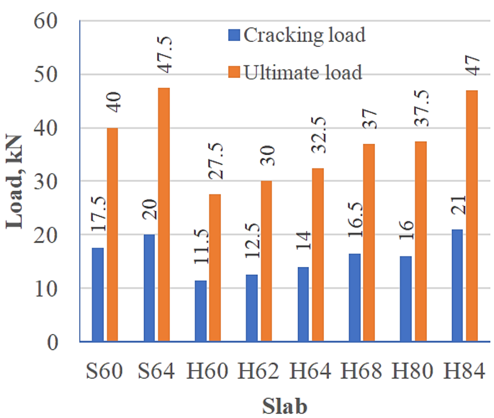

Figure 13. Effect of steel fibers on cracking and ultimate loads.

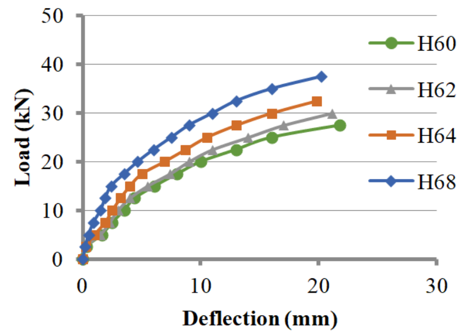

Figure 14. Load-deflection curves of hollow slabs with ρ = 0.58 %.

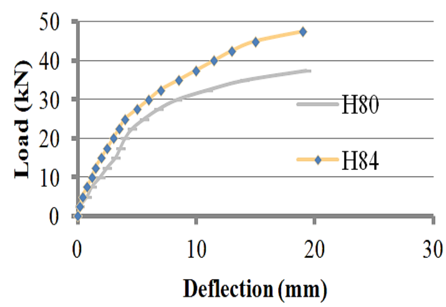

Figure 15. Load-deflection curves of hollow slabs with ρ = 1.03 %.

Load-deflection curves for fibrous hollow slabs with longitudinal reinforcement of 0.58% show higher stiffness (lower deformation) as steel fibers ratio increases from 0 to 0.2%, 0.4%, and 0.8% as shown in Fig. 14 and higher toughness by 2.7%, 6.8%, and 31.6%, respectively. Fig. 15 shows similar behavior but higher steel fibers influence for fibrous hollow slabs of 1.03% longitudinal reinforcement (H84 and H80) with a toughness increase of 20.9% for the former compared to the latter.

Table 6. Effect of steel fibers on results of slabs.

Slab	Hollows Ratio, %	Reinf. Ratio (ρ), %	Steel fibers Ratio (V_f), %	P_{cr}, kN	% Increase	P_u, kN	% Increase	Toughness, kN.mm	% Increase
S60	0	0.58	0	17.5	-	40	-	711	-
S64	0	0.58	0.4	20	14.2	47.5	18.7	798	12.2
H60	22.86	0.58	0	11.5	-	27.5	-	408	-
H62	22.86	0.58	0.2	12.5	8.6	30	9.1	419	2.7
H64	22.86	0.58	0.4	14	21.7	32.5	18.1	436	6.8
H68	22.86	0.58	0.8	16.5	43.4	37	34.5	537	31.6
H80	22.86	1.03	0	16	-	37.5	-	530	-
H84	22.86	1.03	0.4	21	31.2	47	25.3	641	20.9

4.6 Comparison of Alternatives

Using longitudinal hollows in slabs has two opposing effects on the strength. Slab self-weight is decreased which is a portion of the dead loads that represent a significant amount of the overall loads on the slab. The negative effect is a reduction in the ultimate strength. As mentioned, hollow slabs show lower strength and higher deformation than corresponding solid slabs. Taking a nonfibrous solid slab of 0.58% longitudinal reinforcement (S60) as a reference, Table 7 lists the percentage difference in cracking load, ultimate load, and toughness of all other slabs. It can be seen that, as compared to S60; hollow slabs H68 and H80 are good alternatives as they have lower weight (22.86% weight and materials reduction) with the least strength reductions of 5.7%, and 8.6% for cracking load, 7.5% and 6.3% for ultimate load and 24.5% and 25.5% for toughness, respectively.

Moreover, hollow slab H84 with 1.03% longitudinal reinforcement and 0.4% steel fibers show higher cracking and ultimate loads by 20% and 17.5%, respectively than solid slab S60 with the toughness of H84 still lower than S60, but by only 9.8%. These results show that increasing longitudinal reinforcement and/or incorporating steel fibers in hollow slabs can overcome the strength reduction of such slabs.

Table 7. Comparison of all slabs.

Slab	Hollows Ratio, %	Reinf. Ratio (ρ), %	Steel fibers Ratio (V_f), %	P_{cr}, kN	% Difference	P_u, kN	% Difference	Toughness, kN.mm	% Difference
S60	0	0.58	0	17.5	-	40	-	711	-
S64	0	0.58	0.4	20	14.3	47.5	18.8	798	12.2
S80	0	1.03	0	22	25.7	53	32.5	954	34.2
H60	22.86	0.58	0	11.5	-34.3	27.5	-31.3	408	-42.6
H62	22.86	0.58	0.2	12.5	-28.6	30	-25.0	419	-41.1
H64	22.86	0.58	0.4	14	-20.0	32.5	-18.8	436	-38.7
H68	22.86	0.58	0.8	16.5	-5.7	37	-7.5	537	-24.5
H64s	11.42	0.58	0.4	15.5	-11.4	35	-12.5	490	-31.1
H80	22.86	1.03	0	16	-8.6	37.5	-6.3	530	-25.5
H84	22.86	1.03	0.4	21	20.0	47	17.5	641	-9.8

5. Conclusions

Reinforced concrete one-way slabs with longitudinal hollows having weight reduction up to 22.86%, show reductions in strength up to 32% and toughness up to 45% and higher deflections as compared to corresponding solid slabs. These reductions in strength and toughness of hollow slabs can be minimized to 27.5% and 24.5%, respectively by using 0.8% steel fibers or 6.3% and 25.5%, respectively by increasing longitudinal reinforcement from 0.58% to 1.03%. Increasing longitudinal reinforcement from 0.58% to 1.03% along with using 0.4% steel fibers in a hollow slab gives a strength gain of 17.5% with a reduction in toughness of 9.8% compared to reference solid slab with 0.58% longitudinal reinforcement and 0% steel fibers. Increasing longitudinal reinforcement from 0.58% to 1.03% in hollow slabs increases strength up to 44.6% and toughness up to 47%. It affects cracking loads (39.1 – 50% increase) more than ultimate loads (36.3 – 44.6% increase). A similar effect is also observed for steel fibers. Increasing steel fibers from 0% to 0.4% and 0.8% in hollow slabs with 0.58% longitudinal reinforcement increases strength by 18.1% and 34.5% and toughness by 6.8% and 31.6%, respectively. In contrast, using 0.4% steel fibers in hollow slabs with 1.03% longitudinal reinforcement increases strength by 25.3% and toughness by 20.9% which is more effective than using the same ratio in hollow slabs with 0.58% longitudinal reinforcement. Hollow slabs show stiffer load-deflection behavior (lower deflections) and fewer maximum crack widths as longitudinal reinforcement and/or steel fibers increase.

Competing Interests

The authors declare there are no competing interests.

Author Contribution:

Jawad K. Al-Bayati: proposed the research problem. All authors conducted the work equally.

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Conflicts of Interest

The authors declare no conflict of interest

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