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Structural Behavior of Hollow-core One Way Slabs of High Strength Self-compacting Concrete

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P A P E R I N F O

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A B S T R A C T

Reinforced concrete hollow-core slab (HCS) is a new type of lightweight slabs in which the longitudinal voids provide the ability to reduce the concrete amount. Reducing the concrete amount causes a reduction of the dead loads which consequently leads to cost-saving, fast construction, and getting long-span. The experimental program includes constructing and testing slab species with dimensions 1700×435×125mm to investigate the effect of eliminating concrete ratio by changing the size of the longitudinal void and the number of longitudinal voids on the performance of HCS. The experimental results showed that elimination of the concrete with percentages 10.83, 17.20 and 24.37% from the hollow-core high strength slabs using three longitudinal voids of diameters 50, 63, and 75mm, respectively, resulted in saving the ultimate strength by 90.06, 87.84 and 85.07%, and increasing the ultimate deflection by 5.48, 10.80 and 17.44%. While, elimination of the concrete with percentages 16.25, 24.37 and 32.50% from the hollow-core high strength slabs using two, three, and four longitudinal voids of 75mm diameter resulted in saving the ultimate strength with percentages 89.29, 85.07 and 80.61%, and increasing the ultimate deflection with percentages 7.57, 17.44 and 22.81% respectively when compared with the reference solid slab.

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NOMENCLATURE

Hollow-core slab	HCS	American Society for Testing and Materials	ASTM
Near-surface mounted	NSM	Shear span to effective depth ratio	a/d
Concrete compressive strength	*fc*	American Concrete Institute	ACI
Linear variable deflection transducer	LVDT	British Standards	B S
Solid slab	**SS**		

1. INTRODUCTION

Reinforced concrete slabs are the members that used as floors and roofs in the building and used in the decks of bridges [1]. The floor system can tack many forms such as solid slabs, precast slabs, and ribbed slabs, the slabs may be supported on a concrete beam, steel beam, and wall or directly on the column [1]. Several attempts in the past have been carried out on reinforced concrete slabs to reduce its self-weight with a minimum reduction in the flexural capacity of the slabs, the reduction in the self-weight of the slab will reduce the deflection and will make slabs with larger span length without using intermediate supports [2]. Waffle, Bubbled and Hollow-core slabs were used to reduce the slab self-weight and to provide slabs with a long span [2]. Hollow-core slab (HCS) is a concrete slab with continuous voids that extend through the long direction of the slab, these voids provided for reducing the weight and cost of the slabs and for running the mechanical or electrical facilities. The HCS provides high structural efficiency with low material consumption [3]. Pajari [4] has made an experimental program to study the pure torsion tests on pre-stressed hollow-core slabs, the result showed that the

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torsional stiffness of the hollow-core with 400mm depth was so close to the predicted values of the elementary calculation. Cuenca and Serna [5] studied the effect of steel fiber on the behavior of hollow-core slabs, the result showed that using the steel fiber in the hollow-core slabs gives higher shear capacity than slabs without steel fibers and increased the ductile behavior of the hollow-core slab. Sarma and Prakash [6] studied the effect of cut-outs (openings) on the pre-stressed hollow-core slabs, the test results showed that presence of the opening at the center of slabs causes a reduction in the ultimate load by 44% due to the local cracks around the opening and failure of the slab. Kankeri and Prakash [7] studied strengthening the hollow-core slab by bonded overlay and by near-surface mounted (NSM) glass fiber reinforced polymer bar, the researcher found that Strengthening the hollow-core slabs by hybrid the NSM with the bonded overly increase the ultimate load by 238% without compromise the ductility when compared with the reference slab. Al-Azawi and Abdul Al-Aziz [8] have made an experimental program to study the lightweight aggregate hollow-core slabs, the test result showed that using the lightweight aggregate hollow-core slabs with constant (a/d=2.9) gives a reduction in self-weight by 32.92% and reduction in the ultimate load and the first crack load by 5.18% and 12%, respectively when compared with the solid slab. Khalil, et al. [9] studied the shear behavior in composite hollow-core Slab, the researcher found that using the longitudinal steel reinforcement in the hollow-core slab delayed the apparition of the shear crack and reduce the crack width. Lee, et al. [10] studied the shear performance of hollow core slab, the researcher found that the shear performance satisfied the requirements of ACI 318-19. Mahdi and Ismael [11] studied normal strength hollow core slabs, the result thowed that using the HCS can save the ultimate load by 82.92 to 93.47%, but the ultimate deflection increased by 6.58 to 28.31%. From the previous studies which dealt with the field of the structural behavior of hollow-core slabs, it can be noted that most of these studies focused on investigating the effect of using concrete topping, strengthening, using steel fiber, cutout (opening), and some other parameters, but did not study the effect of the reduction the concrete volume on the structural behavior of hollow-core high strength slabs. Therefore, this paper presents an experimental study to investigate the effect of eliminating concrete ratio by changing the size of the longitudinal void (50mm, 63mm, and 75mm) and the number of longitudinal voids (two, three, and four) on the structural behavior of hollow-core high strength self-compacted concrete slabs. In hollow-core slabs, the recycled plastic pipes were placed in the middle of the slab thickness where the flexural stress is minimum, to eliminate some amount of concrete. This process leads to reduce the self-weight of the slabs and therefore it leads to reducing the embedded energy and the CO_2 emission from the cement industry and this process is considered environmental-friendly action which contributes to the sustainability process. Figure 1 shows the research methodology of this paper.

2. EXPEREMENTAL PROGRAM

2. 1. Slabs Description The experimental program includes casting and testing six reinforced high strength self-compacted concrete one-way slabs, all the slab have 1700mm length, 435mm width, and 125mm thickness, these slabs were divided into two groups as they are presented in Table 1. The first group consists of one solid slab as a control slab and three hollow-core slabs which have three longitudinal voids with a different diameter (50mm, 63mm, and 75mm) with designation names 3V50, 3V63, and, 3V75, chosen these diameters due to existent these pip diameters in the market. Also, these diameters satisfy the planned percentages of eliminating concrete. The purpose of this group is to study the effect of longitudinal voids diameter on the structural behavior of high strength hollow-core slabs, and the second group consists of the same solid slab in group one and three

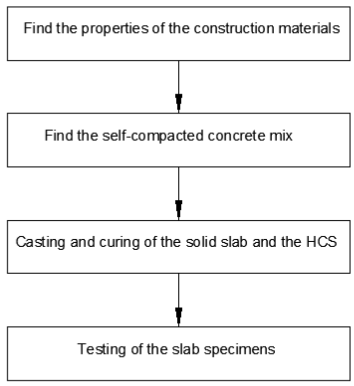

Figure 1. The research methodology

TABLE 1. Experimental parameters details

Group No.	Parameter	Slab designation	Number of longitudinal vids	Diameter of longitudinal voids (mm)
1	Longitudinal voids diameter	SS	---	---
		3V50	3	50
		3V63	3	63
		3V75	3	75
2	Longitudinal voids number	SS	---	---
		2V75	2	75
		3V75	3	75
		4V75	4	75

hollow-core slabs with different numbers of 75mm diameter longitudinal voids (two, three, and four) with designations name 2V75, 3V75, and 4V75 respectively. The slab 3V75 is the same slab in the first group, the purpose of this group is to study the effect of longitudinal voids numbers on the structural behavior of high strength hollow-core slab. Figures 2-4 show details of the solid and hollow-core slabs in groups one and two, respectively.

2. 2. Materials

• Cement: The ordinary Portland cement (type I) was used in this work. This cement has physical properties and chemical composition which confirm according to British Standards Institution (BS 12) [12].

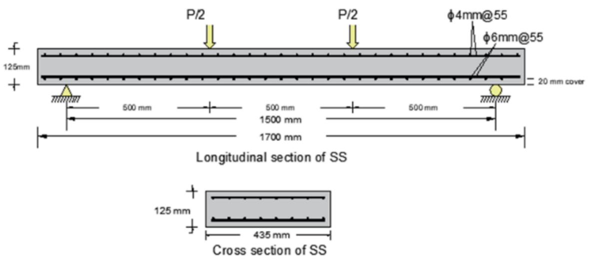

Figure 2. Details of the solid slab

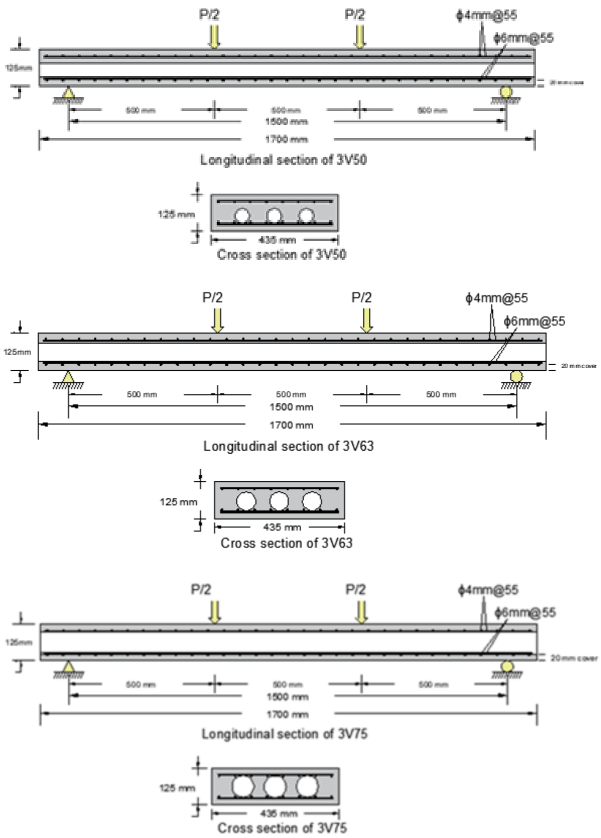

Figure 3. Details of the HCS slabs in group one

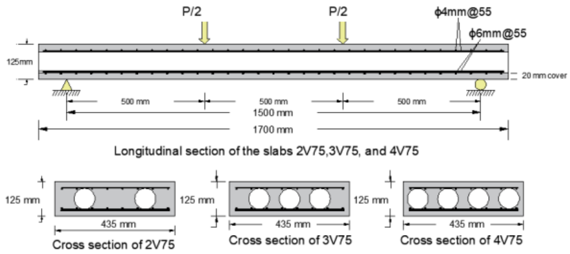

Figure 4. Details of the HCS slabs in group two

• Fine Aggregate: The used fine aggregate has 2.38 fineness modulus, the grading and the physical properties of this fine aggregate indicated that it is within the Limits of B.S.882 [13].

• Coarse Aggregate: The maximum size of the used coarse aggregate is 14mm, the grading and the physical properties of this coarse aggregate are within the Limits of B.S.882 [13].

• Limestone Powder: The ground limestone powder was used in this work as a filler to get better cohesiveness and better segregation resistance, it has a particle size less than 0.125mm according to EFNARC, [14]

• Superplasticizer: The third generation of high-performance superplasticizers (ViscoCrete®-5930L) was used for producing self-compacted concrete. This superplasticizer meets the requirement of ASTM C494 type F [15].

• Steel Reinforcement: Deformed steel bars with diameters of 6mm and yield stress of 497Mpa were used as main steel reinforcement and deformed steel bars with a diameter of 4mm and yield stress of 430Mpa were used as secondary steel reinforcement, the steel reinforcement bars were tested according to ASTM A615/A &M [16]

• Plastic Pipes: The recycled plastic pipes were used to create the longitudinal voids in the hollow-core slabs, these pipes have different diameters (50mm, 63mm, and 75mm).

2. 3. Concrete Mixture

In this study, the trail mixes were made many times to obtain the concrete mixture which has 60.8MPa compressive strength at 28 days, these concrete mixture satisfied the requirement of the high strength self-compacted concert according to EFNARC [14] and European guidelines [17]. Table 2 shows the concrete mixture of quantities. Measuring the concrete compressive strength (*fc*) is done by testing three cylindrical concrete for each slab specimens with dimensions 150mm and 300mm according to ASTM C39/C39M-15a [18].

2. 4. Test Specimens

The slab specimens were tested by using a universal hydraulic machine with a capacity of 600kN. Before starting the applied load, the linear variable deflection transducer sensor (LVDT) was fixed in the bottom mid-span slabs to measure the

TABLE 2. Quantities of the concrete mixture per cubic meter

Materials	Cement	Sand	Gravel	Limestone powder	Water	Superplasticizer
Quantities (kg/m^3)	550	855	767	50	150	20

deflection. Also, an electrical strain gauge was fixed in the center of top mid-span slabs to measure the concrete strain during increasing the applied load. The slabs were tested as a simply supported slab under two-point loads with a clear span of 1500mm as shown in Figure 5.

3. RESULTS AND DISCUSSION

3. 1. First Crack Load and Ultimate Load Capacity

Table 3 shows the first crack load and the ultimate strength of all the tested slabs, it can be noted that elimination of the concrete with percentages 10.83, 17.20 and 24.37% from the hollow-core high strength slabs 3V50, 3V63, and 3V75, respectively cause a reduction in cracking load by 5.58, 8.37 and 13.49%, and reduction in ultimate strength by 9.94, 12.16 and 14.93%. Also, elimination the concrete with percentages 16.25, 24.37 and 32.50% from the hollow-core high strength slabs 2V75, 3V75, and 4V75 with two, three, and four longitudinal voids with diameter 75mm, respectively; resulted in reducing the first crack load with percentages 8.84, 13.49 and 17.21%, and reducing the ultimate strength with percentages 10.71, 14.93 and 19.39%. These decreases can be attributed to the presence of the longitudinal voids which leads to decrease the moment of inertia of the beam section; thus, the flexural rigidity will decrease with increasing diameter or number of longitudinal voids in the hollow core slabs. Figure 6 shows the reduction in ultimate load of the hollow core slabs with different diameter and number of longitudinal voids, it can be noted in this figure that increasing diameter of longitudinal voids has more effect on the reduction in ultimate load than increasing number of longitudinal voids due to increase in approaching the longitudinal voids from the compression zone with increasing the diameter of longitudinal voids, so, the optimum slab in this study was the slab 3V50 to preserve the ultimate strength and satisfy the economical consideration.

Figure 5. Testing of the slab specimens

3. 2. Load-deflection Relationship

Figures 7 and 8 show the load-deflection curve of the solid and hollow-core high strength slabs with different diameter and number of longitudinal voids, respectively; it can be noted that elimination of the concrete with percentages 10.83, 17.20 and 24.37% from the hollow-core high strength slabs 3V50, 3V63, and 3V75, respectively cause an increase in the ultimate deflection by 5.48%, 10.80 and 17.44%. Also, elimination the concrete with percentages 16.25, 24.37 and 32.50% from the hollow-core high strength slabs 2V75, 3V75, and 4V75 with two, three, and four longitudinal voids with diameter 75mm, respectively; result in increased the ultimate

TABLE 3. The first crack load and ultimate strength of all the tested slabs

Group No.	Slab designation	Elimination concrete (%)	Cracking load Pcr (kN)	Decrease (%)	Ultimate load Pu (kN)	Decrease in Pu%
1	SS	---	21.5	---	71.32	---
	3V50	10.83	20.3	5.58	64.23	9.94
	3V63	17.20	19.7	8.37	62.73	12.16
	3V75	24.37	18.6	13.49	60.67	14.93
2	SS	---	21.5	---	71.32	---
	2V75	16.25	19.6	8.84	63.68	10.71
	3V75	24.37	18.6	13.49	60.67	14.93
	4V75	32.50	17.8	17.21	57.49	19.39

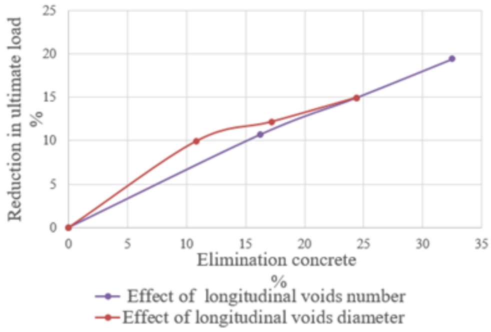

Figure 6. The reduction in ultimate load of HCS with different diameter and number of longitudinal voids

deflection with percentages 7.57, 17.44 and 22.81%, this increase in the ultimate deflection of the HCS belong to the presence of the longitudinal voids which leads to decrease the moment of inertia of the beam section thus, the flexural rigidity will decrease with increasing diameter or number of longitudinal voids.

3. 3. Load-strain Relationship

Figure 9 shows the effect of longitudinal voids diameter on the concrete compressive strain and steel tensile strain of the hollow-core high strength slabs. It can be noted that elimination of the concrete with percentages 10.83, 17.20 and 24.37% from the hollow-core high strength slabs 3V50, 3V63, and 3V75 with three longitudinal voids with diameter 50, 63, and 75mm, respectively; resulted in increased the ultimate concrete strain with percentages 14.14, 24.14 and 30.40%, and decreased the ultimate steel strain with percentages 10.59, 13.36 and 16.56%. Figure 10 shows the effect of longitudinal voids number on the concrete compressive strain and steel tensile strain of the HCS. It can be noted that elimination the concrete with percentages 16.25, 24.37 and 32.50% from the hollow-core high strength slabs 2V75, 3V75, and 4V75 with two, three, and four longitudinal voids with diameter 75mm, respectively; resulted in increased the ultimate concrete compressive strain with percentages 22.95, 30.40 and 38.95%, and decreased the ultimate steel strain with percentages 9.81, 16.56 and 32.25%. Increasing the concrete compression strain belong to the presence of the longitudinal voids in the hollow-core slabs which leads to eliminating part of concrete from the middle of the slabs and focusing the stress in the region between the plastic pipes. Decreasing the steel tensile strain of hollow-core slabs can be attributed to reducing the ultimate strength of the hollow-core high strength slabs with increasing diameter or number of longitudinal voids.

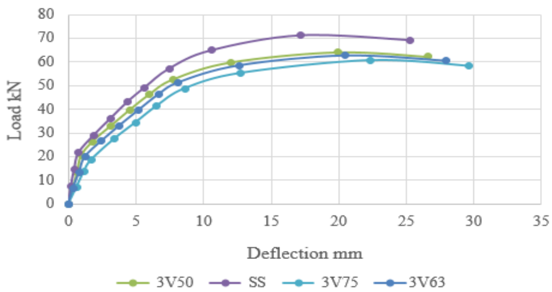

Figure 7. Effect of longitudinal voids diameter on the load-deflection curve of hollow-core high strength slabs

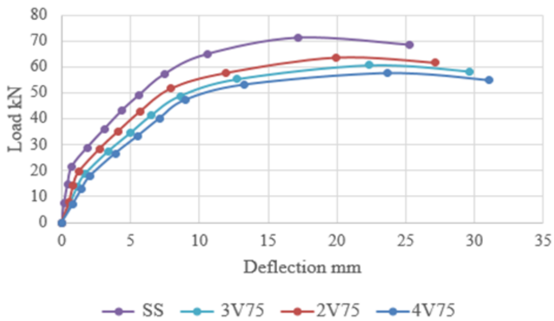

Figure 8. Effect of longitudinal voids number on the load-deflection curve of hollow-core high strength slabs

3. 4. Crack Pattern and Failure Mode

The first observed crack is first seen in the middle bottom at the

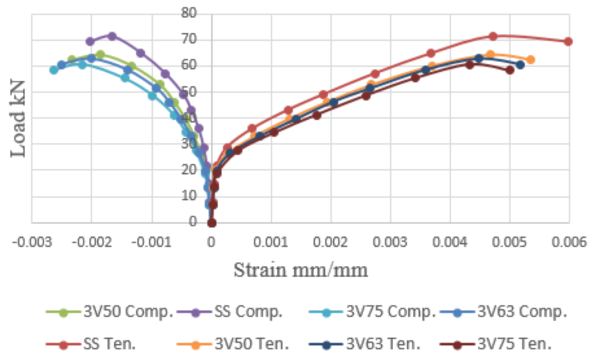

Figure 9. Effect of longitudinal voids diameter on the concrete compressive strain and steel tensile strain of the HCS

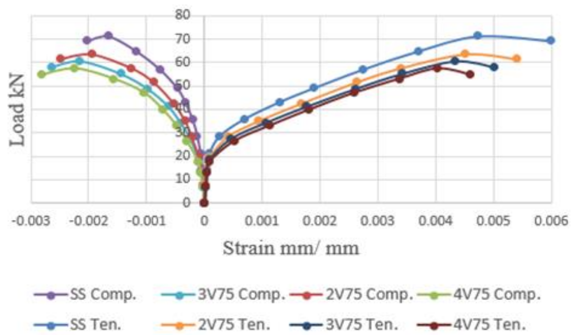

Figure 10. Effect of longitudinal voids number on concrete compressive strain and steel tensile strain of the HCS

tension zone of all the slabs when the concrete tensile stress exceeds the value of its tensile strength, after increasing the applied load other cracks appeared at right and left of the first crack, these cracks extended upward and the flexural shear cracks appear in the hollow-core slabs. The flexural failure occurred in all the slabs when one of the cracks in the middle of slabs split into two directions before it reaches the upper face of the slab. The increasing diameter of longitudinal voids in hollow-core high strength slabs decrease the number of crack from 13 in the solid slab to 12, 12, and 11 in hollow-core slabs (3V50, 3V63, and 3V75), and increases the crack width of the hollow-core slabs at yield load by 13.83, 27.4 and 39.13%, respectively when compared with the solid slab. Also, an increasing number of longitudinal voids in the hollow-core slabs from two to three and four decreases the number of cracks from 13 in the solid slab to 12, 11, and 8 respectively in hollow-core slabs (2V75, 3V75, 4V75), but the crack width of the hollow-core slabs at yield load increased by 21.74, 39.13 and 56.52%, respectively when compared with the reference solid slab. Extend the cracks up will be gradually in the solid slab, but in the hollow-core slabs extended the cracks will be opposed by the plastic pipes, so the path of the cracks deviate around the plastic pipes, this leads to increase length and width of the cracks and delay the spread of the cracks and that lead to decrease the number of cracks in hollow-core slabs. Figures 11 and 12 show the effect of longitudinal voids diameter and number respectively on the crack pattern of hollow-core high strength slabs.

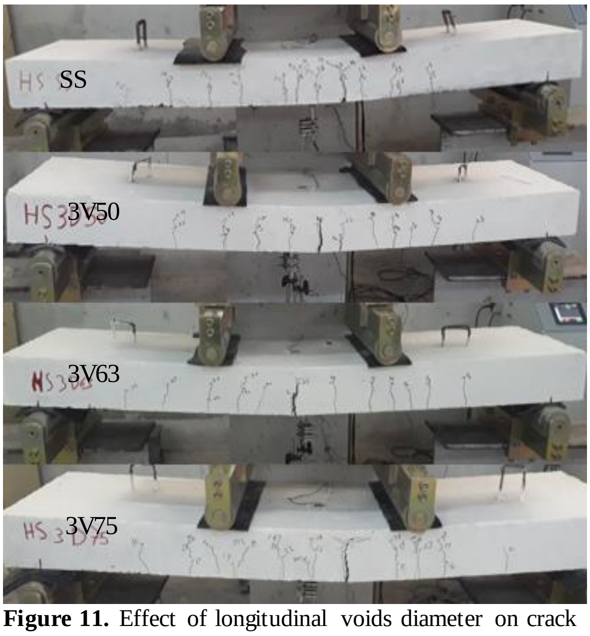

Figure 11. Effect of longitudinal voids diameter on crack pattern of hollow-core high strength slabs

Figure 12. Effect of longitudinal voids number on crack pattern of hollow-core high strength slabs

4. CONCLUSION

Using the hollow-core slab was a very effective method to reduce the self-weight of the slabs with maintaining most of the structural behavior of the solid slabs as they are presented below:

1. Elimination of the concrete with percentages 10.83, 17.20 and 24.37% from the hollow-core high strength slabs with three longitudinal voids with diameter 50, 63, and 75mm respectively gives a reduction in cracking load by 5.58, 8.37 and 13.49%, saving the ultimate strength by 90.06, 87.84 and 85.07%, and increasing the ultimate deflection by 5.4, 10.80 and 17.44%.
2. Elimination of the concrete with percentages 16.25, 24.37 and 32.50% from the hollow-core high strength slabs with two, three, and four longitudinal voids with diameter 75mm respectively, resulted in reducing the first crack load with percentages 8.84, 13.49 and 17.21%, saving the ultimate strength with percentages 89.29, 85.07, 80.61%, and increasing the ultimate deflection with percentages 7.57, 17.44 and 22.81%.
3. The ultimate concrete compressive strain of the high strength hollow-core slabs was larger than the ultimate strain in solid slab and increased with increasing diameter or number of longitudinal voids.
4. The high strength hollow-core slabs make a reduction in ultimate steel tensile strain by 10.59%, 13.36%, and 16.56% with an increasing diameter of longitudinal voids, and by 9.81%, 16.56%, and 23.25%, respectively; with increasing number of longitudinal voids.
5. Increasing the diameter of longitudinal voids have more effect on the reduction in the ultimate load than the increasing number of longitudinal voids.

6. There is a good agreement with existing reported data in terms of saving the ultimate load and the load-deflection relationship
7. The crack width increased and the number of cracks decreased with increasing diameter or number of longitudinal voids.

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Persian Abstract

چکیده

دال هسته توخالی بتن آرمه (HCS) نوع جدیدی از اسلب های سبک است که در آن حفره های طولی توانایی کاهش مقدار بتن را فراهم می کنند. کاهش مقدار بتن باعث کاهش بارهای تلف شده می شود که در نتیجه منجر به صرفه جویی در هزینه ها ، ساخت سریع و طولانی شدن مدت می شود. این برنامه آزمایشی شامل ساخت و آزمایش گونه های دال با ابعاد ۱۷۰۰×۴۳۵× ۱۲۵ میلی متر برای بررسی اثر حذف نسبت بتن با تغییر اندازه خلا طولی و تعداد حفره های طولی بر عملکرد HCS است. نتیجه آزمایشی نشان داد که حذف بتن با درصد ۱۰,۸۳٪ ، ۱۷,۲۰٪ و ۲۴,۳۷٪ از اسلبهای با مقاومت بالا در هسته توخالی با استفاده از سه حفره طولی به قطر ۵۰ ، ۶۳ و ۷۵ میلی متر به ترتیب باعث صرفه جویی در مقاومت نهایی توسط ۹۰,۰۶، ۸۷,۸۴ و ۸۵,۰۷٪ و افزایش انحراف نهایی ۵,۴۸، ۱۰,۸۰ و ۱۷,۴۴٪. در حالی که ، حذف بتن با درصد ۱۶/۲۵، ۲۴/۳۷ و ۳۲/۵۰ ٪ از اسلبهای با مقاومت بالا در هسته توخالی با استفاده از دو حفره طولی دو ، سه و چهار طول قطر ۷۵ میلی متر منجر به صرفه جویی در مقاومت نهایی با درصد ۸۹/۲۹ ، ۸۵/۷ درصد گردید ، و ۸۰,۶۱، ، و افزایش انحراف نهایی به ترتیب با درصد ۷,۵۷، ، ۱۷,۴۴، و ۲۲,۸۱ در مقایسه با دال جامد مرجع گردید.