Structural Behaviour of Hollow Core Reinforced Self Compacting Concrete One Way Slabs

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Abstract. Hollow-core slab (HCS) is a voided slab that has longitudinal voids made by recycled plastic pipes that were placed in the middle of the slab thickness where the flexural stress is minimum. These longitudinal voids can reduce the volume of slabs to more than 30% which leads to save raw materials and satisfying sustainability, economic considerations, and a clean environment. The experimental program comprised casting six slabs with dimensions of 1700mm x 435mm x 125mm, one of them was solid slab as a reference slab and the other five slabs were HCSs. These slabs were divided into two groups, the first group consisted of three HCSs with different numbers of longitudinal voids, and the second group consisted of three HCSs with different diameters of longitudinal voids. The results of the test showed that increasing numbers of longitudinal voids can save the ultimate load with percentages 93.47%, 87.63%, and 82.92%, with increasing the ultimate deflection by 8.72%, 21.57%, and 28.31%. Also, increasing the diameter of longitudinal voids can save the ultimate load with percentages 93.37%, 90.01%, and 87.63% and increase the ultimate deflection by 6.58%, 13.26%, and 21.57% respectively when compared with the reference slab.

Keywords: hollow-core slabs, longitudinal voids numbers, longitudinal voids diameters and ultimate strength

1. Introduction
The reinforced concrete slab is the largest member consuming concrete in the building [1]. The thickness of the slab should be increased when increasing the span of the slab to attain the requirement of the deflection. That increase in the thickness of the slab leads to an increase in the size of beams, columns, and foundations and that increase will consume more materials and more cost [1]. Various attempts have been made in the past to reduce the self-weight of the reinforced concrete slabs with a minimum reduction in the flexural capacity of the slabs, this reduction in weight will reduce the deflection and will make a large span slab without intermediate supports Waffle slab, Bubbled slab, and Hollow-core slab (HCS) were used for reducing the self-weight of the slab to provide a larger span length [2]. The HCS is a concrete slab with longitudinal voids that run through the long direction of the slabs, these voids provided to reduce the weight of the slab also used for running the electrical and mechanical facilities [3]. Pajari (2004) studied the pure torsion tests of the pre-stressed hollow-core slabs, the test result showed that the torsional stiffness of the hollow-core slabs with 400mm depth was so close to the predicted values of the elementary calculation, but in hollow-core slabs with 200 mm depth, the predicted stiffness values were less than experimental value by 30% [4]. Rahman, et al. (2012) have
made an experimental program to study the effect of slab thickness on the flexural and shear strength of hollow-core slabs, the result showed that at depth greater than 200 mm, the failure mode of these slabs changed from flexural to flexural shear [5]. Baran (2015) studied the effect of concrete topping on the flexural behavior of hollow-core slabs, the results showed that adding 5cm concrete topping over the hollow-core slabs cause an increase in the cracking moment, but the ultimate load was decreased [6]. Foubert, et al. (2016) studied strengthening the hollow-core slabs with near-surface mounted (NSM) carbon fiber reinforced polymer (FRP), the researchers found that strengthening the hollow-core slab with NSM enhanced both the flexural and shear capacity of the pre-stressed hollow-core slabs [7]. Mutashar (2017) has made an experimental program to study the effect of steel fiber ratio on the voided slabs, the results show that increasing the steel fiber ratio from 1% to 2% causes an increase in the ultimate load of bubble and hollow-core slabs by 43% and 24% respectively, and decreases the deflection by 30% and 20% [8]. Qassim and Abdulstar (2018) studied the opening in ultra-high-strength hollow-core, the researcher found that using a square opening with size 100mm×100mm and 150mm×150mm causes a reduction in the ultimate load by 4.93% and 20.42% respectively when compared with the hollow-core slab without opening [9]. This research presents an experimental investigation to study the structural behavior of hollow-core reinforced concrete one-way slabs with different numbers and diameters of longitudinal voids and compare this result with the structural behavior of the solid slab.

2. Experimental program

2.1. Specimens description

The experimental program of this study includes casting and testing six reinforced concrete one-way slabs. The dimensions of all slabs were 1700mm×435mm×125mm. The slabs were divided into two groups according to the longitudinal voids number and diameters as shown in Table 1. The first group consists of four slabs, one of them was solid slab (SS) as a reference slab and the other three slabs were hollow-core slabs with different number of 75mm diameter longitudinal voids (two, three, and four) with designations name 2D75, 3D75, and 4D75 respectively. This group presents the effect of changing the longitudinal voids number on the structural behaviour hollow-core slabs. The second group consists of four slabs, the first slab was the same solid slab in group one as a reference slab and the other three slabs were hollow-core slabs having three longitudinal voids with diameter 50mm, 63mm, and 75mm with designation name 3D50, 3D63, and 3D75 respectively, the slab 3D75 is the same slab in group one. This group presents the effect of changing the diameter of the longitudinal voids on the strength and behaviour of hollow-core slabs. Figures 1, 2 and 3 show details of solid and hollow-core slabs with different diameter and number of longitudinal voids respectively.

| Group No. | Parameter                         | Slab designation | Number of longitudinal voids | Diameter of longitudinal voids (mm) |
|-----------|----------------------------------|-----------------|-----------------------------|-------------------------------------|
| 1         | Number of longitudinal voids     | SS              | ***                         | ***                                 |
|           |                                  | 2D75            | 2                           | 75                                  |
|           |                                  | 3D75            | 3                           | 75                                  |
|           |                                  | 4D75            | 4                           | 75                                  |
| 2         | Diameter of longitudinal voids   | SS              | ***                         | ***                                 |
|           |                                  | 3D50            | 3                           | 50                                  |
|           |                                  | 3D63            | 3                           | 63                                  |
|           |                                  | 3D75            | 3                           | 75                                  |
**Figure 1.** Details of solid slab.

**Figure 2.** Details of HCS with different diameter of longitudinal voids.
2.2. Materials

- Cement: the ordinary Portland cement (type I) have been used in this work, this cement has been manufactured in Iraq by the Tasluja factory. The chemical composition and the physical properties of the used cement conform to Iraqi standard specification No. 5, 1984 [10].

- Fine aggregate: Alssidour natural sand was used in this work as fine aggregate, it has a 2.38 fineness modulus. The grading and the physical properties of the sand is within the limits of zone two in Iraqi specification No.45, 1984 [11]. Figure 4 shows the grading curve for sand.

- Coarse aggregate: Alssidour natural gravel with 14mm maximum size was used in this work as a coarse aggregate, it was washed and dry on air. The grading and the physical properties of the coarse aggregate is within the limits of Iraqi specification No.45, 1984 [11].

- Limestone powder: the grinded limestone powder was used as a filler to produce self-compacted concrete and to get better cohesiveness and better segregation resistance. The limestone powder has a particle size of less than 0.125mm according to EFNARC, 2002 [12].

- Water: the tap water was used in all the mixing and curing.

- Steel reinforcement: deformed steel bars with 6mm diameter were used as main steel reinforcement and 4mm diameter deformed steel bars were used as secondary steel reinforcement, these bars were tested at the laboratory of construction materials/ college of Engineering / Diyala University according to ASTM A615/A 615M, 2009 [13]. Table 2 shows the properties of the steel reinforcement bars.
Table 2. Properties of the tested steel reinforcement bars

| Bar diameter (mm) | Measured diameter (mm) | Yield stress (MPa) | Ultimate stress (MPa) | Modulus of Elasticity (GPa) |
|------------------|------------------------|--------------------|-----------------------|---------------------------|
| 4                | 4.44                   | 429.3              | 514.7                 | 194                       |
| 6                | 5.93                   | 497.1              | 572.5                 | 197                       |

- Superplasticizer: high-performance superplasticizer concrete admixture (ViscoCrete®-5930L) from Sika Company was used to produce self-compacted concrete. It is the third generation of high-performance superplasticizers for concrete and mortar which is used for producing concrete with the highest flowability without segregation. This superplasticizer complies with the requirement of ASTM C494 type F, 2015 [14].
- Plastic pipes: high-density polypropylene pipes were used to make longitudinal voids along the length of the slabs, these pipes manufactured from recyce plastic at Assajad factory in Iraq, these pipes manufactured from nonporous material which does not react chemically with the steel reinforcement or with the concrete. The diameters of these pipes were 50, 63, and 75 mm.

2.3. Concrete mixture
Several trail mixes were made in this study to get the concrete mixture with a compressive strength of about 28.6MPa at 28 days, Table 3 shows mix proportion per cubic meter. In order to verify that the mixes used in this study satisfy the requirement of the self-compacted concrete (SCC), three tests were carried out (slump flow, T500 slump flow, and L-box test), these test are used to investigate flowability, viscosity, passing ability, and segregation resistance according to the specification stated in EFNARC, 2002 [12] and European guidelines, 2005 [15]. Table 4 shows test results of the SCC withe acceptance criteria.

Table 3. Mix proportion per cubic meter.

| Materials                  | Cement | Sand | Gravel | Limestone powder | Water | Superplasticizer |
|---------------------------|--------|------|--------|------------------|-------|-----------------|
| Quantities (kg/m³)        | 375    | 797  | 767    | 195              | 190   | 1.6             |

Table 4. Test results of the SCC withe acceptance criteria.

| Test type         | Unit | Measured | Typical range Value [12] | Typical range Value [15] |
|-------------------|------|----------|--------------------------|--------------------------|
| Slump flow        | mm   | 710      | 650-800                  | 550-850                  |
| T500 slump flow   | Sec  | 3        | 2-5                      | ≥ 2                      |
| L-box             | (H2/H1) | 0.93   | 0.8-1                    | ≥ 0.8                    |

2.4. Testing the slab specimens
At age 28 days, the slabs were cleaned and coated with white colour for revealing the propagation of the cracks, an electrical strain gauges were fixed at the middle top face of all slabs to measure the average concrete strain, then the slabs were tested in the laboratory of civil Engineering of Diyala University by a universal hydraulic testing machine with capacity of 600kN. The linear variable deflection transducer (LVDT) sensor was fixed at the centre of mid-span slabs to measure the deflection during loading, each slab was tested as simply supported slab having clear span 1500mm under two-point static load as shown in Figure 5.
3. Experimental results and discussions

3.1. The ultimate load of the tested slabs

In the first group, increasing numbers of longitudinal voids cause a reduction in the ultimate strength of the hollow-core slabs for the slabs 2D75, 3D75, and 4D75 by 6.53%, 12.37%, and 17.08% and cause a reduction in the first crack load by 6.06%, 11.36%, and 16.67% respectively, when compared with the reference solid slab. Also, in the second group, increasing the diameters of longitudinal voids reduce the ultimate strength of the hollow-core slabs for the slabs 3D50, 3D63, and 3D75 by 6.63%, 9.99%, and 12.37% and reduce the first crack load by 2.27%, 5.30%, and 11.36% respectively, when compared with the reference solid slab. This decrease in the ultimate load of hollow-core slab belong to increase the reduction in concrete volume by 16.25%, 24.37%, and 32.5% respectively with increasing number of longitudinal voids in group No. one, and by 10.83%, 17.20%, and 24.37% respectively with increasing the diameter of the longitudinal voids in group No. two which leads to decrease the moment of inertia (I) and then decrease the flexural stiffness (EI). Table 5 shows the result values of the tested slab. The selection of optimum slab in this study is presented in Figures 6 and 7 by comparison the longitudinal voids number and diameter with the reduction in concrete volume and reduction in load, the more approaching of the curves were in slab 3D50, which produces the optimum reduction in concrete volume with a lower reduction in cracking load and ultimate strength 2.27% and 6.63% among all the other specimens when the longitudinal voids are demanded in the slab for the sake of preserving ultimate strength as well as satisfying the economic considerations.

Table 5. Result values of the tested slabs.

| Group No. | Slab designation | Reduction in vol. of slabs % | Cracking load (Pcr) (kN) | Decrease in Pcr % | Ultimate load (Pu) (kN) | Decrease in Pu % | Ultimate deflection (Δu) (mm) | Increase in Δu % |
|-----------|------------------|----------------------------|--------------------------|-------------------|------------------------|----------------|----------------------------|----------------|
| 1         | SS               | ---                        | 13.2                     | ---               | 52.46                  | ---            | 33.096                    | ---            |
|           | 2D75             | 16.25                      | 12.4                     | 6.06              | 49.03                  | 6.53           | 35.982                    | 8.72           |
|           | 3D75             | 24.37                      | 11.7                     | 11.36             | 45.97                  | 12.37          | 40.235                    | 21.57          |
|           | 4D75             | 32.50                      | 11.0                     | 16.67             | 43.50                  | 17.08          | 42.465                    | 28.31          |
| 2         | SS               | ---                        | 13.2                     | ---               | 52.46                  | ---            | 33.096                    | ---            |
|           | 3D50             | 10.83                      | 12.9                     | 2.27              | 48.98                  | 6.63           | 35.273                    | 6.58           |
|           | 3D63             | 17.20                      | 12.5                     | 5.30              | 47.22                  | 9.99           | 37.484                    | 13.26          |
|           | 3D75             | 24.37                      | 11.7                     | 11.36             | 45.97                  | 12.37          | 40.235                    | 21.57          |
3.2. Load-deflection relationship
Figures 8 and 9 show effect of longitudinal voids number and diameter respectively on the load-deflection of the hollow-core slabs. It can be noted that increasing numbers of longitudinal voids in group one cause an increase in the ultimate deflection of the hollow-core slabs for the slabs 2D75, 3D75, and 4D75 by 8.72%, 21.57%, and 28.31% respectively, when compared with the reference solid slab. Also, in group two increasing diameters of longitudinal voids increase the ultimate deflection of the hollow-core slabs (3D50, 3D63, and 3D75) by 6.58%, 13.26%, and 21.57% respectively, when compared with the reference solid slab, this increase in the ultimate deflection can be attributed to the reduction in the flexural stiffness due to decrease the moment of inertia with increasing numbers or diameters of longitudinal voids.

3.3. Average concrete surface strain
Figures 10 and 11 show effect of longitudinal voids number and diameter respectively on concrete compressive strain of hollow-core slabs. It can be noted from these figures that in all the tested slabs, the strain increases linearly with small rate with the applied load until appearance the first crack then the strain increase with a faster rate with the applied load. After appearance the first crack, the strain in the hollow-core slabs increases faster than the strain in solid slab and increased with increasing numbers or diameters of longitudinal voids.
3.4. Strain in Longitudinal Steel Reinforcement

The strain in steel reinforcement was measured by using two electrical resistance strain gauges that were fixed at the bottom middle of the two intermediate steel reinforcement in each slab specimens. Figures 12 and 13 show effect of longitudinal voids number and diameter respectively on steel tensile strain of hollow-core slabs. In these figures, the ultimate steel strain of the hollow-core slabs decrease with increasing numbers of longitudinal voids in group one for the slabs 2D75, 3D75 and 4D75 by 8.99%, 15.60%, and 22.22% respectively, and decrease with increasing the diameters of longitudinal voids in group two for the slabs 3D50, 3D63, and 3D75 by 10.15%, 12.66%, and 15.60% respectively when compared with the reference solid slab, this decrease in steel strain belong to reducing the ultimate load of the hollow-core slabs with increasing numbers or diameters of longitudinal voids.

3.5. Crack pattern and mode of failure

For all the tested slabs the first crack observed in the bottom middle of the tension zone when the concrete tensile strain reaches to the maximum value. When increasing the applied load the crack will extend up gradually in the solid slab, but in the hollow-core slabs extension of the cracks will be opposed by the plastic pipes, so the crack path deviates around the plastic pipes. This behavior 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 from 13 in the solid slab to 11, 11, and 9 respectively in hollow-core slabs with different number of longitudinal voids, and to 12, 11, 11 in hollow-core slabs with different diameter of
longitudinal voids. Figures 14 and 15 show the effect of longitudinal voids number and diameter respectively on the crack pattern of hollow-core slabs. It can be noted that the mode of failure of the solid and the hollow-core slabs was flexural failure mode due to placing the plastic pipes in the middle of slab cross-section were the flexural stress is minimum.

![Figure 14. Effect of longitudinal voids number on crack pattern of HCS.](image1)

![Figure 15. Effect of the longitudinal voids diameter on crack pattern of HCS.](image2)

4. Conclusions
From the result of the experimental test investigations, the following conclusions can be listed below:

- Increasing numbers of longitudinal voids in the hollow-core slabs reduce the volume of concrete in the slabs by 16.25%, 24.37%, and 32.5%, and can save the ultimate load with percentages 93.47%, 87.63%, and 82.92% respectively as compared with the references solid slabs.
- Increasing diameters of longitudinal voids in the hollow-core slabs can save the ultimate load with percentages 93.37%, 90.01%, and 87.63% with a reduction in the concrete volume by 10.83%, 17.20%, and 24.37% respectively as compared with the references solid slabs.
- The first crack load of the hollow-core slabs reduced from 2.27% to 16.67% when compared with the solid labs.
- Using the hollow-core slab with three longitudinal voids with diameter 50mm is considered the optimum slab for the sake of preserving ultimate strength as well as satisfying the economic considerations.
- The ultimate deflection of the hollow-core slabs was larger than the ultimate deflections of the solid slab and increase with increasing numbers or diameters of longitudinal voids.
- The ultimate concrete compressive strain in the hollow-core slabs was larger than the ultimate concrete stain in the solid slabs and increase with increasing numbers or diameters of longitudinal voids.
- The ultimate steel tensile strain in the hollow-core slabs was smaller than the ultimate steel strain in the solid slabs and decrease with increasing numbers or diameters of longitudinal voids.
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