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Structural Behavior of Hollow-core Reinforced Self-compacting Concrete Two-way Slabs

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Abstract. This study presents an experimental study to investigate the structural behavior of two-way slabs of hollow-core reinforced self-compacting concrete. The experimental program involves the testing of six slabs with size dimensions (450x450x70mm). The slab specimens were divided into two groups, the first group with a hollow-core change in diameter, and the second group with a hollow-core change in number. The experimental results indicated that the increasing the diameter of the hollow core from 15 to 23 and 30 mm decreases the first crack load by 7 percent to 9.65 percent and 14.5 percent and reduces the ultimate load by 4.7 percent to 10.1 percent and 15.8 percent respectively compared with the solid slab. Increasing the diameter of the hollow core and the amount of the hollow core also makes the load-deflection less stiff and decreases ultimate deflection.

Key word: Structural, Hollow-core, Reinforced concrete, Self-compacting concrete, Slabs

1. Introduction

Hollow core slabs for different structures, such as buildings, cultural facilities and high-rise buildings, have recently been used as floor systems. The effectiveness of longitudinal cores decreased the dead load and resulted in an effective structural structure [1-3]. Elevator or escalator post-construction repair, introduction of new floors, heat and ventilation ducts, added skylights, advantages (electricity and telephones) and architectural aspects of the flooring slab [4] are needed. Abed [5] An experimental performance study was conducted by comparing the a/d ratios of longitudinal hollow core reinforced concrete slabs with volumes and loading conditions compared. The results showed that the ultimate strength decreased by 21 percent and 33 percent respectively for solid slabs with an a/d ratio of 2 to 3. The ultimate capacity of circular hollow cores decreased by about 5.49 percent, 15.7 percent and 20.6 percent using circular diameters of 75, 100 and 150 mm. Mahdi and Ismael [6] studied the structural behavior of one-way slabs of hollow-core reinforced self-compacting concrete. Foubert et al [7] It studied the behavior of flexural reinforced hollow-core slabs. These slabs were reinforced with a near-surface mounted carbon fiber reinforced polymer strip (CFRP) (NSM). This study showed that reinforcement with NSM laminates improved both the deflection, ductility and energy ductility of prestressed hollow core slabs, unlike non-prestressed concrete slabs. Al-Azzawi et al [8] The action of one-way concrete slabs with styrofoam blocks has been studied. The results show that, despite the existence of cracks in the styropor block slab with loads lower than those in the solid slab, the production and width of cracks in the styropor block slab is significantly reduced due to the
presence of a reinforcement mesh in the upper concrete section. Abdul Al-Aziz [9] evaluated behavior in reinforced lightweight aggregate concrete hollow core slabs. The results of the laboratory show that the decrease in shear length to the active thickness ratio for solid slab with lightweight aggregate resulted in an increase in the strength of flexural failure and an increase in the deflection of the slab at failure load. Wariyatno et al. [10] using PVC pipe and Styrofoam with differentiated reinforcement, the flexural behavior of precast hollow core slab was investigated. The test specimens are made of a solid slab as a reference slab and a type 1 hollow core slab (HCS) and type 2 HCS (using PVC pipe to create the cavities) (using Styrofoam to build the cavities). The results showed that the weight of HCS Type 1 and Type 2 could be decreased by 24 percent and 25 percent relative to the solid slab. HCS Type 2 is flexural strength is higher than HCS Type 1. Prakashan et al. [11] An experimental study of the flexural behavior of hollow core concrete slabs was performed. In predicting the capacity of hollow core slabs, the performance of the conventional flexural power equation was evaluated. The study concluded that for hollow core slabs, the conventional flexural strength equation can also be used, and they have improved results in terms of load deflection behavior and serviceability than solid concrete slabs. Hussein and Khalil [12] The structural behavior of sustainable hollow core slabs strengthened with hybrid fibers has been studied. The findings suggest that fiber-reinforced sustainable hollow core slab can be used as a roofing system in construction. Abbas [13] investigated behavior of reinforced reactive powder concrete hollow core slabs with vertical opening. The results reveal that increasing of steel fiber content causes an increase in ultimate load. The ultimate load is greatly reduced by adjusting the shear period to the effective depth ratio. The effect of hollow core on self-compacting concrete reinforced slabs was not studied in all previous studies; therefore, this study investigates the effect of hollow core diameter and number on the performance of two-way reinforced self-compacting concrete slabs.

2. Experimental Program
The experimental program involves testing six hollow core slabs made using self-compacting concrete. The specimens are divided into two parts. The first group variable changes the diameter of the hollow core, and the second group variable changes the number of the hollow core as shown in the Table 1. The slabs all have the same dimensions (450 mm x 450 mm x 70 mm). The cross sections of the slabs are shown in Figure 1.

| Group No. | Details of group          | Slab Type | No. of hollow core | Hollow core diameter(mm) | Percentage of concrete decreasing |
|-----------|---------------------------|-----------|--------------------|---------------------------|----------------------------------|
| 1         | Change diameter of hollow core | S1        | Solid              | -                         | -                                |
|           |                            | S2        | Hollow core slab   | 3                         | 15                               | 1.7                              |
|           |                            | S3        | Hollow core slab   | 3                         | 23                               | 3.6                              |
|           |                            | S4        | Hollow core slab   | 3                         | 30                               | 6.7                              |
| 2         | Change No. of hollow core  | S1        | Solid              | -                         | -                                | -                                |
|           |                            | S4        | Hollow core slab   | 3                         | 30                               | 6.7                              |
|           |                            | S5        | Hollow core slab   | 4                         | 30                               | 8.98                             |
|           |                            | S6        | Hollow core slab   | 5                         | 30                               | 11.22                            |
3. Materials

3.1. Cement
Ordinary Portland cement (Type I) from the Tasluja factory was used in this study. The results of the test have shown that the physical and chemical properties of the cement comply with Specification No.5/1984 for Iraq [14].

3.2. Fine aggregate
Natural sand from the Al-Sodur region is used in this study's concrete blend. Before using it, the sieve analysis is performed at the Material Laboratory at the Engineering College of Diyala University. The test results showed that the fine grading of the aggregate complies with Specification No.45/1984 requirements for Iraq [15].

3.3. Coarse aggregate
The crushed gravel from the Al-Sodur region has a maximum size of 10 mm. The sieve analysis is performed at the Material Laboratory of the Engineering College of Diyala University before it is used to ensure its mixing validity and the primary proportions of mixed materials are selected. The test results
have shown that this coarse aggregate grading satisfies the requirements of the Iraqi Standard No.45/1984 [15].

3.4. Limestone powder
Limestone powder, locally named 'Al-Gubra,' has been used as a filler in self-compacting concrete. The particle size of limestone powder is less than 0.125 mm (Sieve No. 200), which complies with EFNARC [16] guidelines.

3.5. Super plasticizer
The super plasticizer used in this study is commercially known as "GLENIUM 51". It is compatible with all types of cement from Portland, including resistant sulphate, and complies with ASTM C494 [17].

4. Steel Reinforcement
For flexural strengthening of all the slabs, deformed 8 mm diameter steel bars were used with 488 MPa yield stress, 650 MPa ultimate strength and 200 GPa young modulus. The test results for bar 8mm satisfies the requirements of ASTM A615 [18].

5. Plastic Pipes
The plastic pipes used in the research were manufactured locally from recycled plastic which is poured in steel forms. The diameter of pipes is 15, 23 and 30 mm as shown in Figure 2. The plastic pipes were placed in one direction of the slab.

Figure 2. Pipes used in the study
6. Concrete Mix Proportions
Several mix ratios have been tried to obtain normal concrete self-compacting (SCC). The final quantity by weight of the materials used in the preparation of SCC per cubic meter for the mix adopted in this research is shown in Table 2.

| Mix type | Cement (kg/m³) | Limestone (kg/m³) | Water (kg/m³) | Sand (kg/m³) | Gravel (kg/m³) | Super plasticizer (kg/m³) |
|----------|----------------|------------------|--------------|--------------|---------------|--------------------------|
| SCC      | 370            | 200              | 190          | 797          | 767           | 2                        |

A rotary mixer unit was used to perform the process of mixing. The SCC mixing process can be defined as follows: at the beginning, the fine aggregate, coarse aggregate, was mixed for 2 minutes, then the limestone was added with the cement and mixed for 1.5 minutes, then gradually adding water after the second stage to the mixture. Finally, after and super plasticizer adding water super plasticizer, the mixing process was continued for two more minutes to get a more homogeneous mix.

7. Fresh SCC’s Tests and Results
In order to determine the fresh concrete of each mix, four standard tests are carried out: T50 cm slump flow, slump flow, L-box and V-funnel inspection, as shown in Figure 3. Four test results and comparisons with the standardized limitations mentioned in EFNARC [16] are shown in Table 3. It should be noted that the results of all mixed tests comply to the requirements of EFNARC [16].

| Mix name      | Slump flow (mm) | T50 (sec) | V-funnel (sec) | L-box (H2/H1) |
|---------------|-----------------|-----------|----------------|----------------|
| SCC           | 710             | 4         | 7              | 0.85           |
| Limits of EFNARC [16] | 650-800       | 2-5       | 6-12           | 0.8-1          |

Figure 3. V-funnel, slump flow and L-box tests of fresh concrete

8. Hardened SCC’s Mechanical Properties
To test the mechanical properties of SCC, the control samples (cylinders and prisms) were cast with the slabs for each batch. In compliance with ASTM C39[19], compressive strength tests (f’c) on cylinders (150x300 mm) were carried out. Flexural strength (f r) (rupture module) tests on prisms (100×100×500mm) were conducted in accordance with ASTM C78 [20], whereas indirect tensile strength (f t) (splitting tensile strength) tests on cylinder (150x300 mm) were conducted in accordance with ASTM C496 [21]. Table 4 reports the outcomes of those studies.
Table 4. Tests of mechanical property performance for hardened SCC

| Slab | Compressive strength (MPa) | Splitting tensile strength (MPa) | Modulus of rupture (MPa) |
|------|---------------------------|---------------------------------|-------------------------|
| S1   | 32.3                      | 3.2                             | 4.4                     |
| S2   | 32.5                      | 3.4                             | 4.6                     |
| S3   | 32.1                      | 3.2                             | 4.3                     |
| S4   | 32.4                      | 3.6                             | 4.7                     |
| S5   | 32.6                      | 3.3                             | 4.5                     |
| S6   | 32.2                      | 3.4                             | 4.6                     |

9. The Slabs Testing
At the age of 28 days, all the slabs were removed from the curing water tank and then painted white so that cracks could be immediately found. At the Structural Engineering Laboratory, College of Engineering, Diyala University, the machine used for the tests is a universal hydraulic machine with a capacity of (2000 kN). A rigid steel square frame with dimensions of (425x425 mm) (center to center) has a circular section of 50 mm in diameter that forms the basic support under the slabs, the support state of each slab. In order to transmit the load developed by the universal hydraulic machine, the slabs were loaded with a rigid steel cylinder with a diameter of 100 mm, mounted at the center of the top face. The vertical deflection was measured using electric linear variable displacement transducers (LVDTT) at each loading stage. The LVDT was placed towards the middle in the slab lower edge for data acquisition conditions and linked to the channels system. Figure 4 demonstrates the setup for the slab test. Using a data acquisition device, the applied load, central deflection, was registered electronically.

Figure 4. One of the slab test setup
10. Results and Discussion

10.1. General behaviour and crack patterns
Figures 5 illustrate crack patterns in the failure of the slabs. The slab tests showed that in flexural mode all the slabs failed and these slabs had general behavior that can be defined as follows: the load in this process is known as the first crack load at the initial stage of loading, the first cracks started at the center of the lower edge. Radial cracks begin to spread from the center towards the slab corner with increasing loads. The cracks are growing in number and growing wider at the same time. A complete failure occurred by increasing the load, and all tested slabs failed to move through the development of steel reinforcement.

![Figure 5. Crack Patterns in slab failure](image)

10.2. First crack load and ultimate load

10.2.1 Effect of the diameter of hollow core on first crack load
The first cracking load on the tested slabs is shown in Table 5. In general, it should be noted that increasing the diameter of the hollow core leads to a decrease in the first crack load. However, the test results in Table 5 showed that the change in hollow core diameter for 15, 23 and 30 mm decreased the first crack load by 7 percent, 9.65 percent and 14.5 percent compared to solid slab, respectively. These decreasing can be attributed to that presence the hollow core leads to decrease the moment of inertia of the slab section thus, the flexural rigidity will decrease the first crack.
Table 5. First crack load results of the slabs

| Parameter          | Slab | No. of hollow core | Hollow core diameter (mm) | First crack load (kN) | Decreasing percentage (%) |
|--------------------|------|--------------------|---------------------------|-----------------------|---------------------------|
| Change in diameter of hollow core | S1   | -                  | -                         | 22.8                  | -                         |
|                    | S2   | 3                  | 15                        | 21.2                  | 7                         |
|                    | S3   | 3                  | 23                        | 20.6                  | 9.65                      |
|                    | S4   | 3                  | 30                        | 19.5                  | 14.5                      |

10.2.2 Effect of number of hollow-core on first crack load

Table 6 shows the first crack load of the tested slabs. Generally, it can be noted that increase number of hollow cores made the first crack load decreases. However, the test results in Table 6 showed that the change in number of hollow cores for 3, 4 and 5 of hollow core made the first crack load decreases with percentage 14.5 %, 18 % and 23.7 % respectively as compared with solid slab.

Table 6. First crack load results of the slabs

| Parameter          | Slab | No. of hollow core | Hollow core diameter (mm) | First crack load (kN) | Decreasing percentage (%) |
|--------------------|------|--------------------|---------------------------|-----------------------|---------------------------|
| Change in No. of hollow core | S1   | -                  | -                         | 22.8                  | -                         |
|                    | S4   | 3                  | 30                        | 19.5                  | 14.5                      |
|                    | S5   | 4                  | 30                        | 18.7                  | 18                        |
|                    | S6   | 5                  | 30                        | 17.4                  | 23.7                      |

10.3 Ultimate load

10.3.1 Effect of diameter of hollow core on ultimate load

Table 7 shows the ultimate load of the slabs being tested. It can generally be mentioned that the effect on the ultimate load of the hollow core diameter, where the increase in hollow core diameter, decreases the ultimate load. However, the study results in Table 7 showed that the change in hollow core diameter for 15, 23 and 30 mm decreased the ultimate load by 4.7 percent, 10.1 percent and 15.8 percent compared to solid slab, respectively. These decreases can be attributed to that presence the hollow core lead decrease the moment of inertia of the slab section thus, the flexural rigidity will decrease the ultimate load.

Table 7. Ultimate load results of the slabs

| Parameter          | Slab | No. of hollow core | Hollow core diameter (mm) | Ultimate load (kN) | Decreasing percentage (%) |
|--------------------|------|--------------------|---------------------------|--------------------|---------------------------|
| Change in diameter of hollow core | S1   | -                  | -                         | 65.4               | -                         |
|                    | S2   | 3                  | 15                        | 62.3               | 4.7                       |
|                    | S3   | 3                  | 23                        | 58.8               | 10.1                      |
|                    | S4   | 3                  | 30                        | 55                 | 15.8                      |
10.3.2 Effect of number of hollow core on ultimate load

Table (8) shows the ultimate crack load of the slabs. Generally, it can be mentioned that the hollow increase in core number, decreases the ultimate load. However, the test results in Table 8 showed that the change in hollow core number of 3, 4 and 5 decreased the ultimate load with a percentage of 15.8 percent, 20.2 percent and 24 percent compared to solid slab, respectively.

Table 8. Ultimate load results of the slabs

| parameter                     | Slab | No. of hollow core | Hollow core diameter (mm) | Ultimate load (kN) | Decreasing percentage (%) |
|-------------------------------|------|-------------------|---------------------------|--------------------|--------------------------|
| Change No. of hollow core     | S1   | -                 | -                         | 65.4               | -                        |
|                               | S4   | 3                 | 30                        | 55                 | 16                       |
|                               | S5   | 4                 | 30                        | 52.2               | 20.2                     |
|                               | S6   | 5                 | 30                        | 49.7               | 24                       |

It can be noted the effect of hollow core diameter on the ultimate load and first crack load are less than the increasing in the number of hollow core.

10.4 Load deflection curve

The effect of the hollow diameter core diameter on a load-deflection curve of the slabs is shown in Figure 6, it should be mentioned that the change in diameter of the hollow core for 15, 23 and 30 mm generally reduces the slab stiffness and the increase in deflection at all loading stages compared to the solid slab. Figure 7 shows the effect of hollow core number on a load-deflection curve of the slabs, it can be seen for hollow core 3, 4 and 5 generally reduces the slab stiffness and the increase in deflection compared to the solid slab in all loading stages. The increasing of the deflection in the hollow core slab at all stages of loading as compared with the solid slab can be attributed to that presence of hollows reduces the flexural rigidity of the slabs due to eliminating a part of concrete which cause a reduction in the moment of inertia of the slab section thus the slab stiffness decreases, while the decrease in ultimate deflection belong to the fact the hollows make the ductility decreases.
10.5 Ultimate deflection

10.5.1 Effect of diameter of hollow core on ultimate deflection

Table 9 displays the ultimate load of tested slabs. It can be noted that the effect diameter of hollow core on the ultimate deflection where the increase in the diameter of hollow core, leads the ultimate deflection decreases. However, the test results in Table 9 showed that the change in diameter of hollow core for 15,
23 and 30 mm made the ultimate deflection decreases with percentage 3.2 %, 5.8 % and 8 % respectively as compared with solid slab.

| Parameter          | Slab  | No. of hollow core | Hollow core diameter (mm) | Ultimate deflection (mm) | Decreasing percentage ( % ) |
|--------------------|-------|--------------------|---------------------------|--------------------------|-----------------------------|
| Change in diameter of hollow core | S1    | -                  | -                         | 4.64                     | -                           |
|                    | S2    | 3                  | 15                        | 4.49                     | 3.2                         |
|                    | S3    | 3                  | 23                        | 4.37                     | 5.8                         |
|                    | S4    | 3                  | 30                        | 4.27                     | 8                           |

### 10.5.2 Effect of number of hollow core on ultimate deflection

Table 10 shows the ultimate load of the tested slabs. It can be noted that the effect of number of hollow core on the ultimate deflection where the increase in number of hollow core, made the ultimate deflection decreases. However, the results in the Table 10 showed that the change in hollow core number for 3, 4 and 5 decreased the ultimate deflection by 8 percent, 9.7 percent and 13.8 percent compared to solid slab, respectively.

| Parameter          | Slab  | No. of hollow core | Hollow core diameter (mm) | Ultimate deflection (mm) | Decreasing percentage ( % ) |
|--------------------|-------|--------------------|---------------------------|--------------------------|-----------------------------|
| Change in No. of hollow core | S1    | -                  | -                         | 4.64                     | -                           |
|                    | S4    | 3                  | 30                        | 4.27                     | 8                           |
|                    | S5    | 4                  | 30                        | 4.19                     | 9.7                         |
|                    | S6    | 5                  | 30                        | 4                        | 13.8                        |

### 11. Conclusions

An experimental research was performed in this paper to study the effect of diameter and number of hollow core slabs on flexural behavior. From the results of this research, it is possible to say that:

- Increasing the hollow core diameter from 15 to 23 and 30 mm led to decrease the first crack load with percentages 7 % to 9.65 % and 14.5 % from the comparison with the solid slab.
- Increasing the hollow core number from 3 to 4 and 5 led to decrease the first crack load with percentages 14.5 % to 18 % and 23.7 % respectively as compared solid slab.
- Increasing the hollow core diameter from 15 to 23 and 30 mm led to decrease the ultimate load with percentages 4.7 % to 10.1 % and 15.8 % from the comparison with the solid slab.
- Increasing the hollow core number from 3 to 4 and 5 led to decrease the ultimate load with percentages 15.9 % to 20.2 % and 24 % respectively as compared solid slab.
- Increasing the hollow core diameter from 15 to 23 and 30 mm led to decrease the ultimate deflection of hollow core with percentages 3.2 % to 5.8 % and 8 % respectively as compared with solid slab.
- Increasing the hollow core number from 3 to 4 and 5 led to decrease the ultimate deflection of hollow core with percentages 8 % to 9.7 % and 13.8 % respectively as compared with solid slab.
Increasing the hollow core diameter from 15 to 23 and 30 mm led to reduce the slab stiffness as compared with solid slab.

Increasing the hollow core number from 3 to 4 and 5 led to reduce the slab stiffness as compared with solid slab.

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