Flexural behavior of self-compacting concrete voided slabs under monotonic loads

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Abstract. This research is devoted to investigate the experimental behavior of normal and moderately high strength self-compacted concrete (SCC) voided slab strips under monotonic loading regimes. Five one-way simply supported slabs were tested including one as a reference slab (solid slab) and the remaining four as voided slabs with three cases of reduction in cross sectional area (6.5%, 13.1% and 14.7%) by creating longitudinal, 3 voids of 50 mm diameter, 6 voids of 50 mm diameter and 3 voids of 75 mm diameter, respectively. The experimental results revealed that for moderate thick reinforced normal SCC one way slab (3 void, dia. =75mm), the ultimate load was reduced by about 20% and the deflection at ultimate load was decreased by about 11% relative to the reference solid slab. While for similar voided slab of moderate high strength SCC, the ultimate load was increased by about 48.3% and the deflection at ultimate load also raised by about 27% with respect to normal strength SCC slab. In addition, the experimental results indicated that for moderate thick reinforced normal SCC one way slab having (3 voids, dia. =50 mm), the ultimate strength was reduced by about 6.7% and the deflection at ultimate load was reduced by 38%, when compared to the solid reference slab. However, for similar slab with (6 void, dia. =50 mm), the reduction in the ultimate strength and deflection at ultimate load were about 9.3% and 42%, respectively.

1. Introduction
One of the approaches for obtaining lighter structures with appropriate strength is by creating voids inside the body of the structure such that no effect on the strength persists. Voids in longitudinal direction of self-compacted concrete one way slab can be considered as one of these approaches. Many studies have been undertaken to deal experimentally and analytically with reinforced concrete slabs with voids. However, a study was carried out by El-behairy et.al to investigate the behaviour of general deformation of six voided reinforced concrete slabs having void diameters of (63mm, 50mm and 40mm). The experimental results show a difference with analytical results that occurred before cracking by about 10%-20% and reached to 20%-30% after cracking. For all six slabs the load deflection curves were similar [1].

A comparative study has been considered between voided flat slabs with solid reduction in weight by 35% from corresponding solid slab. The results showed that the stiffness of the voided slabs was less than that of solid slabs. In addition, there was a reduction in stiffness due to the presence of spherical balls which ranged between (10% and 20%). Also the stiffness of voided slab was increased when thickness of slab was increased[2].

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An experimental study was conducted in 2017 by Liu, to determinate the optimal values of material parameters of slab having dimensions of 10m length (1.2m and 0.27m) width and thickness respectively with 6 longitudinal voids. The agreements in result between experimental work and numerical analysis was compatible [3].

In 2017, Al-Yassri carried out and tested four reinforced concrete hollow core slabs have dimensions of length (1200 mm), span (1100 mm), width (600mm) and thickness (100mm), with the same cross section of hollow core. The slabs had voiding ratio of 26%. The first crack was observed at a load of (21 kN) which represented 26.7% of ultimate load, then the flexural crack occurred at a load level of about (78.7 kN)[4].

Furthermore, in 2017, Daraj, presented study was conducted on eleven one-way simply supported slabs, with reduction in cross sectional area of (23.3% and 29.1%) to investigate the structural behaviour of the slabs. It was found that the strength capacity was increased by 98% for cross sectional reduction of 29.1%[5].

2. Purpose of Research
The main objective of the experimental work was to obtain the perfect ratio of reducing the weight by creating voids in the ineffective region of self-compacted concrete cross section under two point external loads. The obtained ultimate strengths and mode of failure of voided slabs are compared to those of the reference solid slab.

3. Experimental Program
The tested slabs were 1500 mm in length, with a width of 600 mm and a thickness of 150 mm and all the slabs had same steel ratio. They were designed according to ACI 318M-2014 code. The minimum flexural reinforcement for all tested slabs had steel ratio of (0.0027 and 0.0043) for specimens (SNM, 3V50NM, 6V50NM, 3V75NM and 3V75HM) respectively, as shown in figure 1.

In figure 1. the symbol (S) refers to Solid slab and the symbol (V) refers to Voided slab, symbol (N) refers to Normal strength SCC and the symbol (H) refers to High strength SCC the symbol, (3 or 6)
refers to the number of voids and (M) refers to Monotonic load as listed in Table 1. The slabs were tested with an overall clear span of 1380 mm.

Table 1. Details of tested slabs

| Slab designation | Type of concrete | Main rienf. | Transverse rienf. | No. of voids | Void dia.(mm) | flexural steel ratio (ρ) | Void ratio% |
|------------------|-----------------|-------------|-------------------|-------------|---------------|------------------------|-------------|
| SNM NSC          | NSCC            | -           | -                 | -           | 0.0027        | -                      | -           |
| 3V50NM NSC       | NSCC            | -           | -                 | 3           | 50            | 0.0027                 | 6.54        |
| 6V50NM NSC       | NSCC            | -           | -                 | 6           | 50            | 0.0027                 | 13.08       |
| 3V75NM NSC       | NSCC            | Ø8@180mm    | 8 @ 210mm         | 3           | 75            | 0.0027                 | 14.7        |
| 3V75HM HSCC      | HSCC            | Ø8@180mm    | 8 @ 210mm         | 3           | 75            | 0.0043                 | 14.7        |

These specimens were classified according to concrete types normal or high strength SCC, concrete compressive strength (f’c), presence of hollow cores, size of hollow core and number of cores. Table 2 presents some test results that have been carried out on fresh SCC and compared with related standard limitations. The slump flow test, T<sub>500mm</sub> and L-box test were conducted, as shown in Plate 1 and 2. Table 3 presents the properties of reinforcing steel bar used in this work.

Table 2. Test results of fresh properties of SCC which were conducted according specifications and limitations guidelines of EFNARC<sup>[46]</sup>

| Mix designation | Slump flow (mm) | T<sub>500mm</sub> (sec) | L – box (H<sub>2</sub>/H<sub>1</sub>) |
|-----------------|-----------------|------------------------|-------------------------------|
| NSC             | 690             | 3.5                    | 0.85                          |
| HSCC            | 720             | 4.3                    | 0.90                          |
| Limits of EFNARC | 650-800         | 2-5                    | 0.8-1                         |
| Limits of ACI-237 | 450-760         | 2-5                    | 0.8-1                         |

Table 3. Properties of steel reinforcement.

| Nominal Diameter (mm) | Measured diameter (mm) | Surface texture | Bar area (mm<sup>2</sup>) | Yield stress (MPa) | Ultimate stress (MPa) |
|-----------------------|------------------------|-----------------|---------------------------|-------------------|-----------------------|
| 8                     | 7.9                    | deformed        | 49                        | 440               | 655                   |
The normal strength SCC had \( f'c < 41 \text{ MPa} \) according to ACI 363R [7]. While the high strength SCC had \( f'c > 41 \text{ MPa} \)[8]. The properties of SCC mix as shown in Table 4. and the mechanical properties of SCC are listed in Table 5., the presented strength for SCC depended on the average test results of three cylinders (150 x 300mm) for compressive strength, three cylinders for modulus of elasticity and three cylinders for splitting tensile for each test, also three cubes (150x150x150mm) and three prism (400x100x100mm) has been tested.

**Table 4. Proportions of SCC mixes per cubic meter**

| Mix type               | Mix name | Cement (kg) | Limestone powder (LSP) (kg) | Water (liter) | Sand (kg) | Gravel (kg) | Super plasticizer (liter) |
|------------------------|----------|-------------|-----------------------------|---------------|-----------|-------------|--------------------------|
| Normal strength concrete (NSCC) | NSCC | 400 | 150 | 157 | 772 | 835 | 7.5 |
| High strength Concrete (HSCC) | HSCC | 550 | 50 | 152 | 784 | 951 | 20 |

**Table 5. Mechanical properties of SCC obtained for mixes at age of testing slabs.** The properties are concrete compressive strength \( f'c \), splitting tensile strength \( f_t \), modulus of rupture \( f_r \) and modulus of elasticity \( E_c \). The values presented in this table represent the average results of three specimens

| Mix name | \( f'c \) (MPa) | \( f_t \) (MPa) | \( f_r \) (MPa) | \( E_c \) (MPa) |
|----------|----------------|----------------|----------------|----------------|
| NSCC     | 31.52          | 3.16           | 3.49           | 25390         |
| HSCC     | 45.17          | 4.3            | 5.11           | 32527         |

4. **Instruments used in the study**
The instruments that have been used to measure the response of surface strains of the concrete and tensile strain at flexural reinforcement were two types of pre-wired (120Ω) electrical strain gauges that applied at top and bottom faces of concrete and at flexural steel rebar. Strain gauges were pasted on the smooth cleaned surfaces that were prepared before. The vertical deflection of all specimens were measured by linear variable transformer (LVDT) cable connected with data logger to measure the deflection at middle of the span of specimens, as shown in figures 2 and 3.
5. Testing Procedure
All the slabs have been tested at the construction laboratory of the Civil Engineering Department at Al-Nahrain university by using the universal testing machine of 2000 kN maximum capacity, at each 5kN of loading increment, the test measurement values of applied load, deflection of the slab at mid span; strain in steel flexural reinforcement flexural, and strain in compression and tension faces of specimens were recorded. The cracks have been marked together with value of load that formed the crack, Plate3.
Plate 3. A control displacement hydraulic jack of 2000kN machine used to carry out the tests.

6. Test Results and Discussion
6.1 Flexural Behaviour and Crack Patterns:
The flexural crack appeared at the tension face of slab in the middle zone, after that they slowly propagated in direction normal to the longitudinal axis of the slab. With increasing the applied load, cracks have been increased and extended through the thickness of slab. Some of the cracks propagated faster and reached the compression face before other cracks, as shown in Plates 4 to 8

Plate 4. Crack pattern of solid slab SNM

Plate 5. Crack pattern of voided slab 3V50N

Plate 6. Crack pattern of voided slab 6V50N under two point monotonic load

Plate 7. Crack pattern of voided slab 3V75N under two point monotonic load

Plate 8. Crack pattern of high strength SCC voided slab3V75H under two point monotonic load
As shown in these plates the formed flexural cracks are nearly parallel and there are no cracks on both sides of specimen close to the support regions. Clearly, as shown in plate (4 to 8), the development of cracks at tension surface are closely parallel also there is no cracking on both sides of the specimen near the support regions. However, it was observed that the developed of cracks propagated upward vertically in direction parallel to the thickness of slabs. Finally, the failure mode for specimens took place by causing yielding of tension steel.

6.2 Cracking and Ultimate loads
The experimental results of tested specimens are given in Table 6, the cracks occurred at initial stage (first crack) of test. The flexural cracks occurred, at a range of (32.38% to 45.92%) of the maximum peak load of the specimens. In addition, the experimental results revealed that, there is a decrease in the first crack load by about (17.43% and 37.8%) for slabs 3V50NM and 3V75NM compared to the control specimen SNM.

| Specimens designation | Cracking load (Pcr) (kN) | Ultimate load (Pu) (kN) | % Pcr/Pu | % decrease in first cracking load with respect to control slab | % decrease in ultimate load with respect to control slab |
|-----------------------|-------------------------|-------------------------|----------|-------------------------------------------------------------|-------------------------------------------------------|
| SNM                  | 23.92                   | 57.35                   | 41.7     | control                                                   | control                                                |
| 3V50NM               | 22                      | 53.52                   | 41.1     | 8                                                         | 6.7                                                   |
| 6V50NM               | 23.90                   | 52                      | 46       | -                                                         | 9.32                                                  |
| 3V75NM               | 25.87                   | 45.83                   | 56.4     | -                                                         | 20                                                   |

It was found that a (73.65%) increase has been occurred in the load capacity of high strength SCC specimen (3V75HM) compared with specimen (3V75NM). Also, it was noticed a decrease in ultimate load capacity of normal strength SCC specimens compared to control specimen from (6.68% to 20%) but an increase has taken place in slab 3V75HM by about 48.73% with relative to slab 3V75NM. As shown in Table 7.

| Specimens designation | Cracking load (Pcr) (kN) | Ultimate load (Pu) (kN) | % Pcr/Pu | % increase in first cracking load with respect to control specimen | % increase in ultimate load with respect to control specimen |
|-----------------------|-------------------------|-------------------------|----------|----------------------------------------------------------------|----------------------------------------------------------|
| 3V75NM               | 25.87                   | 45.83                   | 56.4     | Control                                                   | Control                                                  |
| 3V75HM               | 38                      | 68                      | 55.88    | 47                                                         | 48.3                                                   |

6.3 Load-Deflection Behavior
The response of the specimens is considered at service load stage and failure load as shown in Table 7. The limitation of serviceability is about (70% - 75%) of peak load [9]. Generally for all specimens there is a gradual increase in load and linear relation between load and deflection in the elastic stage. The cracks started to occur causing a rapid increase deflection at center of the span of specimens at this stage. The behavior of load versus deflection is linear until the yielding of flexural reinforcement took place. After that the deflection was still increased without considerable increase in the load. The experimental results are listed in Table 8. From this table, it has been noticed that an increase in deflection was occurred at 70% of maximum load for specimens 3V50NM, 6V50NM and 3V75NM with respect to the control specimen SNM by about (32%, 58.72% and 200%) respectively.

Figures 4 and 5 show the load deflection response of tested specimens.
Also, there is an approximate compatibility of deflection at first crack load relative to control specimen. It has been observed that a decrease in ultimate deflection of about (38% and 42%) which is related with the increase in the void ratio by about (6.54% and 13.1%) in specimens (3V50NM and 6V50NM). The percentage decrease is reduced in to 11% in specimen 3V75NM with void ratio equal to 14.7%. However, it can be observed that the influence of increasing the compressive strength of SCC of slab 3V75HM causes a decrease in the first crack deflection by about 81% with respect to normal SCC of 3V75NM slab as listed in Table 9. It was found that, there is an increase of about 48.5% in deflection at failure load for the same control specimen, as shown in figure 5.

### Table 8. Response of the specimens, at service load stage (70% of maximum load of control specimens) and at ultimate stage.

| Specimens designation | Deflection at service load of control specimen (mm) | % increase in deflection at service load | Deflection at first cracking load (mm) | Deflection at ultimate load (mm) | % decrease in ultimate deflection with respect to control specimen |
|-----------------------|---------------------------------------------------|----------------------------------------|--------------------------------------|-------------------------------|---------------------------------------------------------------|
| SNM                   | 13.64                                             | Control                                | 3.25                                 | 58.5                          | Control                                                      |
| 3V50NM                | 18                                                | 32                                     | 2                                    | 36.2                          | 38                                                           |
| 6V50NM                | 21.65                                             | 58.72                                  | 2                                    | 34                            | 42                                                           |
| 3V75NM                | 42                                                | 200                                    | 2.88                                 | 52                            | 11                                                           |

![Figure 4](image1.png) **Figure 4.** Effect of void ratio on load-central deflection behavior of tested specimens

![Figure 5](image2.png) **Figure 5.** Effect of concrete compressive strength on load-central deflection behavior of tested specimens 3V75NM and 3V75HM.

### Table 9. Response of the specimens at service load stage (70% of maximum load of control specimens) and at ultimate stage.

| Specimens designation | Deflection at service load of control specimen (mm) | %Decrease in deflection at service load level | Deflection at first cracking load (mm) | Deflection at ultimate load (mm) | %Decrease in ultimate deflection with respect to control specimen |
|-----------------------|---------------------------------------------------|----------------------------------------------|--------------------------------------|-------------------------------|---------------------------------------------------------------|
| 3V75NM                | 42                                                | Control                                      | 2.88                                 | 52                            | Control                                                      |
| 3V75HM                | 8                                                 | 81                                           | 4                                    | 66                            | 48.5                                                          |

### 6.4 Ductility
The ductility index is the ratio of deflection at maximum load level to the deflection at first crack load of tested specimens. According to the listed results in Tables 10. And 11. It was found that the reduction in ductility index was 8.33% for moderate high strength SCC slab (3V75HM) with respect to normal SCC specimen (3V75NM) specimen.

| Specimen designation | Ultimate load (kN) | Deflection at first cracking load (mm) | Deflection at ultimate load (mm) | Ductility factor | Void ratio |
|----------------------|-------------------|--------------------------------------|---------------------------------|-----------------|------------|
| SNM                  | 57.3              | 3.2                                  | 58.5                            | 18.3            | -          |
| 3V50NM               | 53.5              | 2                                    | 36.2                            | 18              | 6.54       |
| 6V50NM               | 52                | 2                                    | 34                              | 17              | 13.08      |
| 3V75NM               | 45.8              | 2.88                                 | 52                              | 18              | 14.7       |

In addition, it has been noticed for all normal SCC voided slabs, this is a clear drop in ductility factor with the increase of the voiding ratio when compared to the control specimen SNM, as shown in figures 6 and 7.

Table 11. Ductility factor of the tested normal SCC and moderate high strength SCC slab

| Specimen designation | Ultimate load (kN) | Deflection at first cracking load (mm) | Deflection at ultimate load (mm) | Ductility factor | Void ratio |
|----------------------|-------------------|--------------------------------------|---------------------------------|-----------------|------------|
| 3V75NM               | 45.8              | 2.88                                 | 52                              | control         | 14.7       |
| 3V75HM               | 68                | 4                                    | 66                              | 16.5            | 14.7       |

**Figure 6.** Ductility factor versus concrete compressive strength of tested load.

**Figure 7.** Ductility factor versus voiding ratio of tested load

6.5 Load-Strain response
The load-strain relation is an important variable for understanding the behavior of reinforced SCC voided slabs. This relation has been measured by monitoring the strain at top (compression surface) and bottom (tension surface) face of the concrete and at the flexural reinforcement. It has been noticed that from figure 8, that the flexural steel reinforcement was yielded at (2000, 1750, 1500 and 1500) micro strain for normal SCC slab specimens NSM, 3V50NM, 6V50NM and 3V75NM.

Figure 8. Curves of load strain response at the top surface of concrete.

Also, the maximum compressive strain at top surface is (850, 850, 1750 and 3100) micro strain, as shown in figure 9. However, for the moderate high strength SCC slab, the flexural steel reinforcement yielded at (1750) micro-strain with a maximum compressive strain at top face of concrete (3750) micro-strain.

7. Conclusions

Based on the experimental results of solid and voided slabs, the main conclusions drawn and can be summarized as follows:

1. All tested specimens were failed in flexural failure mod that occurred after yielding of flexural steel, in the other side the initial cracks usually formed at middle third of bottom surface on slab, then extended in direction normal to the longitudinal axis of span of the specimen.
2. It has been observed that the propagation of cracks in voided slab tended to divert in curved form and then the cracks connected together.
3. The number of the cracks was increased with increasing number of voids. Meanwhile, the crack became less in number and wider when size of voids was increased for the same loading stage.
4. It was found that the presence of voids in SCC slab with void ratio of 6.54% causes small decrease in the maximum load by 6.7% relative to control solid slab. This percentage of decrease became 9.32% for slab having same size of voids with doubled number of voids which has 13.1% ,but the decrease in ultimate load became 20% when the size of the voids in void ratio increase to 14.7% which was close to 13.1% void ratio.
5. Obviously, the ultimate load of moderate high strength SCC has been increased by about 48.3% with respect to normal strength SCC.
6. The deflection at ultimate load decreased by 38% for slab with void ratio 6.54% with respect to control solid slab. This decrease has been used incremented to reach to 42% when doubled number of same size of voids (13.1% void ratio). For a slab with a void ratio 14.7% the deflection was increased by 11%.
7. In moderate high strength SCC, the increase of the ultimate deflection was 27% with respect to normal strength SCC.
8. The load strain response flexural steel rebar of all slab was similar and the strain at the extreme compressive fiber followed a nonlinear behaviour with load till failure of specimen.
8. References

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