# PERFORMANCE EVALUATION OF HOLLOW CORE SLABS MADE OF SELF COMPACTING CONCRETE

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## ABSTRACT

In recent years, an emerging technology termed self-compacting concrete (SCC) has seen wide-spread use in the precast concrete industry. A full-scale experimental program was carried out to investigate the flexural behavior of precast prestressed hollow core slab (HCS) units made using SCC. The flexural behavior of SCC-HCS was compared with that of HCS fabricated using the dry cast concrete (DCC) technique commonly used for production of HCS. The test variables were the use of SCC and the size of the HCS units. The results of the experimental investigation are presented in terms of load-deflection characteristics, cracking behavior, strain characteristics and load carrying capacity. A comparison between the experimental results and theoretical calculations based on the ACI 318 code provisions is also presented. The outcomes of this investigation revealed that the flexural behavior of SCC-HCS units was comparable to that of DCC-HCS units. Furthermore, the flexural capacity of SCC units was accurately predicted by the relevant ACI 318 design expressions.

**Keywords—**flexural behavior, hollow core slab, self-compacting concrete, prestressed concrete.

## 1. INTRODUCTION

Hollow core slab (HCS) is an efficient precast structural element which is increasingly gaining popularity in the local construction industry. HCS allows for fast-track construction of floor/roof of buildings and at the same time has a high quality of concrete as the units are manufactured in factory under controlled conditions. HCSs are typically produced in one of two ways; either as part of a wet-cast system where the slabs are slip-formed, using normal-slump concrete or as part of a dry-cast system where the slabs are extruded, using very low-slump concrete. The common manufacturing technique used in Saudi Arabia is the dry cast system where prestressing strands are first tensioned above a long bed; a very low slump concrete is then forced through the machine and compacted around the cores with augers or tubes. After hardening of the concrete, the ends of the strands are released and the long slab is saw-cut into units of desired length. In the USA and many other countries including Saudi Arabia, the design of HCS is governed by ACI 318 code [1-2] and design guidance can also be found in PCI design manual [3] of hollow core slabs.

Recently, with the introduction of deeper HCS, one major disadvantage became apparent. Tests of HCS units by several U.S. manufacturers [4] have shown that for deeper sections of the HCS units, some of the tested units failed in web shear at 60% or less of the load predicted by ACI 318-05 [5]. As a consequence, ACI 318-08 [1]requires minimum shear reinforcement to be provided in hollow-core units with depths greater than (315 mm) if the factored shear force exceeds 50% of the design shear strength of the concrete. Otherwise, the web shear capacity must be reduced by 50%. Since placing stirrups in the extruded HCS is not practical because of the special manufacturing technique used, alternative manufacturing methods to improve the shear strength of the HCS units are being explored by researchers [6]. Recently, the use of steel fiber reinforced concrete to enhance the shear resistance of deep HCS was investigated [7-8]. It was concluded that introduction of fibers improve the shear resistance as HCS with fibers achieved higher loads and more ductile behavior than those HCS units without fiber reinforcement. An alternative approach for solving the problems of deep HCS members is to use self-compacting concrete (SCC) which allows placing shear reinforcement specified by the code without difficulties.

SCC is a new, innovative technology which represents one of the most significant advances in concrete technology during the last two decades [9-11]. Due to its specific properties, SCC may contribute to a significant improvement of the quality of concrete structures and may also offer many significant benefits to the precast industry, where the elimination of the compaction work results in reduced costs of placement, a shortening of the construction time and therefore an improved productivity. The application of SCC also leads to a reduction of noise during casting, better working conditions and excellent surface quality without blowholes or other surface defects.

In this paper, the experimental investigation data on the flexural behavior of HCS specimens made using SCC compared to dry cast concrete (DCC) are presented in terms of load-deflection characteristics, cracking behavior, strain characteristics and load carrying capacity. The present investigation is part of an extensive experimental research program at King Saud University to examine the structural behavior of full scale HCS.

## 2. EXPERIMENTAL INVESTIGATION

As part of an ongoing investigation on the structural behavior of HCS using SCC, full-scale HCS were manufactured under close supervision at a local precast plant and tested at the Structural Laboratory of the Civil Engineering Department, King Saud University (KSU). In this paper, the flexural behavior of four full-scale precast prestressed HCS was presented. The development and casting of the HCS were done with the collaboration of Saif Noman precast factory in Riyadh. The HCS units included two slabs manufactured using SCC and two slabs manufactured using DCC. Two different slab depths were employed in this study including 300 mm and 470 mm. Table 1 shows relevant details of the tested specimens.

**Table 1:** Details of the tested specimens

| Slab ID | Width (mm) | Depth (mm) | No. of strands | Actual compressive strength at transfer (MPa) | Actual compressive strength at 28 days (MPa) |
|---|---|---|---|---|---|
| DCC-300 | 1,200 | 300 | 5 strands 12.7 | 29.9 | 52.2 |
| SCC-300 | 1,200 | 300 | 5 strands 12.7 | 29.0 | 51.0 |
| DCC-470 | 900 | 470 | 2 strands 15.2 4 strands 12.7 | 33.6 | 54.2 |
| SCC-470 | 900 | 470 | 2 strands 15.2 4 strands 12.7 | 31.0 | 54.7 |

## 2.1 Material properties

The materials used in this study were the same as those used by Saif Noman precast factory in Riyadh which cooperated in this study by providing all facilities for fabrication and casting of HCS at the plant. Prior to casting the HCS specimens with SCC, many trial mixes were prepared to obtain the fresh concrete properties as well as the required concrete strength. The maximum size of graded coarse aggregate used was 10 mm with fineness modulus of 2.96, specific gravity of 2.64, and water absorption of 1.11%. For the fine aggregates, crushed sand and white silica sand with fineness modulus of 5.59 and 2.24, specific gravity of 2.67 and 2.62, and water absorption of 1.10% and 0.71%, respectively. Both types of SCC and DCC mixtures utilized type I Portland cement which meets the requirements of ASTM C 150 **[12]**. The properties of standard tendons used by the precast plant for prestressed concrete conform to the ASTM **A416/A-416M12 [13]** for low relaxation strands. In this study, the prestressing strands used were 12.7 mm and 15.2 mm in nominal diameter with a reported ultimate strength of 1,862 MPa, and a modulus of elasticity of 193 GPa. The concrete clear cover was 40 mm. The initial prestressing force at jacking was 70% of the ultimate tensile strength of strands.

## 2.2 Development of SCC mix

Several SCC trial mixes were carried out at KSU Concrete Laboratory to arrive at the desired fresh concrete properties as well as the target concrete strength prior to casting HCS specimens. The trial mixes were conducted by varying the proportions, type and dosage of chemical admixtures.Based on the results of these trial mixes, one mix from these trials was selected since it met EFNARC's **[14]**recommendations for flowability without segregation and yielded adequate compressive strength at 24 hrs. Full-scale field trial was conducted on the selected mix at the precast plant using their central stationary mixer and materials from their stockpiles. The results of the field trial were consistent with the results of laboratory trial as shown in Table 2. This successful mix was used for casting the HCS specimens. The mix proportions for the selected mix are given in Table 3 along with the DCC mixes.

**Table 2:** Comparison of lab and field trials for selected SCC mix

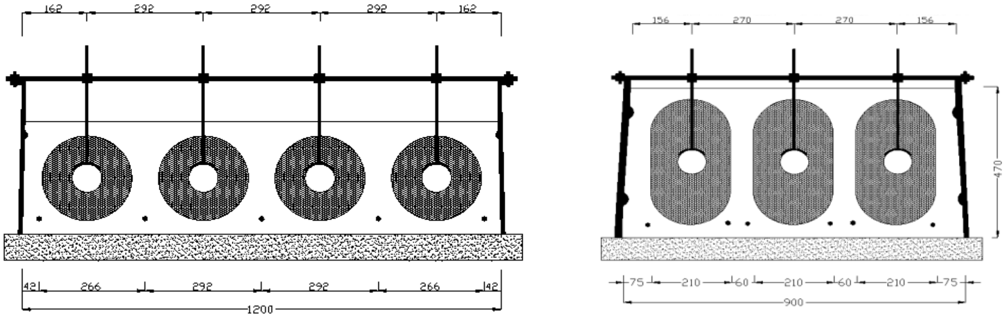
| Description | Date | Fresh properties of SCC | | | Compressive strength at transfer (MPa) |
|---|---|---|---|---|---|
| | | Flow spread (mm) | T500 (s) | V-funnel (s) | |
| Lab. trial | 04-9-2013 | 760 | 3.9 | 12.3 | 29.6 |
| Field trial | 08-9-2013 | 720 | 4 | 8.6 | 28.3 |
| EFNARC [14] recommended limits | - | 650 - 800 | 2-5 | 6-12 | - |

**Table 3:** Mix proportions for DCC and SCC mixtures

| Description | DCC for 300 HCS | DCC for 470 HCS | SCC |
|---|---|---|---|
| Cement Type-I | 420 Kg | 480 Kg | 453 Kg |
| 10 mm Aggregate | 342 Kg | 324 Kg | 600 Kg |
| 20 mm Aggregate | 801 Kg | 759 Kg | - |
| Crushed sand | 268 Kg | 254 Kg | 460 Kg |
| White silica sand | 488 Kg | 463 Kg | 660 Kg |
| Water ( Total ) | 142 Kg | 158 Kg | 180 Kg |
| Glenium 51 | - | - | 4.8 Lit |
| CONPLAST P 211 | 2.87 Lit | 3.28 Lit | - |

### 2.3 Fabrication and casting of HCS units

Before concrete placement of SCC, the manufacturer’s regular production using DCC done by a spiroll type hollow-core extruder was first cast early in the morning. Casting of SCC was scheduled at the line end to minimize the effect of vibration by the machine during the DCC process. One casting line 1200 mm wide was utilized for the fabrication of two HCS (SCC and DCC) specimens with depth 300 mm that were manufactured on the same bed and cast on the same day. The utilized second casting line for HCS with depth 470 mm line was 900 mm wide. Two HCS were manufactured on the same bed and cast also on the same day. One was part of the manufacturer’s regular production using DCC and the other one was cast using SCC. Each HCS specimen for depth 300 mm and 470 mm was 6200 mm long, sharing a common geometry with same depth, and designed with same numbers of strands and web width. It was expected during casting the SCC that the void forms consisting of temporary styro-foams may tend to float up in the fresh concrete due to the high uplift pressure. To prevent this from happening, a void hold down system was used. A sketch of the typical hold-down system for tested SCC-300 mm and -470 mm depth HCS specimens is shown in Figure 1. It should be pointed out that the hold down system used in this study is not practical to be used for mass production in the plant. A more practical system to be used for regular production in the plant has been patented recently [6].



**(a)** Hold down system for depth 300 mm. **(b)** Hold down system for depth 470 mm.

**Figure 1:** Schematic of the typical hold down system arrangement

### 2.4 Visual inspection of cast HCS

Inspection of cast HCS units indicated less bug holes and surface blemishes for SCC compared with DCC slabs. For deeper HCS units, however, some longitudinal cracks appeared at the webs and top surface of SCC HCS as shown in **Figure 2**. The causes of these types of cracks are not fully understood, but they are reported common with wet mixes **[15]**.

(a) Horizontal crack in webs.

(b) Longitudinal crack in top flange.

**Figure 2:** Longitudinal and horizontal cracks in SCC HCS units.

## 2.5 Test set-up and instrumentation for flexural testing of HCS

The HCS specimens were tested in flexural under four-point bending system. Other aspect of the test set-up used in this study closely resemble those of the standard HCS test found in Annex J, of European Product Standard EN-1168 [16]. Static loading was applied for testing the HCS specimens by using a closed-loop actuator with a capacity of 1000 kN. The test slabs were made up of full-width elements with a nominal clear span length of 6000 mm. The support condition for each test consists of 60 mm diameter rod forming a pinned support placed beneath the end of the HCS unit, while a roller bearing support was placed at the opposite end so that no axial forces can be generated by the rotation of the HCS units during the test. Each HCS specimen was instrumented with electrical resistance strain gauges installed on the top concrete surface at mid span of the HCS unit. The deflection of the slab at the mid span and mid shear spans was measured by linear variable displacement transducers (LVDTs). In addition, two LVDTs were installed at each end of the HCS to measure the slippage of two selected strands. All the strain gauges and LVDTs were connected to a multi-channel system for continuous data acquisition. The schematic arrangement for the four-point bending system test is represented in Figure 3.

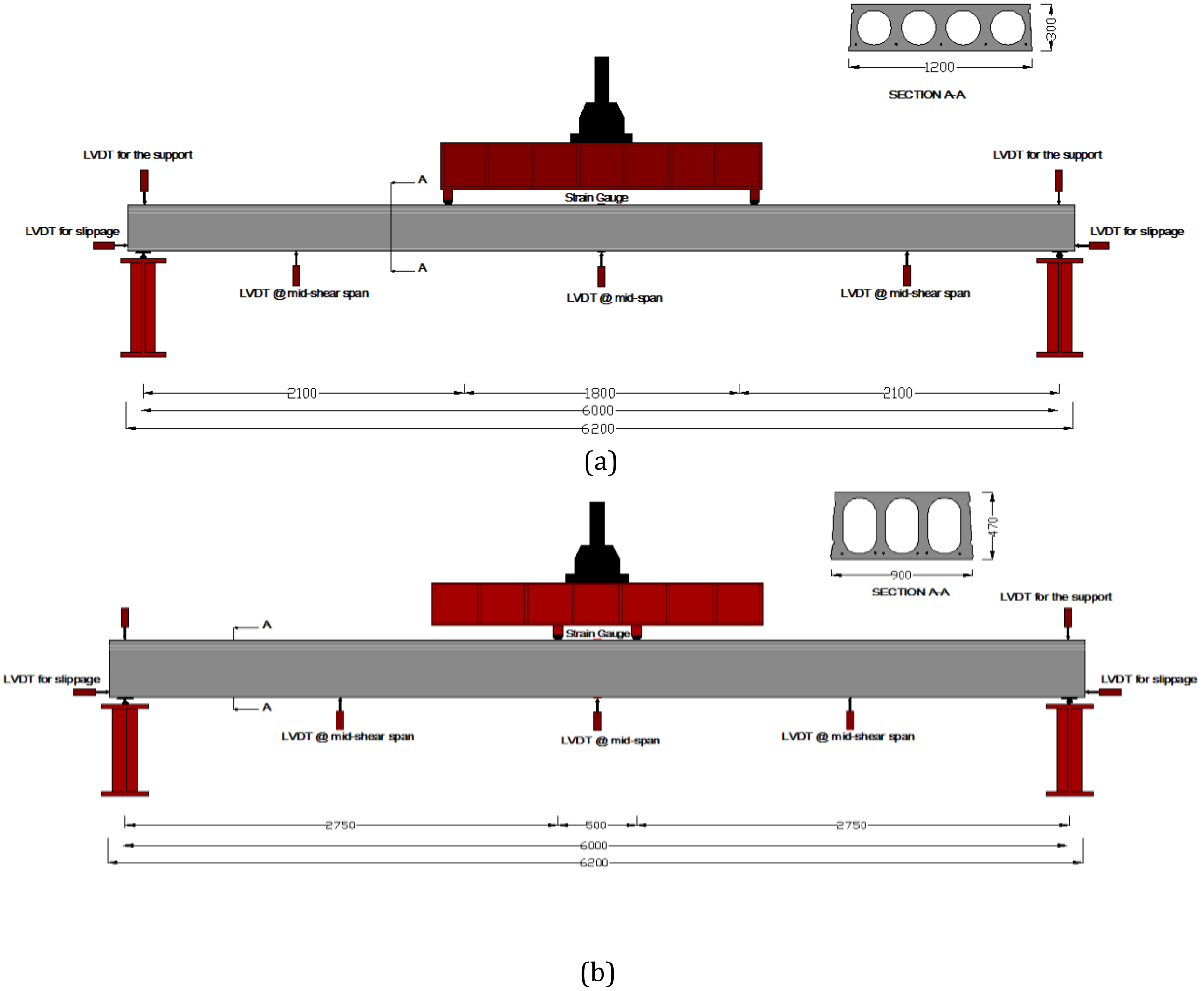


**Figure 3:** Typical test set-up elevation for HCS with depth (a) 300 mm and (b) 470 mm.

## 3. TEST RESULTS AND DISCUSSION

The applied moment vs. mid span deflection curves for the four tested specimens are shown in Figure 4. From the figure, the first part of the curve represents the stiffer behavior of the HCS before cracking, and once cracks start in the concrete, the slope of the curve decreases, indicating a loss of stiffness. The second part of the curve extends up to yielding of the prestressing strands. The third part starts after yielding indicating dramatic loss in stiffness.

All tested HCS specimens exhibited ductile behavior as indicated by the large deflection in Figure 4 except for SCC-470 slab. At the same deflection before the cracking moment, it was evident that the stiffness was almost similar for both SCC and DCC specimens, despite that SCC mixture had higher paste content and lower content of coarse aggregates than the DCC mixture. Slab SCC-300, however showed slight increase in stiffness over that of slab DCC-300. Flexure mode of failure was observed for specimens DCC-300, SCC-300 and DCC-470. During the tests for these specimens, the flexural cracks were first initiated between the concentrated point loads. As the load increased, additional flexural cracks opened within the shear span, and suddenly cracks became inclined and propagated to the point of application of line load but without causing flexure-shear failure. The flexural crack located at the center of the slab extended across the width and the specimens failed in pure flexural mode by crushing of concrete at mid-span. For specimen SCC-470, the failure appeared in shear span but it was not a typical flexure shear, because it was not initiated by flexure cracking at that zone. The slab failed prematurely due to the horizontal crack that was already visible at the webs before testing. The width of the horizontal cracks became wider and extended through the shear span as the applied load was increased, and suddenly cracks became inclined and causing sudden shear failure. The experimental cracking moments, ultimate moments and modes of failure of the tested HCS specimens are summarized in Table 4. The crack patterns for the tested specimens are illustrated in Figure 5.

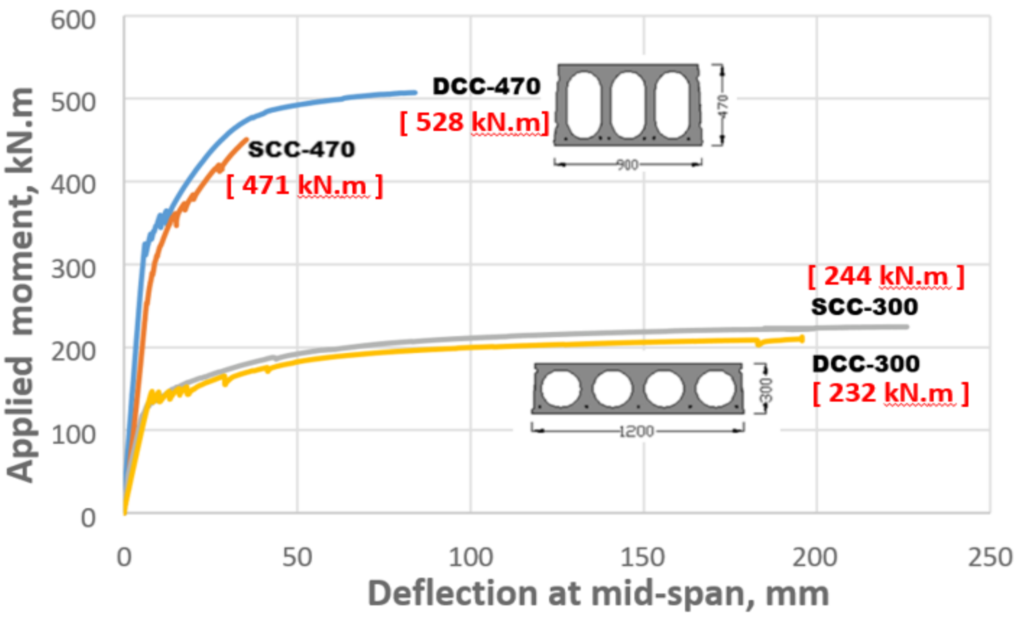


**Figure 4:** Applied moment vs. deflection response for tested specimens.

**Table 4:** Summary of test results

| Slab ID | Applied load (kN) | Cracking moment[a] $M_{cr}$ (kN.m) | Failure moment[a] $M_u$ (kN.m) | Mid-span deflection at cracking (mm) | Mid-span deflection at failure (mm) | Max. strain of concrete ($\mu\varepsilon$) | Ductility Index | Observed failure mode |
|---|---|---|---|---|---|---|---|---|
| DCC-300 | 203.0 | 164.9 | 232.2 | 12.6 | 196.0 | -2,864 | 4.5 | F |
| SCC-300 | 214.0 | 155.0 | 244.1 | 8.5 | 226.0 | -2,079 | 4.3 | F |
| DCC-470 | 369.0 | 342.4 | 527.8 | 6.7 | 83.1 | -2,076 | 2.6 | F |
| SCC-470 | 328.0 | 274.9 | 471.2 | 6.6 | 35.4 | -1,087 | 1.2 | FS |

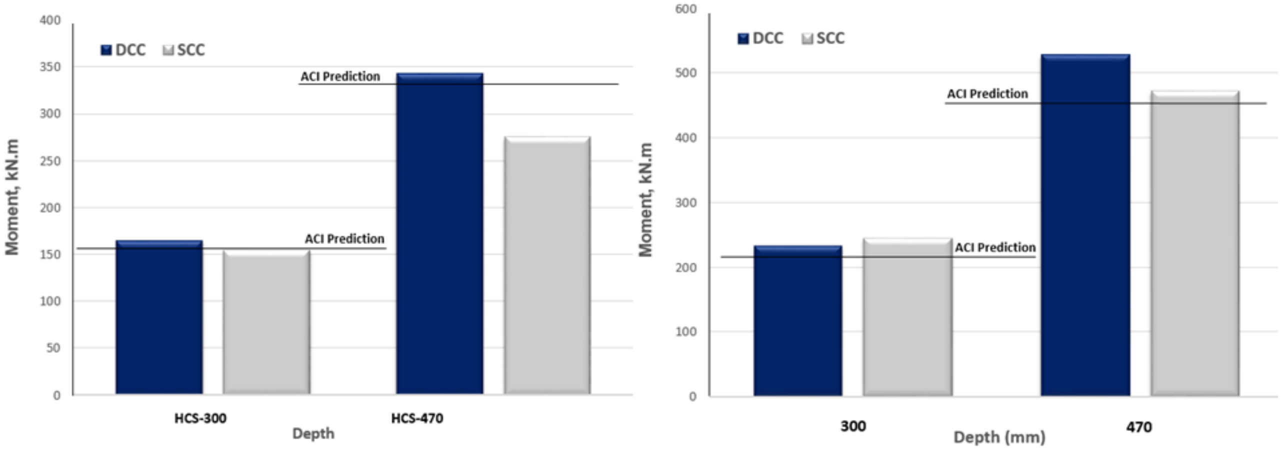
[a] including the effect of self-weight **F**= flexure mode of failure **FS**= flexure shear mode of failure

(a) DCC-300 (b) SCC-300

(c) DCC-470 (d) SCC-470

**Figure 5:** Crack patterns for the tested specimens

The comparison of moment at cracking and failure are shown in Figure 6. As shown in the figure, DCC slabs gave higher cracking moment than SCC slabs by around 6% and 19.7%, respectively for depth 300 mm and 470 mm. The moment capacity of SCC unit with depth 300 mm exceeded the DCC unit by 5.1 %. However, the moment capacity for the tested SCC-470 unit was 10.7% lower than that of DCC-470. This slight decrease of moment capacity might be coming from the defect of the horizontal crack that was already existing in the SCC-470 specimen at the webs before testing.



(a) Cracking moment (b) Failure moment

**Figure 6:** Comparison of moment at cracking and failure.

## 4. COMPARISON OF TEST RESULTS WITH ACI 318 CODE

**Table 5** presents the comparison of experimental and predicted results by ACI 318-11 **[2]** design guidelines. The predictions of cracking moment for the two tested DCC-HCS were almost comparable to the experimental values with the ratio $M_{cr\,EXP} / M_{cr\,ACI}$ of 1.0 and 1.02 for DCC-300 and DCC-470 slabs respectively, as given in Table 5. On the other hand, **Table 5** shows that ACI 318 code overestimated the cracking moment of the SCC slabs as the ratio of $M_{cr\,EXP} / M_{cr\,ACI}$ was 0.95 and 0.82 respectively for SCC-300 and SCC-470 slabs.

**Table 5:** Comparison of experimental and predicted results by ACI 318-11

| Slab ID | Experimental | | ACI 318-11 Calculations | | $M_{cr\,Exp} / M_{cr\,ACI}$ | $M_{u\,Exp} / M_{u\,ACI}$ |
|---|---|---|---|---|---|---|
| | Cracking moment $M_{cr\,Exp}$ (kN.m) | Moment capacity $M_{u\,Exp}$ (kN.m) | Cracking moment $M_{cr\,ACI}$ $(kN.m)$ | Moment capacity $M_{u\,ACI}$ $(kN.m)$ | | |
| DCC-300 | 164.9 | 232.2 | 165.7 | 218.4 | 1.00 | 1.06 |
| SCC-300 | 155.0 | 244.1 | 162.7 | 217.6 | 0.95 | 1.12 |
| DCC-470 | 342.4 | 527.8 | 334.2 | 465.8 | 1.02 | 1.13 |
| SCC-470 | 274.9 | 471.2 | 334.8 | 466.1 | 0.82 | 1.01 |

The ultimate moment capacity $M_{u\,ACI}$, of the slabs was calculated using the ACI 318 equation given as follows:

$$M_{u\,ACI} = A_{ps} \times f_{ps} \left( d_{p} - \frac{a}{2} \right) \tag{1}$$

$$a = \frac{A_{ps} \times f_{ps}}{0.85 \times b \times f_c'} \tag{2}$$

$$f_{ps} = f_{pu} \left( 1 - \frac{\gamma_p}{\beta_1} \rho_p \frac{f_{pu}}{f_c'} \right) \tag{3}$$

where $A_{ps}$ is the area of prestressing strands, $f_{ps}$is the stress in prestressed reinforcement at nominal strength, $d_p$is the effective depth of the slab, $a$ is depth of equivalent compression stress block, $b$ is the width of the slab, $\beta_1$ is the factor depending on concrete strength where it shall not exceeds 0.85, $\rho_p = A_{ps}/(b \times d_p)$ which is the ratio of prestressing steel, $f_c'$ is the specified compressive strength of concrete, $f_{pu}$is the ultimate tensile strength of the strands, and $\gamma_p$ is a factor for type of prestressing strands (0.28 for low relaxation strands). As can be noted from Table 5, the predicted values of the ultimate moment capacity for the full scale HCS tested specimens appear to be in a good agreement with the experimental results. The table also shows that there is no influence of the depth of the HCS on the prediction accuracy as the moment exceedance percentages over the calculated moment capacities were within similar ranges when comparing the thicker slabs with the thinner ones for both types of SCC and DCC slabs. This suggests that the SCC mixture proportioning also had no adverse effect on the flexural performance at ultimate moment for the SCC-HCS units with respect to current design procedures or with respect to a comparable dry cast concrete mixture.

## 5. CONCLUSIONS

The following are the main conclusions based on the results of this study:

1. For 300 mm thick units, the cracking moment of SCC slab was comparable to that of DCC unit whereas the ultimate capacity was slightly higher by 5%. On the other hand, both cracking and ultimate moments of the 470 mm thick SCC units were less than those of DCC by 19.7% and 10.7% respectively reflecting the effect of the observed premature cracks for 470 mm SCC slab.
2. The flexural capacity of SCC units with depth 300 mm and 470 mm was closely matching with predicted capacity based on ACI 318 design expression.
3. Both SCC and DCC units showed comparable cracking pattern and mode of failure except for SCC 470 mm slab due to the premature failure mode.
4. SCC can be used for the production of the HCS units from locally available materials.

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