International Journal of Structural Analysis & Design – IJSAD
Volume 1 : Issue 3 [ISSN : 2372-4102]
Publication Date : 30 September,2014

The Use of SCC for Manufacturing Precast Prestressed Hollow Core Slabs

[Majed. O. Khanbari[a], Taher Somaily[a], Abdulaziz. I. Al-Negheimish[b], Ahmed. K. El-Sayed[c] and Abulrahman. M. Alhozaimy[b]]

***Abstract*—** Self compacting concrete (SCC) is a new, innovative technology which represents one of the most significant advances in concrete technology during the last two decades. The use of SCC for the production of hollow core slabs (HCS) is proposed to allow for placing shear reinforcement in deep HCS. However, many researchers have expressed concern that SCC could negatively affect the hardened properties such reductions in the modulus of elasticity as well as shear strength and bond between concrete and steel strands. This paper presents development work on the manufacture of HCS using SCC. Preliminary results of short-term flexure testing of full-scale HCS members made using SCC and conventional dry cast concrete (DCC) are presented and discussed.

Keywords—*Self compacting concrete, hollow core slab, fresh and harden properties, flexural strength, prestressed concrete.*

I. Introduction

Hollow core slabs (HCS) are very popular in the construction industry worldwide. HCS allow for fast-track construction of floor/roof of buildings and at the same time have a high quality of concrete as the units are manufactured in factory under controlled conditions. HCS are typically produced as part of a dry-cast system where the slabs are extruded, using very low-slump concrete. The design of HCS is governed by the American Concrete Institute ACI 318-08 **[1]** and design guidance can also be found in PCI **[2]** design manual of hollow core slabs (2004). HCS are generally designed as simply supported one-way slabs. The prestressing strands in the bottom flange of the cross section are generally used to provide prestressing force and to resist tensile stresses.

Recently, with the introduction of deeper HCS, a number of disadvantages become apparent. Tests of HCS units by several U.S. manufacturers **[3]** 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 **[4]**.

As a consequence, ACI 318-08 **[1]** now requires minimum shear reinforcement to be supplied 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 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 **[5]**. Recently, the use of steel fiber reinforced concrete to enhance the shear resistance of deep HCS was investigated **[6-7]**. 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 the necessary requirements 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 **[8-10]**. 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 use of SCC for the production of HCS is evaluated. The present investigation is part of an extensive experimental research program undertaken at King Saud University to examine the structural behavior of full scale HCS members made using SCC under both short and long-term loadings.

II. Experimental Program

The development and casting of the HCS were done with the collaboration of a local precast factory in Riyadh. As part of the ongoing investigation on the structural behavior of HCS using SCC, full-scale HCS were manufactured under close supervision at the plant and tested at the Structural Laboratory of the Civil Engineering Department, King Saud University.

[a] : Graduate student
College of Engineering / King Saud University
Saudi Arabia

[b] Professor
College of Engineering / King Saud University
Saudi Arabia

[c] Assistant Professor
Center of Excellence for Concrete Research and Testing / College of Engineering / King Saud University
Saudi Arabia

A. Material properties

One of the objectives of this study was to investigate the effects of using SCC from locally available material for producing full scale prestressed precast HCS units and to study their structural performance compared to those made using regular extruded dry cast concrete (DCC). The two mixtures utilized different sand-to-total aggregate and chemical admixtures so as to achieve the necessary desired concrete properties for each mix. Both types of mixtures utilized type I Portland cement (Conforming to the requirements of the ASTM C150 standards). Table I shows the chemical composition and physical characteristics of the Ordinary Portland cement Type-I used for the study.

TABLE I: CHEMICAL COMPOSITION AND PHYSICAL CHARACTERISTICS (OPC) TYPE-I*

Chemical Composition	(Mass %)	Physical characteristics
Al_2O_3	5.99	Consistency 23.7%
SiO_2	19.96	Specific gravity 3.15
Fe_2O_3	3.59	Initial setting time 50 mins.
CaO	62.75	Final setting time 350 mins.
MgO	0.59	Blaine Finesses 315 m^2/kg
SO_3	2.73	-
C_3S	50.6	-
C_2S	19.1	-
C_3A	9.8	-
C_4AF	10.9	-
Alkalis	0.2	-

*Yammama cement plant test sheet.

The sieve analysis and the optimized proportion of fine and coarse aggregate are given in Table II. The optimized proportions of the fine and coarse aggregate are proved to provide the best rheological properties. The physical properties of the fine and coarse aggregates used during this study are shown in Table III.

TABLE II: SIEVE ANALYSIS OF AGGREGATE USED

Sieve size (mm)	Passing (%)		
	White sand	Crushed sand	Coarse aggregate (10mm)
25.4	100	100	100
19	100	100	100
9.51	100	100	93.19
4.75	100	97.83	9.08
2.36	99.13	40.23	0.75
1.18	97.72	1.93	0.68
0.6	94.72	0.51	0
0.3	94.94	0.36	0
0.15	76.42	0.19	0
0.075	6.41	0.06	0

The strands used for the experimental study were 12.7mm diameter uncoated seven-wire strands with ultimate strength of 1862 MPa as per specification of ASTM A416/A 416M-12 Grade low relaxation strands manufactured by the national metal manufacturing and casting Factory in Kingdom of Saudi Arabia.

B. Tests on fresh and hardened concrete

The production of SCC is focused on its ability to flow and consolidate under its own weight without external vibration, and the ability to obtain the homogeneity without segregation of the aggregate. The slump flow and V-funnel were used for assessment of the fresh properties of SCC in this study.

TABLE III: PROPERTIES OF AGGREGATE USED

Type of Aggregate	Specific Gravity	Unit Weight (kg/m^3)	Absorption (%)
10mm C.A	2.664	1,586	1.11
Crushed sand	2.669	1,175	1.10
White sand	2.616	1,727	0.71

The compressive strength of the concrete was determined by using concrete cylinders specimens of 150mm×300mm and cubes specimens of 150mm×150mm. The tests were made directly at the time of prestress release, at 7 days and approximately at 28 days. In addition, several core samples of 50-mm diameter by 100mm long were drilled from HCS webs after structural testing, enabling actual strength of the interior regions of the member to be coupled with strength estimation. The cylinders were tested using fully-automatic compression testing machine in accordance with ASTM C39. The modulus of elasticity E_c, for SCC mixtures were experimentally obtained from testing the 150mm×300mm concrete cylinder as per ASTM C 469 at 28 days.

TABLE IV: CONCRETE MIX DESIGN

Element	Size/Type	Components	
		SCC	DCC
Cement type-I	OPC	453 Kg.	420 Kg.
C. Aggregate	20mm	-	342 Kg.
C. Aggregate	10mm	600 Kg.	801 Kg.
Fine aggregate	Crushed sand	460 Kg.	268 Kg.
Fine aggregate	White silica sand	660 Kg.	488 Kg.
Water	-	180 Kg.	142 Kg.
Admixture	-	4.8 Lit. (Glenium 51)	2.87 Lit. (CONPLAST P 211)

C. Fabrication and Casting of HCS units.

Two types of HCS were manufactured on the same bed and cast on the same day. One was part of the manufacturer's regular production using dry cast concrete (DCC) done by a spiroll type hollow-core extruder. The other was done using

self compacting concrete (SCC). Both HCS specimens shared a common geometry and the same depth of 300 mm, and designed with same numbers of strands and web width. Fig. 1 outlines the specified slab geometry for the tested specimens.

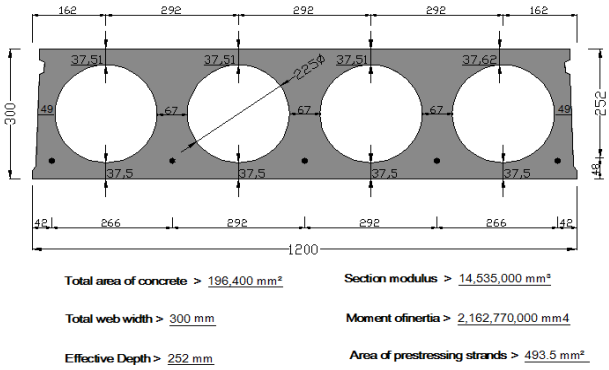


Figure 1. Typical specified slab geometry scheme for the tested specimens

The casting occupied a complete lane in which the prestressed strands were positioned; the extruded machine manufacturing process for producing the dry cast HCS was first formed, and then the SCC was finally cast at the end of the bed so that the vibration during the process of the machine would not affect their fresh properties. It was expected during casting the SCC that the void forms consisting of temporary styrofoams may tend to float up in the fresh concrete due to the high uplift pressure. To prevent this from happening, a hold down system was used which consisted of rigid braces attached at the top of the casting bed. These braces are external to the cross section. Typically, threaded bars are bolted at the top of the braces and extended down to contact 75mm diameter rigid plastic pipe to hold styrofoams in place. The braces are typically spaced every 500mm apart along the length of the casting bed to maintain the web width in place without movement during the casting of concrete. A Schematic of the typical hold down system arrangement is shown in Fig. 2. Figure 3 shows the casting process.

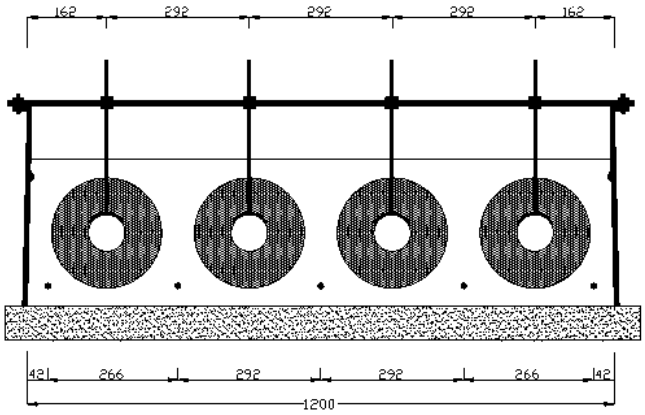


Figure 2. Schematic of the typical hold down system arrangement

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. Development of a practical system to be used for production in the plant is on progress [5].

Figure 3. Preparation and casting procedure.

D. HCS testing set-up

The HCS specimens were tested in four-point bending. The HCS specimens were simply supported over a clear span of 6000mm and shear span of 2100mm. Fig. 4 illustrates a schematic setup for the static testing. The static loading was applied by a closed-loop actuator with a capacity of 1000kN. The controlled actuator holds 300mm thick I-beam stiffened with 10mm thick plates with two movable blocks, each rests on 60 mm diameter rod forming a pinned support at the load point. Layer of gypsum was placed between the slab and the steel pinned support, to prevent load concentrations and to ensure that the load is uniformly distributed across the width of the HCS during loading. Each HCS specimen was instrumented with electrical resistance strain gauges installed on the top concrete surface location across the HCS unite. The displacements at the mid span and mid shear spans were measured by linear variable displacement transducers (LVDTs). In addition, LVDTs were installed horizontally to measure the slippage of some selected strands. All the strain gauges and LVDTs were connected to a multi-channel system for continuous data acquisition. The slabs were loaded gradually to failure under displacing controlled-loading mode and all the measurements were recorded throughout the testing period and the cracking load and the cracks developed in the slabs were monitored.

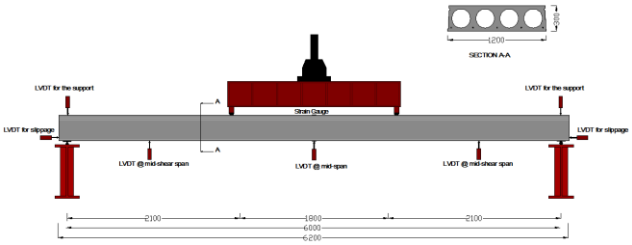


Figure 4. Schematic diagram arrangement for the static testing setup.

III. Results and Discussion

A. Development of SCC mixture

Prior to casting the HCS specimens with SCC, numerous trial mixes were prepared to obtain the fresh concrete properties as well as the target concrete strength. The trial mixes were prepared using different proportions and chemical admixtures. Furthermore, these mixes and their combinations were studied for their fresh and hardened properties. Finally, from the different SCC mixes, the mix designation for SCC mix shown in Table IV, yielded the highest compressive strength with satisfactory fresh properties and was selected for casting the HCS specimens. Fig. 5 illustrates the slump flow of SCC mixes during the development of the SCC.

TABLE V: FRESH PROPERTIES OF SCC FIELD CASTING

Mixture	Truck No.	Type of Test			
		Slump flow		V-funnel (sec)	VSI
		Spread (mm)	T_{500}(sec)		
SCC	T-1	720	4.8	12.5	0
	T-2	740	4.7	12.3	0
	T-3	740	4.8	12.5	0

Figure 5. Development of SCC slump flow (ASTM C1611).

The fresh concrete results during the casting at the precast plant is shown in Table V. From the table, SCC was complying with the requirements found in the European standard [11]. Thus, self-compacting concrete was assumed to having a good consistency and workability after gradually adjusting the chemical admixtures in the mix. The visual inspection of the circular spread of the concrete mixture during the slump flow tests in the field, determined that the SCC mixtures were quite stable and without mortar halo and aggregate segregation in the slump flow spread. Therefore the visual stability index (VSI) value of 0 was assigned to SCC mixtures. The slump flow of SCC was in the range of 690 to 740 mm. However, the casting of the experimental SCC-HCS specimens did not encounter any difficulties and the outcome appeared to be quite satisfactory in terms of surface finishes compared to the DCC-HCS units.

TABLE VI: CONCRETE COMPRESSION STRENGTH

Type of Mix	Cylinder's Age at Testing	Type of Molds	Avg. Strength (MPa)
SCC	Test at 23 HR	Cylinders 150×300	30 MPa
	Test at 7 days	Cylinders 150×300	44 MPa
		Cubes 150×150	50 MPa
	Test at 28 days	Cylinders 150×300	51.2 MPa
		Cubes 150×150	60.4 MPa
DCC	Test @ 23 HR	Cubes 150×150	37.4 MPa
	Test at 7 days	Cubes 150×150	59.4 MPa
	Test at 28 days	Cubes 150×150	65.3 MPa

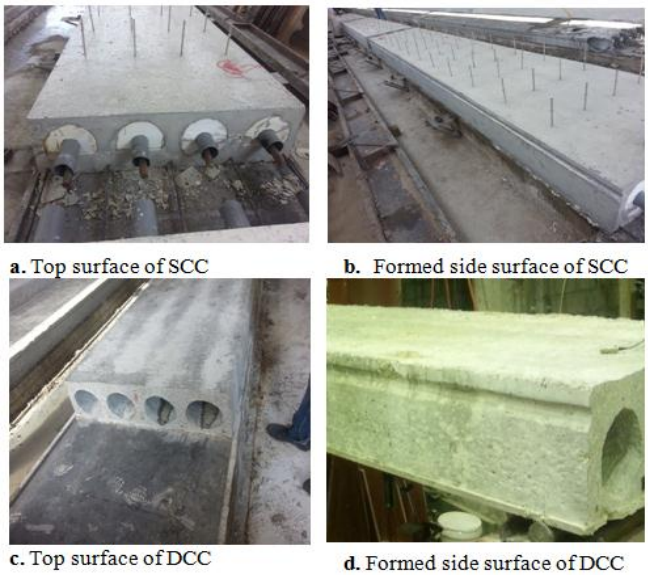
The results of the compression strength and modulus of elasticity are shown in Table VI. The actual compression strength for both SCC and DCC were almost similar at the 28 days. The experimental modulus of elasticity Ec for SCC mixture was 29,730MPa.

B. Visual Evaluation of Cast HCS.

The observation of the hardened concrete of SCC slab indicated less bug holes and surface blemishes when compared with DCC slab. In order to demonstrate this, Fig. 6 illustrate the difference between the formed surfaces of SCC and DCC slabs. For deeper HCS units, however, some longitudinal cracks appeared at the webs and top surface such as shown in Fig.7. The causes of these types of cracks are not fully understood, but they are reported common with wet mixes [12].

C. Behavior of HCS using SCC vs. DCC.

Preliminary results of the ongoing investigation on the structural behavior of HCS using SCC is obtained for two specimens with depth of 300 mm. The applied moment vs. midspan deflection curves are shown in Fig.8. The first part of the curve represents the stiffer behavior of the HCS before cracking. Once tensile cracks accure in the concrete, the slope of the curve decreases, indicating a loss of stiffness. This second part of the curve extends up to yielding of the prestressing strands.



a. Top surface of SCC **b.** Formed side surface of SCC

c. Top surface of DCC **d.** Formed side surface of DCC

Figure 6. Surfaces of SCC compared with DCC.

a. Longitudinal crack in top flange. a. Horizontal crack in webs.

Figure 7. Longitudinal and horizontal cracks in SCC HCS units.

The third part starts after yielding indicating dramatic loss in stiffness. Both tested HCS specimens exhibited a very ductile behavior as indicated by the large deflection and extensive cracking reflected in Fig.9. The stiffer performance of both HCS specimens were slight different from each other. At the same deflection before the cracking moment, it is evident that the stiffness is almost similar for both SCC and DCC slabs. Despite that SCC mixture had higher paste content and lower content of coarse aggregates than the DCC mixture, it showed slight increase in stiffness.

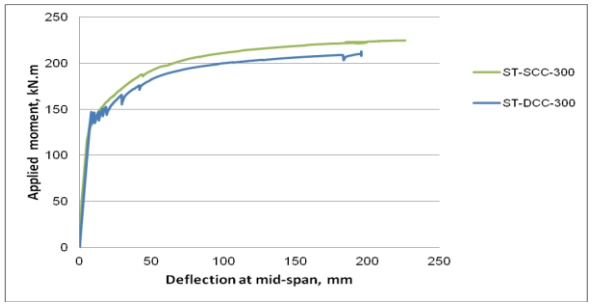


Figure 8. Applied moment vs. deflection response for tested specimens.

Flexure mode of failure was observed for both specimens. The experimental ultimate, cracking moments, and modes of failure of the tested HCS specimens are summarized in Table VII. The given bending moments include the moments due to self-weight of the HCS, which equals to 21.2 kN.m. Fig.9 illustrates the cracking patterns and modes of failure of the tested HCS. The vertical flexural cracking behavior 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 midspan. During testing DCC slab, sudden drops in the load with heard sound then the load recovered again, the drops were reflected in the curve by the observed spikes due to the formation of cracks. For SCC slab, although similar cracks were formed but without any heard sound, the curve appeared to be smooth. The measured deflection using LVDTs for the tested HCS specimens were reliable and showed almost identical results with the actuator piston. Also for both mid shear span LVDTs readings, similar results were observed. Table VII illustrates the LVDTs displacement readings at the mid span and mid shear spans at cracking and failure of the slabs.

a. Flexure failure mode for HCS specimen ST-DCC-300.

b. Flexure failure mode for HCS specimen ST-SCC-300.

Figure 9. Crack pattern and flexure failure for the tested HCS specimens.

TABLE VII: SLAB TEST RESULTS

Slab ID	Failure moment[a] M_u (kN.m)	Cracking moment[a] M_{cr} (kN.m)	Midspan deflection at failure moment (mm)	Midspan deflection cracking moment (mm)	Failure mode
ST-DCC-300	234.2	156.7	196	8.8	F
ST-SCC-300	246	154.6	226	7.6	F

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

Conclusions

Self-consolidating concrete with adequate fresh properties has been developed successfully with locally available materials used to produce HCS at a local precast concrete plant in Kingdom of Saudi Arabia. Further refinement of the production process is underway.

Preliminary results indicate that the flexure behavior of HCS manufactured using SCC is similar to that of conventional dry cast HCS.

Acknowledgment

This paper is a part of a research project funded by King Abdulaziz City for Science and Technology (KACST), Project number AR-34-326. The help of engineers and technicians at the Center of Excellence for Concrete Research & Testing (CoE-CRT) at King Saud University is highly appreciated. We would also like to offer our gratitude to all those individuals at Saif Noman Precast Factory for their cooperation.

References

[1] ACI Committee 318 "Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary (ACI 318R-08)", American Concrete Institute, Farmington Hills, Michigan (2008).

[2] Precast/Prestressed Concrete Institute (PCI) "Design Handbook," 4th Edition, Precast/Prestressed Concrete Institute, Chicago (2004).

[3] Hawkins, N. M. and Ghosh, S. K. "Shear Strength of Hollow-Core Slabs", PCI Journal, Vol. 51, No. 1, pp. 110-114. (2006).

[4] ACI Committee 318 "Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (ACI 318R-05)."American Concrete Institute, Farmington Hills, Michigan.(2005).

[5] Durham, J. Taylor, H. Maydew, N.. "Improvements in or relating to hollow core slabs" Canadian Patents Application CA 2797337.(2011).

[6] Palmer, K. D. and Schultz, A. E. "Experimental investigation of the web-shear strength of deep hollow-core units", PCI Journal. Vol. 55, No. 2, pp. 84-105.(2011).

[7] Cuenca. E, Serna. E " Failure modes and shear design of prestressed hollow core slabs made of fiber-reinforced concrete" part B. 2012.

[8] Ouchi, M, Nakamura, S, Osterson, T., Hallberg, S. and Lwin, M. "Applications of Self-Compacting Concrete in Japan, Europe and the United States" ISHPC,p 2-5. 2003.

[9] Mehta PK, Aitcin "PC.Principles underlying production of high performance concrete. Cement Concrete Aggregate".1990; 12(2):70-80

[10] Okamura H. Self compacting high-performance concrete, in Japanese Tokoyo: Social System Institute; 1999.

[11] EFNARC, the European Guidelines for Self Compacting Concrete,2005.

[12] Precast/Prestressed Concrete Institute (PCI) "Fabrication and shipment cracks in prestressed hollow core slabs and double tees", PCI Journal of prestressed concrete institute, Vol. 28, No. 1.(1983).