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Implementation of HSSCC in Pre- and Post-Tensioned Concrete members

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ABSTRACT

To achieve acceptance for use high strength self consolidating concrete, HSSCC in pre and post tensioned elements, this study was conducted. The aim was to investigate the mechanical properties effects on new concrete generation (HSSCC). For the designed HSSCC mix, the fresh properties (Slump Flow, L-box, V-funnel and J-ring tests) as well as the hardened properties such as compressive and flexural strength, modulus of elasticity, shrinkage and swelling were measured at different ages. In order to establish the adequacy of HSSCC for pre and post tensioned structural applications two T-beams of 9 m length pre-tensioned concrete with constant tendon eccentricity and two post-tensioned concrete continuous slabs of 7.5m length with variable eccentricity were constructed and load tested. With the obtained range of results, it was found that the HSSCC will consolidate exceptionally well under its own weight even for elements containing high amounts of reinforcement.

INTRODUCTION

The development of self consolidating concrete, SCC started in Japan (Tokyo University) in the mid 80-ies with the aim to reduce durability problems in complicated and heavily reinforced concrete structures due to lack of skilled workers and a poor communication between designers and construction engineers [1]. Even though conventional (vibrating) concrete previously (and still today) in some applications was cast without any compaction, this new concrete was deliberately designed to be able to fill every corner of the form and encapsulate all reinforcement with maintained stability only under the influence of gravitational forces.

Since that time, Japanese contractors have used SCC in different applications. In contrast with the Japan, research in Europe, American and Iran started latter[2-4]. The advantageous of SCC offers many benefits to the construction practice; the elimination of the compaction work results in reduced costs of placement, equipment needed on constructions, shortening of the construction time and improved quality control.

With the rapid development of concrete technology in recent decades, for traditional (vibrated) concrete, higher-strength concrete, HSC can be produced much more easily than before, where as considering SCC, reaching high strength self consolidating concrete, HSSCC is a new type of concrete introduced in more recent years. Therefore the author of this paper was thinking to use HSSCC in prestressed concrete elements, but the author was worried about the amount of losses in such elements. He produced and studied[5] experimentally, the engineering properties of HSSCC (a concrete with a 28 days compressive strength more than 55 MPa), and investigate its engineering properties such as compressive and tensile strength, modulus of elasticity, shrinkage and swelling values at short and long term ages. The author concluded that while producing performance SCC, it is possible to reduce the amount of shrinkage and swelling by 69 and 30% respectively when compared with ordinary SCC. In other words, by applying high strength SCC in prestressed elements, it is possible to reduce the total amount of prestress losses. Therefore as a general conclusion, current knowledge of HSC and HSSCC shows that there are definite advantages, both technical and economical in using a higher concrete strength (i.e., traditional concrete or SCC) in reinforced concrete structures. Greater strength per unit cost and per unit weight, increased modules of elasticity and reduced shrinkage and creep are some of these advantages. The theoretical and experimental research is required to understand the effect of concrete strength on SCC.

To achieve acceptance of HSSCC for use in prestressed concrete bridge constructional elements a research program was conducted at Kerman University under the author supervisor[6] (at starting time of this study[6], no literature on the monitoring of bridge girders with HSSCC used in prestressed SCC, PSCC could be found). However, now a day, the literature review is indicating that very rare research report is available[7-13] on PSCC and therefore an urgent research in this field is needed.

This report evaluates the performance of precast pretensioned T- bridge beams (L=9000mm, b_f =535mm, b_w =195mm, t_f =110mm, h=710mm) and unbounded posttensioned continuous slab decks (L=7.5 m, b=1 m, h=0.2 m) using HSSCC. The SCC was examined experimentally in such constructional elements.

PSCC TEST BEAM DETAILS

Four-point bending flexural tests were conducted up to failure on PSCC T-beams. The length, width, and depth ($l \times b_w \times b_f \times d$) of concrete beams were kept as 9000×195×520×668mm. Each prestressed concrete beam was reinforced longitudinally by two types of steel bars (i.e., ordinary bars and prestressing strands) for tension and only ordinary steel bars for compression along with 10-mm-diameter bars at spacing of 90 mm center-to-center for shear reinforcement. The spacing of stirrups and maximum and minimum reinforcement ratios are in accordance with the provision of the American Concrete Institute, ACI[13] standards. The details of the test specimens are shown in Figure 1.

Figure 1 – Details of PSCC beams tested

MEASURMENT AND TEST SCHEME

The beams were loaded in four-point bending to failure with a clear span of 8700 mm, and loading points were located at 1400 mm apart, so that one loading point is on mid-span location and the other one is located 1400 mm away towards left as shown in Figure 2 (this type of load arrangement is same as one recommended by national Iranian code[14]). The locations of measuring sensors including strain gauges and linear variable differential transducers (LVDTs) are shown in Figure 3. The electrical steel strain gauges were attached on the surfaces of internal prestressed strands and reinforcing bars (Figure 3a). At different position of PSCC beams, the demec and electrical gauges were also attached along the height of the beams to measure the concrete strains (Figures 1, 3); these values can be used to find out the strain distribution and the moving neutral axis depth of the PSCC beams tested. Also to measure the load, the load cell was placed on top of the beam (Figure 3).

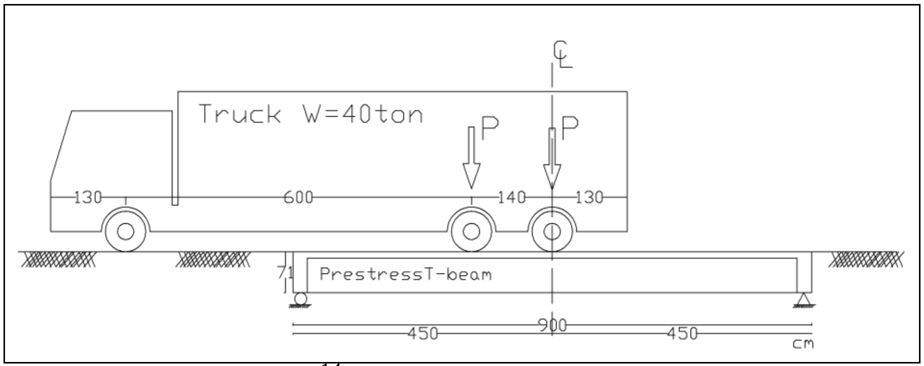

Figure 2 – Loading arrangement[14]

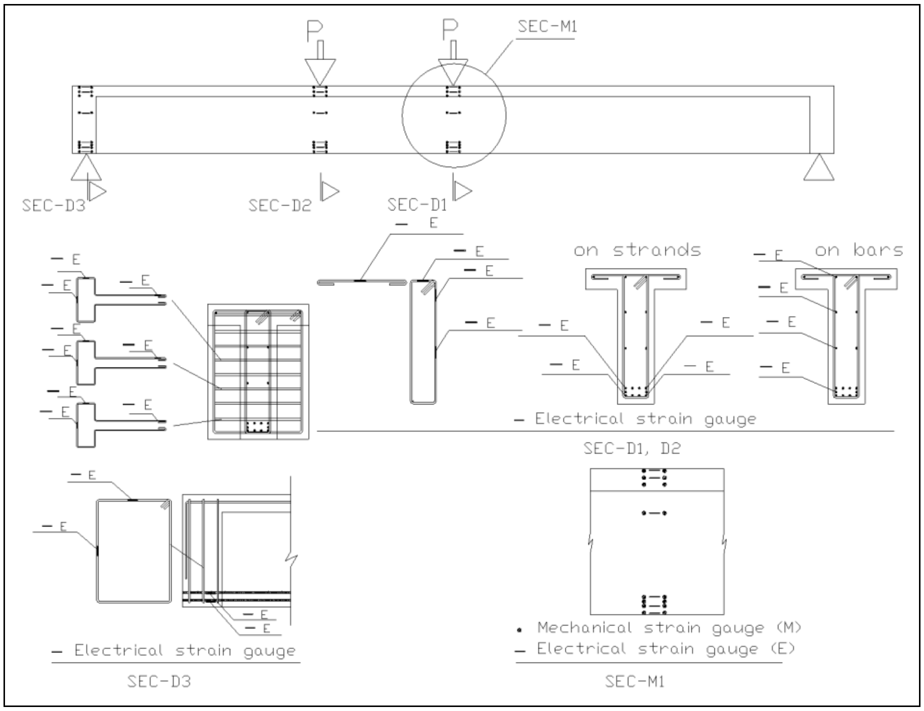

Figure 3(a) – Position of electrical and mechanical strain gauges at sections D1to D3

Figure 3(b) – Close view of details D1, D2

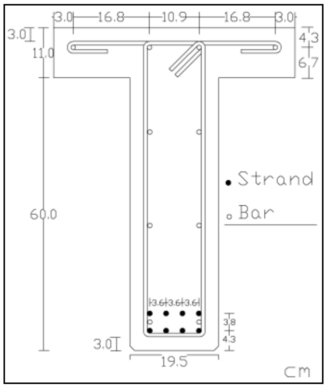

Figure 3(c) –T-beam section

The load was applied step-by-step up to failure in a load control manner of test beams. Different types of electrical resistance disposable strain gauges (for steels and concrete surfaces), manufactured by TML Measurements Group (Japan), and vertical deflections (upward and downward) were measured using linear variable differential transducers (LVDTs) manufactured by TML. The positions of the strain gauges and LVDTs are shown in Figures 1 and 3.

The strain gauges, LVDTs, and the load cell were connected through a data acquisition system to a computer and the data was recorded in the computer.

Unbonded Post-tensioned Test Slabs Details

Four-point bending flexural tests were conducted up to failure on three unbounded posttensioned SCC, UPSCCCS bridge slabs. Each prestressed concrete slab was reinforced longitudinally by two types of steel bars (i.e., ordinary bars and prestressing strands) for tension and only ordinary steel bars for compression (for slab1 and slab2), along with shear reinforcement in slab3. The spacing of stirrups and the variable amount of reinforcement ratios are in accordance with the provision of the American Concrete Institute, ACI-08 standard[13]. The details of the test specimens are shown in Table 1 and Figure 4.

Table 1: Characteristics slabs

Specimens	Characteristics specimens								
	Reinforcment ratio	Number of strand	Diameter of strand (mm)	$\rho_p = \frac{A_{ps}}{bd_p}$	$\rho = \frac{A_s}{bd}$	$\rho' = \frac{A'_s}{bd}$	d_p (mm)	d (mm)	d' (mm)
SCC slab1	ρ_{min} Bottom (Fig.1a)	6	9.54	0.001936	0.002402	0.002402	175	180	25
SCC slab2	ρ_{min} Top and bottom (Fig.1b)	4	11.11	0.001746	0.002402	0.002402	175	180	25
SCC slab3	$0.25\rho_b$ Top and bottom (Fig.1c)	4	11.11	0.001746	0.01005	0.01005	175	180	25

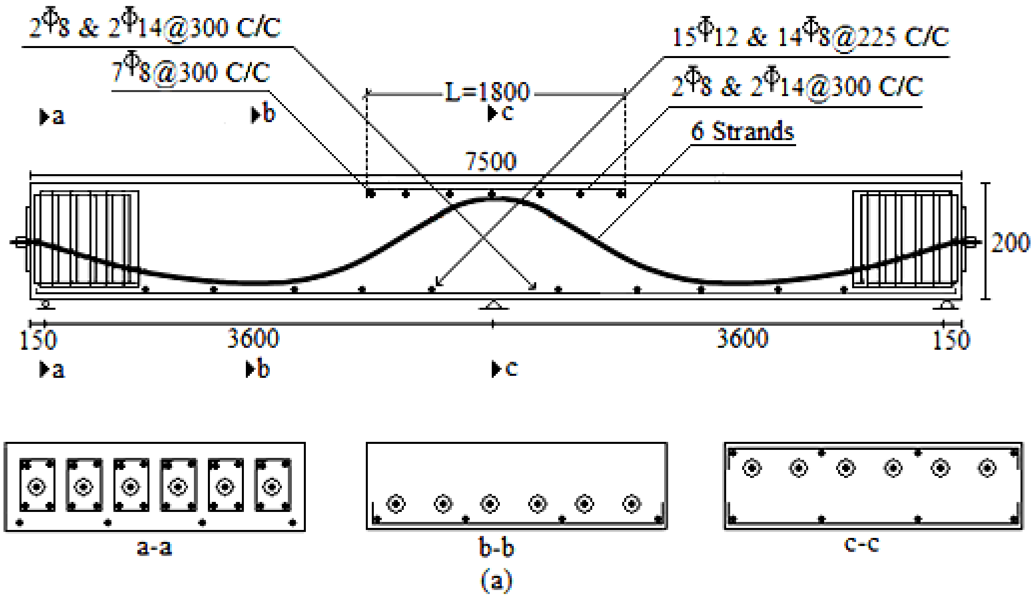

Fig. 4 – Details of UPSCCCS slab1 tested

MEASURMENT AND TEST SCHEME

The slabs were loaded in bending to failure with each clear span of 3600 mm, and loading points were located at 2800 mm apart, so that each loading point is at 1400 mm from central support (i.e., the point of maximum negative moment) as shown in Figure 5. The locations of measuring sensors including electrical strain gauges and linear variable differential transducers (LVDTs) are shown in Figure 5. The electrical steel strain gauges manufactured by TML Measurement Group (Japan) were attached on the surfaces of internal post-tensioned strands and reinforcing bars. At different position of slabs, the demec and electrical strain gauges were also attached along the height of the slabs to measure the concrete strains (Figure 5); these values can be used to find out the strain distribution and the moving neutral axis depth of the slabs under the load test. In addition, to measure the applied load, the load cells were placed on top and underneath of the slab (Figure 6).

The load was applied step-by-step up to failure in a load control manner of test slabs, and vertical deflections (upward and downward) were measured using LVDTs manufactured by TML. The strain gauges, LVDTs, and the load cells were connected through a data acquisition system to a computer and the data was recorded in the computer.

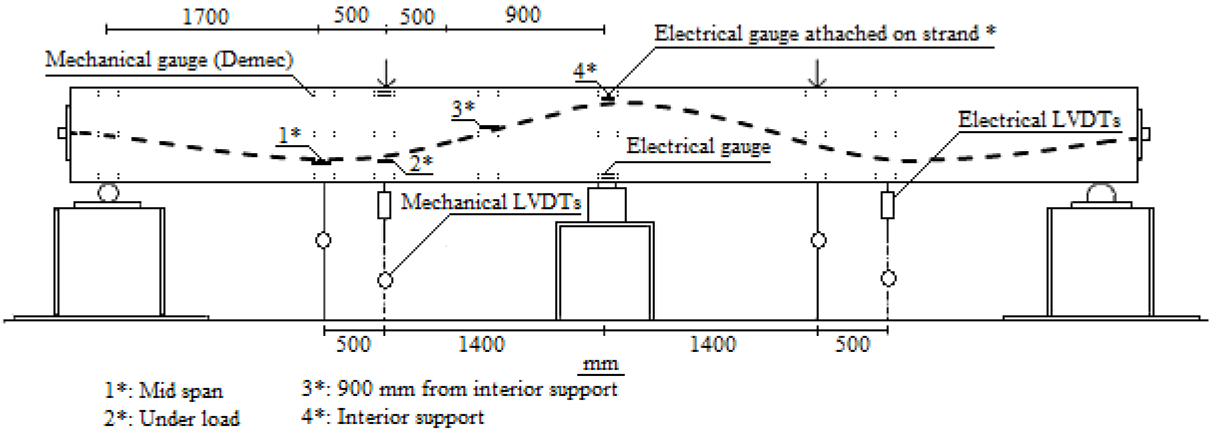

Fig. 5: Position of strain gauges on slab

Fig. 6: A typical tested slab (slab1)

MAJOR TEST VARIABLES AND MIX PROPERTIES

A programmed was scheduled to understand the effect of high strength SCC, HSCC on pretensioned T-beams and UPSCCCS by testing of two (PSCC1 and PSCC2) and three beams and slabs (i.e., UPSCCCS1, UPSCCCS2 and UPSCCCS3) respectively. The main test variables considered in the present study include the effect of use of high strength on SCC in fresh phase, and experimental ultimate moment on constructed elements.

MATERIAL PROPERTIES AND CASTING PROCEDURES

At present three different concepts for the production of SCC are distinguished. In contrast to normal concrete (NC) for the production of SCC the powder content is increased (Powder-Type), a viscosity-agent is used (Viscosity-Agent-Type) or both possibilities are combined (Combination-Type). Whereas here, a Powder-Type was chosen. Based on these results, the following HSSCC mix was suggested by the author with some modifications made on[5], and its particle aggregate size distribution and its mix fresh properties are summarized in Tables 2 and 3.

Table 2– Particle size distribution of coarse aggregates and sand (by mass)

Screen size	Coarse aggregate	Screen size	Fine aggregate
(mm)	(% passing)	(mm)	(% passing)
4.75	100	4.75	98
2.36	-	2.36	84
1.18	-	0.15	2.5

Table 3– Properties of HSCC Mix for 1 m^3

Material	HSCC
Cement (N)	500
Microsilica (N)	510
Water (N)	2000
LSP (N)	1000
Coarse Aggregate (N)	8000
Fine Aggregate (N)	8400
PCE (Liter)	8.0
W/CM*	0.39

* CM: Cement+MS

FRESH AND HARDENED PROPERTIES OF HSSCC SPECIMENS

The tests on fresh properties of HSSCC mixtures were carried out and the average range of results of fresh and hardened properties of concrete are presented in Table 4.

For tested elements, the flow ability of SCC was determined by the slump flow test. The slump of SCC ranged between 650-700 mm satisfied the recommended slump flow for SCC. The deformability of SCC through and ease of flow through restricted area without blocking were evaluated by the V-funnel[15] and L-box[16] tests. The flow ranged between 3.2-3.9 seconds satisfied the requirement of maximum 6 seconds recommended for SCC. The L-box index for SCC ranged between 0.70-0.77 with a mean value of 0.75 (close to the recommended range of 0.8 to 1.00 for a good SCC) was considered satisfactory. For hardened concrete, the compressive strength of SCC was determined by 100x100x100 mm control cubes for each batch, and test results of three cubes for each batch of concrete were used to get the mean compressive strength at different ages (see Table 4).

Table 4: Test results of hardened and fresh concrete

Characteristics of hardened and fresh concrete								
Specimen	f_{ci}* *(MPa)*	f_{cu}** *(MPa)*	L- box		V-funnel t (sec)	J- ring		Slump flow D (mm)
			h_1/h_2 (mm)	t (sec)		$h_2 - h_1$ (mm)	D (mm)	
PSCC1	54.0	65.1	0.83	0.40	6.5	13.0	750	760
PSCC2	51.1	63.2	0.93	0.30	7.2	11.0	760	750
UPSCCCS1	60.0	65.0	0.88	0.39	6.3	12.5	760	770
UPSCCCS2	59.0	67.7	0.83	0.40	6.5	13.0	750	760
UPSCCCS3	61.0	65.8	0.91	0.37	7.5	12.0	770	780

* Average compressive cube strength at transfer

** Average compressive cube strength at 28 days

With the obtained range of results in fresh phase, it was found that the HSSCC was consolidate exceptionally well under its own weight even for PSCC2 beam which is contained more reinforcement than the PSCC1 beam and for end block regions of slabs having a more congested reinforcement compare to the other part of slabs. For each mix, the concrete cube specimens were made at the time of casting, and three cubes were tested in compression at the age of transfer of prestressing strands and another three at slab testing age (Table 4). The average of three compressive cube results was considered. The 28-days average compressive cube strength (f_{cu}) was 66.2 MPa. The relationship of cylinder strength (f'_c) and cube strength is 56.2 MPa (f'_c=0.85 f_{cu}). The volume of concrete was about 1.5 m^3 for each slab and fresh and hardened concrete samples.

Depending on the diameter of the steel bars three different types of electrical strain gauges for prestressing strands and ordinary steels mounted at specific locations to monitor the development of conventional and prestressing steel strains throughout the loading history [6,12].

Observations during construction of T-beams girder and slabs

The jacking operations of strands, the mix preparation of SCC and concrete casting all were done in a private precast concrete company named as ATEBAN which is located in the city of Kerman (i.e., South of Iran). The prestressing jack prepared from CCL Company of England and that pulled strands one by one on 3 steps for each strand. The members were then transferred to the Kerman University lab for testing. Pouring of concrete to be fulfilled by a mixture and value of concrete was about 1.9 and 1.5 m^3 for each girder and slab respectively and fresh and hardened concrete samples. The close observations were indicating that before and during the transfer of prestressing force to the girders, there was no visible crack, neither on the flange surface nor along T-beams length. However, the cracks were observed a day after the beams were placed on four supports in concrete precast company before delivering beams to the University for testing purposes.

Also the close observations were indicated that before and during the transfer of prestressing force to the slabs, there was no visible crack for slab2 and slab3 but for slab1 after transfer of prestressing force, one visible crack of 0.12 mm width was observed on bottom at central support of slab. However, the cracks were observed a day after on slab2.

EXPERIMENTAL PROGRAM

The load-deformation behavior of members loaded to failure the, ultimate moment and ductility is investigated and reported [6,12]. However, here the mode of failure and experimental ultimate moment of tested members are reported. The failure types and the typical crack patterns occurred on the specimens during the tests are illustrated in Figures 6-11.

Figure 7 – Failure of PSCC1 T-beam

Figure 8 – Failure of PSCC2 T-beam

Fig. 9 – Rupture of tow tendons in SCC slab1

Fig. 10 – Failure mode of slab2

Fig. 11 – Failure mode of slab3

It is clear that for the tested T-beams and slab1 and slab2 failure was by crushing of the concrete, where as, for slab3, the failure occurred by shear (Fig. 11).

Experimental ultimate moment

For constructed elements the experimental ultimate moment values are obtained by test and the results are shown in Table 5.

Table 5 – Experimental values of ultimate moment

Specimen	Experimental moment
PSCC1	823.5
PSCC2	841.8
UPSCCCS1	80.1
UPSCCCS2	32.2
UPSCCCS3	117.3

The comparison of results presented in Table 5, cause to conclude that, the performance of the pretensioned and post-tensioned SCC constructed members, under ultimate moment is comparable to that of the conventional prestressed concrete members, and therefore similar calculations suggested by these codes for conventional concrete can be used for the SCC.

CONCLUSIONS

The implementation of high strength self-consolidating concrete, HSSCC for Pre tensioned T-beams and unbonded post tensioned concrete continuous slabs was investigated. The study examined the material in a plastic and hardened state. The goals of the research were to assess the performance of HSSCC use in pre tensioned and post tensioned elements. These goals were achieved through a series of material tests, T-beams and continuous slabs construction, and through ultimate load testing.

With the obtained range of results in fresh phase, it was found that the HSSCC was consolidate exceptionally well under its own weight even for PSCC2 beam which is contained more reinforcement than the PSCC1 beam and for end block regions of slabs having a more congested reinforcement compare to the other part of slabs. Based on experimental data obtained from this investigation, it is concluded that, the performance of the pre tensioned members and unbonded post tensioned HSSCC constructed slabs, under ultimate moment is comparable to that of the conventional elements, especially the mode of failure and ultimate load. In other words, such elements with HSSCC are safe for this reason.

The material test results (strands and HSSCC) indicate that they should perform well when used in full scale slabs, as no sign of horizontal cracks in the concrete-steel bond region (in the tension zone in the vicinity of the tension steels) were observed. In other words, the bond between the steel and the surrounding concrete for HSSCC was excellent. Also, the failure of a concrete cover along the tensile reinforcement wasn’t observed.

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