DEVELOPMENT LENGTHS OF HIGH STRENGTH SCC BEAMS

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ABSTRACT

Self-Consolidating Concrete (SCC) is a type of concrete that can be placed without consolidation and is beginning to be widely accepted. The constituent materials of SCC differ very little from conventional concrete. The constituent materials are the same, but SCC typically contains more fine aggregate and cement, but less coarse aggregate. These differences may affect the length of prestress transfer and flexural bond performance for SCC specimens when compared to conventional concrete specimens. This research program compares the measured development lengths of SCC members to those of conventional high strength concrete. A total of 19 beam specimens containing two 0.60 inch diameter prestressing strands were produced. The beam specimens measured 6.5 in. by 12 in. and were 18 feet in length. Thirteen beams were cast with SCC while the remaining 6 beams were cast with a high strength concrete mixture. The targeted release strengths for all girders were 7000 psi and the 56 day strength for all girders was 12,000 psi. The development lengths for all beams were between 30 and 40 inches.

Keywords: SCC, Development Length, Prestress Losses, Prestressed Bridge Girders

INTRODUCTION

Self-consolidating concrete (SCC) is a category of high performance concrete developed in Japan in the 1980s that exhibits extremely high deformability in the fresh state and can be placed and compacted without vibration[1]. SCC was developed in order to reduce the amount of labor required for placement and finishing of the concrete. The high deformability allows for placement of the concrete through large amounts of reinforcement without the skilled workers necessary for vibration[2]. SCC has therefore seen extensive use as material for architectural projects, but it also has a great deal of potential for use in highly congested members with narrow cross-sections, such as prestressed beams.
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This research program measured the development lengths for beams cast using SCC and compared these development lengths to those determined from beams cast with conventional high strength concrete. The primary objectives of this program were to determine the effect of using SCC on development length of prestressed concrete beams, if the ACI/AASHTO equations used to estimate development length are applicable to beams cast using SCC, and what modifications might be made to these equations.

BACKGROUND

Numerous research programs concerning the bond characteristics of reinforcing strand in prestressed concrete members have been conducted beginning with Janney's work in the 1950's[3]. Much of this previous research used conventional concrete mixtures; but, the following discusses some of the recent research work on transfer and development length of SCC members.

Hamilton et al. conducted structural tests on six, AASHTO Type II girders. Three girders were cast using SCC and three using a conventional mix. Two of the beams from each mix were cast with a composite section to simulate the action of a bridge deck. The other beam from each mix was tested without this composite section. Structural tests were performed on the beams. Two beams were tested for shear behavior, two beams for combined shear and flexure, and two beams for strand slip failure. All of these failure modes were used to compare the behavior of SCC girders in relation to conventional girders. No significant differences were noted in flexural capacity, shear capacity, or web cracking between the SCC and conventional beams. It was noted that abrupt prestress transfer may have contributed more to beam failure than concrete type for strand slip failures[2].

Burgueno and Haq evaluated the transfer and development lengths of 0.5 in. diameter seven wire prestressing strands on small scale T-beams. Three different SCC mixtures were used that bounded the approaches to achieve SCC behavior as well as a conventional mixture for comparison. All mix designs had a design compressive strength of 7000 psi and entrained air content of 6 percent[4].

Transfer length was measured using both measured strand slip and measurement of concrete strain at the level of the steel. Two tests for development length were conducted on each beam specimen for a total of four tests for each mix design. An iterative approach was used to determine flexural bond length by bounding the flexural and bond-slip failure modes. Transfer lengths for the SCC mixtures were found to be within the bounds of the ACI/AASHTO equation. SCC mixtures with a moderate w/c ratio containing moderate amounts of admixtures performed closer to conventional concrete than did those containing high fines or high aggregate. These had lower bond strengths and longer transfer lengths than conventional concrete. Development length tests were not complete at the time this article was published[4].

Hegger et al. examined the bond strength and shear capacity of SCC members in order to collect information on the structural behavior of SCC beams. Tests for transfer length were conducted using 6, 6 ft long, rectangular test specimens containing 0.5 in. 7 wire prestressing strands. A prestress of 185 ksi was used, and strain was calculated using DEMEC points on the concrete surface. Prestress was released gradually. It was noted that prestress transfer length was affected by the type of concrete mixture with some increase due to reduced bond strength. However it was observed that the current calculations for transfer length are valid for SCC mixtures as they contain adequate safety margins[5].

Larson et al. studied the material and bond characteristics of prestressed bridge girders made with self-consolidating concrete. Initial large block pullout tests using 0.5 in. strand and SCC indicated that specimens made using SCC had smaller first slip and ultimate load values than specimens made with conventional concrete. These small loads indicated poorer bond strengths in the SCC specimens. This indicated that full-scale development length tests were necessary[6].

Eleven specimens containing a single strand were tested for development length. These specimens were used to evaluate two embedment lengths. Two cross-sections were used in these tests. The first was an 8 in. x 12 in. cross-section with the strand at a depth of 10 in., and the second was an 8 in. x 24 in. cross-section with strand located 22 in. from the bottom. These larger beams were used to simulate the “top bar effect” where there is more than 12 in. of concrete below the reinforcement. These beams also were reduced to a total depth of 12 in at mid-span so that results could be compatible. Neither of these two sections contained shear reinforcement. Multiple strand T-beams were also cast for evaluation of development length of multiple strands with close spacing. These beams had 5 bottom strands at a depth of 19 in., a total height of 21 in., and a compression flange with a width of 36 in. Shear reinforcement consisted of 0.5 in. diameter stirrups on 6 in. centers. Larson et al. concluded that the current equations for development length were adequate for this SCC mixture and these beam geometries. All beams failed in strand rupture at both the 100% and 80% values of development length. Transfer lengths were within the AASHTO and ACI requirements as well[6].

Girgis and Tuan investigated the bond strength of SCC mixtures using Moustafa pullout tests on 0.6 in. prestressing strands. In addition to the pullout tests, three concrete bridge girders were cast using the two SCC mixes and the conventional mix. Transfer lengths were measured for each of these girders using DEMEC points to calculate the strain in the steel. It was concluded from this study that the bond strength with SCC is adequate. However, viscosity modifying admixtures (VMA) in SCC may reduce early compressive strength and bond strength with prestressing strands which can lead to longer transfer lengths. Transfer lengths can be up to 50 percent longer for SCC members. These transfer lengths indicate that SCC has a lower early bond strength, but the Moustafa pullout tests failed to reveal this. This may be a result of the same stress not being present in the test as is in the actual member. However, SCC had higher bond strength at 28 days than conventional concrete, so shorter development lengths may be possible for SCC. It was shown through all pullout tests that smaller bar diameters had higher bond strengths[7].

Since self-consolidating concrete is a fairly recent innovation in the concrete industry, less research has been done on the characteristics of prestressed members cast with SCC. Most research programs have determined that some differences do exist between SCC members and conventional members, but that the equations are conservative enough to handle the differences. However, this research is still in progress and fully comprehensive data are not yet available.

EXPERIMENTAL PROGRAM

The research program consisted of casting 18 prestressed beams that contained two 0.60 in. diameter, low relaxation, prestressing strands. The development length was measured for each beam. The cross-section for the beams is shown below in Figure 1.

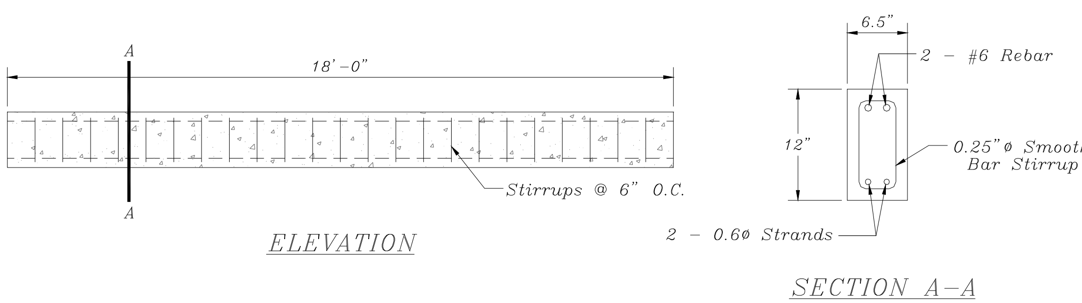

Fig. 1 Typical Beam Specimen Detail

Thirteen of the 19 beams were cast with two SCC mixtures, and the remaining 6 were cast using a conventional high strength concrete (HSC) mixture. All three mixtures had target initial compressive strengths at release of 7 ksi and 28 day compressive strengths of 12 ksi. The SCC mixtures use proportions similar to those outlined by Khayat.[8] The three mix designs are shown below in Table 1. The development of the SCC mixtures and the properties of these mixtures (fresh and hardened) was discussed in greater detail in an earlier paper by the authors[9].

Table 1. Mix Designs

Materials	HSC	SCCI	SCCIII
Cement (lb/yd^3)	900	950	808
Fly Ash (lb/yd^3)	0	0	142
Coarse Aggregate (lb/yd^3)	1800	1350	1350
Fine Aggregate (lb/yd^3)	1207	1474	1400
Water (lb/yd^3)	234	285	304
Water/Cement Ratio	0.26	0.30	0.32
ADVA 170 (fl. oz/cwt)	9 – 10	7.8 – 14.5[a]	8 - 9[a]
ADVA 555 (fl. oz/cwt)	0	0 - 3[a]	0
VMAR-3 (fl. oz/cu. yd)	0	0 – 30.4[a]	0 – 30.4[a]

Note: 1 lb. = 0.454 kg; 1 oz = 29.57 ml

[a] Dosages of admixtures varied due to variations in ambient air temperatures during time of batching for individual mixes.

Each beam specimen was cast using two batches. This was due to the limited size of the laboratory mixer (~ 9 ft^3). Initially, the first batch would be placed into the formwork after the strands were tensioned. This batch would on average fill the formwork from end to end to a depth of 7 inches. This ensured that all the concrete within the localized area of influence for both of the strands would have the same concrete properties. Immediately after the first batch was emptied out of the mixer, the second batch for each beam specimen would be batched and placed in the form. The time between the final placing of the first batch to initial placing of the second batch into the formwork was within 45 minutes for all specimens. Additionally, limited internal vibration was used in some instances in which ambient air temperatures would cause the top layer of the first mix within the formwork to form a thin crust. This procedure would ensure that both batch 1 and batch 2 for the beam specimen would be thoroughly mixed, and protect against the formation of cold joints within the beam.

Each beam was allowed to cure 1 day within the formwork until the mixtures achieved the target release strengths. Once the initial readings were taken and the concrete had reached the desired strength, the strands were released gradually. Each gradual release was accomplished by slowly relieving the pressure simultaneously in each of the hydraulic rams used during the tensioning process.

BEAM TESTING

Evaluation of development length for the selected beams was performed using flexural load tests. A single point load was applied to the beam at a specified distance from the beam end, and the beam was loaded to failure. The location of the load was based on the embedment length, L_E. The embedment length is defined as the distance from the end of the beam to the section that can develop its full strength when the load is applied. This section is also known as the critical section. By varying the location of the point load, upper and lower bounds for development length can be established. The behavior of the strands at failure is used to determine whether the tested embedment length is longer or shorter than the development length. If strand slip occurs before the nominal moment is reached, then the embedment length is shorter than the development length and a longer embedment length is used for the next test. Conversely, if no strand slip is detected after the beam achieves the nominal moment, the embedment length is greater than the development length and a shorter embedment length is used for the next test. For the case where the embedment length is equal to the development length, failure by flexure occurs at the same time as strand slip after the nominal moment is reached.

TEST SETUP

The flexural tests used a setup consisting of a simple span beam loaded with a single concentrated load. The beam was placed within a testing frame and load was applied using a hydraulic jack. The load frame setup is shown in Figure 2.

Fig. 2 Load Frame

INSTRUMENTATION

The applied load was measured using a pressure transducer connected to the hydraulic lines of the hydraulic jack. Applied loads were continually monitored using the data acquisition system while pressure was applied with a hand pump. Displacement was measured at the point of load. Linear voltage displacement transducers (LVDTs) were used to measure strand slip. One LVDT was attached to each strand at the end of the beam being tested. Readings from the LVDTs were continuously monitored using the data acquisition system in order to detect the beginning of any strand slip. Strand movements as small as 0.001 in. could be detected by the LVDTs.

CONCRETE PROPERTIES

The measured fresh and hardened properties for each beam are shown below in Tables 2 through 4. For all beams except for SCCI – 1 and SCCI – 2, two values are reported for each fresh concrete property. These two values represent the slump flow, T_{20} (time for the spread to reach 20 inches), and VSI (visual stability index) for each of the two batches used to cast the beam. For beams SCCI – 1 and SCCI – 2, the three values for each of the fresh concrete properties represent each of the three batches needed to cast the beams.

The compressive strength results shown in Tables 2 through 4 represent the average of three cylinder tests from each batch used to cast the beam. The first column, f'_{ci}, is the average concrete compressive strength at release which was at approximately 24 hrs after casting. The second column, f'_c, is the average 28 day strength of the concrete, and the final column, f_{cld}, is the concrete's compressive strength at the time the development length was measured. Since prestress losses were measured for some of the beams, the time at which development length was tested ranged from 3 months to 12 months after casting. This nine month time frame accounts for the range in compressive strength results that were present when the flexure tests were conducted.

Table 2. Concrete Properties of SCCI Beams

Beam ID	Fresh Concrete Properties			Concrete Strengths		
	Slump Flow (in.)	T_{20} (sec)	VSI	f'_{ci} (psi)	f'_c (psi)	f_{cld} (psi)
SCC I – 1	26.0 26.0 27.0	4.0 3.0 4.0	1.0 1.0 0.5	8,520	13,870	16,000
SCC I – 2	30.0 25.0 24.0	3.0 4.0 3.4	0.5 1.0 1.0	8,700	14,420	17,390
SCC I – 3	27.5 30.0	2.8 2.0	1.5 1.5	7,220	11,320	13,350
SCC I – 4	30.0 28.0	2.0 2.8	1.5 0.5	5,900[a]	12,150	12,980
SCC I – 5	30.0 31.0	2.6 2.2	--- ---	7,430	11,420	13,550
SCC I – 6	28.5 27.0	3.3 2.8	--- ---	7,330	11,730	14,000
SCC I – 7	27.0 25.5	3.9 4.2	0.5 0.5	8,450	11,000	12,250
SCC I – 8	29.5 29.0	4.6 2.5	1.5 0.5	8,550	12,030	14,640
Average	-	-	-	7,760	12,240	14,270

Table 3. Concrete Properties of SCCIII Beams

Beam ID	Fresh Concrete Properties			Concrete Strengths		
	Slump Flow (in.)	T_{20} (sec)	VSI	f'_{ci} (psi)	f'_c (psi)	f_{cld} (psi)
SCC III – 1	28.5 27.5	1.9 1.3	0.5 0.5	7,080	10,920	13330
SCC III – 2	26.0 25.0	1.6 1.9	0.5 0.5	6,880	10,260	13140
SCC III – 3	29.0 25.5	1.9 1.9	1.0 0.5	7,080	10,340	13170
SCC III – 4	26.5 29.0	2.4 2.5	1.0 0.5	7,450	10,800	13790
SCC III – 5	24.0 25.0	3.2 2.4	0.5 0.5	8,230	12,880	12550
Average	-	-	-	7,540	11,420	13,200

Table 4. Concrete Properties of HSC Beams

Beam ID	Fresh Concrete Properties	Concrete Strengths		
	Slump (in.)	f'_{ci} (psi)	f'_c (psi)	f_{cld} (psi)
HSC – 1	9.75 7.50	8,830	12,630	15,390
HSC – 2	9.75 10.00	8,840	12,690	14,420
HSC – 3	9.75 9.25	9,920	12,510	13,430
HSC – 4	9.75 10.00	9,850	12,670	12,670
HSC – 5	10.50 7.00	8,270	10,700	13,730
HSC – 6	9.75 9.25	9,580	13,100	14,240
-	-	9,220	12,380	13,980

DEVELOPMENT LENGTH RESULTS

As has been previously mentioned, experimental determination of development length is an iterative process. Beam tests were performed in order to obtain a range of embedment lengths where the development length is estimated to be. The result of this process was a high and low value consisting of the longest and shortest embedment length that bound the development length. Nineteen flexural tests were performed using one end of each specimen. The specimens were split among three types of concrete with three being cast with HSC, and 13 from the two SCC mixtures (SCCI and SCCIII). The results of the flexural tests are summarized in Table 5.

In each set of specimens tested, at least one beam exhibited strand slip before the nominal moment capacity (M_n) was achieved, and at least one failed without strand slip occurring. This information, combined with comparing the moment when slip occurred (M_{slip}) to the nominal moment, allowed a fairly good range of values to be developed for an estimate of the development length for each different concrete type. This was not without some question, however. For the SCCIII specimens, shear failures at short embedment lengths made determination of development length somewhat difficult. Also slippage below and above the nominal moment for specimens at certain embedment lengths in each group made determination of results somewhat complicated. Because development length is considered to be the embedment length where strand slip occurs at the same time as flexural failure when the specimen reaches nominal moment, there was difficulty.

Table 5. Development Length Results.

Beam ID	L_E (in.)	M_n (k-in.)	M_{slip} (k-in)	M_{max} (k-in.)	M_{slip}/M_n	M_{max}/M_n
HSC – 1	35	1076	---	1322	---	1.23
HSC – 2	30	1069	1118	1366	1.05	1.28
HSC – 3	35	1060	1161	1223	1.10	1.15
HSC – 4	40	1054	---	1268	---	1.20
HSC – 5	30	1063	990	1213	0.93	1.14
HSC – 6	47	1067	---	1337	---	1.25
SCCI – 1	37.5	1081	1044	1191	0.97	1.10
SCCI – 2	37.5	1090	1162	1272	1.07	1.17
SCCI – 3	40	1061	---	1274	---	1.20
SCCI – 4	35	1057	916	1262	0.87	1.19
SCCI – 5	30	1061	1008	1232	0.95	1.16
SCCI – 6	40	1065	---	1305	---	1.23
SCCI – 7	45	1050	---	1195	---	1.14
SCCI – 8	35	1070	---	1242	---	1.16
SCCIII – 1	32.5	1059	1285	1300	1.21	1.23
SCCIII – 2	35	1058	---	1351	---	1.28
SCCIII – 3	32.5	1058	1043	1107	0.99	1.05
SCCIII – 4	35	1063	---	1283	---	1.21
SCCIII – 5	30	1052	999.8	1021	0.95	0.97

Since no strand slip occurred in specimen HSC-1, tested at an embedment length of 35 in., it can be determined that the development length is less than 35 in. Strand slip occurred in both HSC-2 and HSC-5 tested at 30 in. However, slip occurred in HSC-2 at a moment 5% greater than the nominal moment, and slip occurred in HSC-5 at a moment 7% below the nominal moment. From this data, it can be determined that for HSC specimens, the development length is most likely near, but greater than, 30 in., and that it is probably located between 30 and 35 in.

Both SCCI specimens SCCI-3 and SCCI-6, tested at an embedment length of 40 in., failed without detection of strand slip. Specimen SCCI-4, subsequently tested at an embedment length of 35 in, exhibited strand slip at a moment 13% below the calculated nominal moment. This information leads to the determination that the development length is located between 35 and 40 in. Specimen SCCI-1 was tested at an embedment length of 37.5 in., and exhibited strand slip at a moment 3% below the nominal moment. Conversely SCCI-2 was tested at an embedment length of 37.5 and exhibited strand slip at a moment 7% greater than the nominal moment. This leads to the determination that the development length is near 37.5 in. and is most likely between 35 and 37.5 in.

No slip was detected in specimens SCCIII-2 and SCCIII-4 tested at an embedment length of 35 in. Specimen SCCIII-5 was tested at an embedment length of 30 in. and failed in shear before reaching the nominal moment. Slip occurred at a moment 5% below the nominal moment, but this was after the maximum moment had been reached and the shear failure had occurred. Therefore, it is difficult to determine exactly how this should be interpreted. Specimens SCCIII-1 and SCCIII-3 were subsequently tested at an embedment length of 32.5 in. Specimen SCCIII-1 exhibited slip at a moment 21% greater than the nominal moment while specimen SCCIII-3 exhibited slip at a moment 1% below the nominal moment. However, slip in SCCIII-3 occurred after the maximum moment had been reached and shear failure had occurred. Therefore, it can be determined from this data that the development length for the SCCIII specimens is less than 32.5 in., and is most likely near but greater than 30 in. More testing should be done for SCCIII specimens to validate the 30 in. lower boundary.

DEVELOPMENT LENGTH COMPARISONS

Both the ACI Code and AASHTO Specifications estimate development length using the relationship

$$L_d = (f_{se}/3)d_b + (f_{ps} - f_{se})d_b,$$

where f_{se} is the effective stress in the strands after all prestress losses (ksi), f_{ps} is the nominal stress in the strand (ksi), and d_b is the diameter of the strand (inches). The calculated values obtained using this equation and the embedment length values determined from the testing are compared in Table 6. This table also includes values of f_{se} and values of f_{ps} obtained from calculations based on strain compatibility. It can be seen from this table that the development length predictions using the ACI/AASHTO equation are significantly greater than those found experimentally. An experimentally estimated development length between 30 and 35 inches was found for HSC specimens, in contrast to the prediction of between 86.3 and 88.4 inches. This is an overestimation of 60% to 66%. The SCCI specimens had an experimentally determined development length of 35 to 37.5 inches while the prediction was 86.1 to 88.3 inches. This is an overestimation of 60% to 66% as well. The SCCIII specimens had an experimentally determined development length of 30 to 32.5 inches while the prediction was 89.2 to 89.4 inches. This is an overestimation of 64% to 67%.

It appears that HSC and SCC specimens have similar development lengths. SCCI specimens show a development length slightly greater than that of HSC, and SCCIII specimens appear to have a development length in the same range as HSC specimens. It should be noted that the average concrete compressive strength for HSC and SCCI were very similar, 14.51 ksi for HSC and 14.77 for SCCI, while the average compressive strength of SCCIII was somewhat lower, 13.19 ksi. The results obtained from this study concur with previous research suggesting that development length can be predicted by using the ACI/AASHTO equation with a reduction factor of 50%.

Table 6. Measured vs. Predicted Development Lengths

Beam ID	f_{se} (ksi)	f_{ps} (ksi)	L_E (in.)	Development Length (in.)	
				Observed	ACI/AASHTO
HSC – 1	178.5	266.3	35	30<L_d<35	88.4
HSC – 2	178.5	266.1	30		88.3
HSC – 3	182.9	265.8	35		86.3
HSC – 4	181.9	265.6	40		86.6
HSC – 5	178.5	265.9	30		88.2
HSC – 6	180.4	266.1	47		87.5
SCCI – 1	179.3	266.4	37.5	35<L_d<37.5	88.1
SCCI – 2	179.3	266.6	37.5		88.3
SCCI – 3	179.3	265.9	40		87.8
SCCI – 4	179.3	265.7	35		87.7
SCCI – 5	183.5	265.9	30		86.1
SCCI – 6	179.3	266.0	40		87.9
SCCI – 7	179.6	265.6	45		87.5
SCCI – 8	181.6	266.2	35		87.1
SCCIII – 1	175.3	265.8	32.5	30<L_d<32.5	89.4
SCCIII – 2	175.3	265.7	35		89.3
SCCIII – 3	175.3	265.7	32.5		89.3
SCCIII – 4	175.3	265.9	35		89.4
SCCIII – 5	175.3	265.6	30		89.2

CONCLUSIONS

Results obtained from the flexural load tests show that SCC and HSC beams have similar development lengths. Detailed conclusions are as follows:

- The development length of all beams tested (HSC, SCCI, and SCCIII) was less than 37.5 inches.
- SCCI beams had a slightly longer development length than both HSC and SCCIII beams.
- The ACI/AASHTO Equation overestimated the development length for all beams by more than 60%.
- All three concrete mixtures achieved similar differences between calculated nominal moment and applied moment at failure.

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